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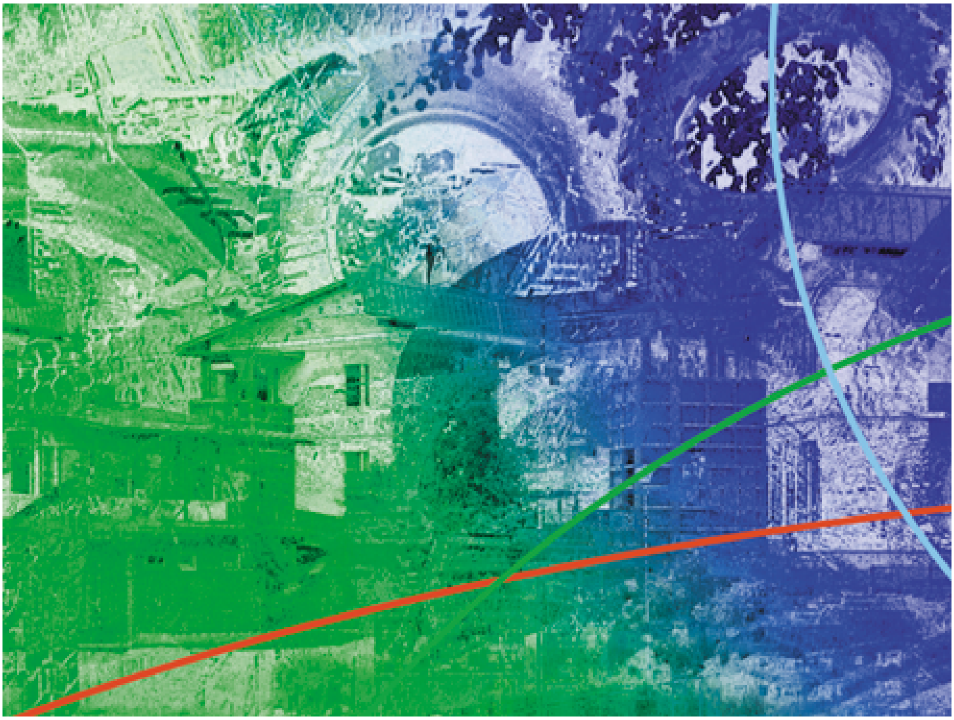
VTT SYMPOSIUM

International Conference on Practical Applications in Environmental Geotechnology

ecogeo ♲ 2000



TECHNICAL RESEARCH CENTRE OF FINLAND ESPOO 2000

VTT SYMPOSIUM 204

Keywords: environment, environmental protection, geotechnology, water pollution, air pollution, soil pollution, decision making, landfills, refuce disposal, remediation, groundwater

International Conference on Practical Applications in Environmental Geotechnology

ecogeo ♻ 2000

Helsinki, Finland,
4–6 September, 2000

Edited by

Markku Tammirinne

VTT Communities and Infrastructure

Organised by

National Technology Agency of Finland
Geological Survey of Finland
Finnish Environment Institute
Helsinki University of Technology
Technical Research Centre of Finland

TECHNICAL RESEARCH CENTRE OF FINLAND
ESPOO 2000

ISBN 951–38–5701–8 (soft back ed.)
ISSN 0357–9387 (soft back ed.)

ISBN 951–38–5702–6 (URL: http://www.inf.vtt.fi/pdf/)
ISSN 1455-0873 (URL: http://www.inf.vtt.fi/pdf/)

JULKAISIJA – UTGIVARE – PUBLISHER

Valtion teknillinen tutkimuskeskus (VTT), Vuorimiehentie 5, PL 2000, 02044 VTT
puh. vaihde (09) 4561, faksi 456 4374

Statens tekniska forskningscentral (VTT), Bergsmansvägen 5, PB 2000, 02044 VTT
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Otamedia Oy, Espoo 2000

Preface

Today, complex inter- and intra-relations between water, air and soil pollution, together with various time lags between the causes and effects, make practical decision-making in environmental matters very challenging. The temptation to postpone necessary decisions is in these circumstances perhaps understandable, but could be argued.

ECOGEO 2000 – The International Conference on Practical Applications in Environmental Geotechnology has the ambition to build a bridge between science and practical solutions to minimise the time lags in information and knowledge transfer. The scope of the conference is wide, as the reality in implementation projects.

ECOGEO 2000 provides a forum for transferring knowledge on practical applications concerning the technical and environmental aspects of industrial by-product utilisation, remediation of contaminated soils, and barrier structures for groundwater protection. The environmental risks connected with the use of industrial by-products are covered very thoroughly and the remediation methodology of contaminated soils is presented widely.

The conference is intended for corporate environmental managers, earth construction contractors, environmental experts and decision-makers from municipal and government sectors, entrepreneurs and private consultants as well as researchers.

The ECOGEO 2000 conference also concludes the Finnish five-year ecogeotechnology research programme, co-ordinated by Tekes, the National Technology Agency of Finland. The programme focused on the utilisation of industrial by-products in earth construction, on investigations and remediation of contaminated soils and groundwater protection technologies. The programme was financed by Tekes, private Finnish enterprises and R&D organisations. The total budget was about USD 10 million (FIM 60 million).

The results of the programme's individual R&D projects will be presented at ECOGEO 2000. They form the major part of presentations in the congress but, however, in addition a highly qualified collection of scientific papers from Finland and other countries are presented and included in this Conference Proceedings thus giving an excellent overview about the modern ecogeotechnological research.

From the offered papers the scientific advisors selected 67 papers for presentation at the conference. This Conference Proceedings volume includes 60 papers of those accepted. About two thirds of the papers are presented in three oral sessions titled:

1. use of industrial by-products in earth construction
2. contaminated soils
3. barrier structures for landfills and groundwater protection.

The remaining papers are presented in a separate poster session.

The Organising Committee of ECOGEO 2000 wants to thank all the authors, all attendants and sponsors for their contributions to this Conference Proceedings. Special thanks to the National Technology Agency of Finland for the financial support of this Proceedings.

Reijo Salminen

Chairman of the scientific programme of ECOGEO 2000

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USE OF INDUSTRIAL BY-PRODUCTS IN EARTH CONSTRUCTION

Stabilized clay as earth construction material

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ABSTRACT: The aim of this study was to investigate the possibility of using stabilized clay in the sub-base layer of the road structure in the eco-construction area in Viikki, Helsinki. Unconfined compression tests of stabilized clay were made in the laboratory, to discover the best clay-binder combinations and mix ratios. The frost-heave strength of stabilized clay was investigated using frost heave and freeze-thaw tests. Three binder combinations were used to stabilize the clay. The amount of binder was 14% (200 kg/m^3) by weight of the clay mass.

The test road (200 m) was divided into four separate sections, creating three sections with different binder mixtures and one reference section. Stabilized clay was used for the sub-base layer and, because of great variations in the sub-grade, a 200-mm thick drainage course was laid under the sub-base layer, to ensure equal drainage conditions in all sections. The moisture ratio and temperature of the stabilized clay were measured by sensors installed in the layer. The bearing capacity of the test road was measured using the plate-bearing test. The behaviour and strength of the stabilized layer was as planned while the bearing capacity did not decrease due to freezing-thawing conditions.

1. The background and objectives of the clay-road project

The project for utilizing mass-stabilized clay in road construction was initiated by the City of Helsinki, in co-operation with Lohja Rudus Envirotec Ltd. The four-year project was part of the Environmental Geotechnical Research Programme. Mass-stabilization machinery and equipment development was carried out by companies, as part of the same programme. Comprehensive laboratory tests were carried out at Lohja Rudus Ltd. and in the geotechnical laboratory of the University of Oulu. The actual construction and research plans for the test construction and the research reports were prepared by Innogeo Ltd.

A length of road about 200 metres long in the Viikki eco-construction area, about 7 km from the centre of Helsinki, was selected for the test structures. The test structures were built by the City’s Environmental Production Department while the City’s Geotechnical Department carried out monitoring measurements in the field. Twenty hectares of the fifty hectares of the Viikki eco-construction area are on very soft clay. Various ground reinforcement methods are being applied in construction in the area, the mass stabilization experiment being one of them.

The project was intended to investigate the possibility of using surplus clay masses, their design and dimensioning requirements, their structural durability, and the necessary construction techniques. Mass-stabilization was used to reduce the amount of natural rock material required in the area and to minimize the surplus masses created, as well as to improve the properties of low-quality earth materials, so that they could be used, for example, in road construction, infill, and noise-reduction berms. The total costs of the project were about 220.000 euros.

2. Material investigations of the clay to be stabilized

2.1 Purpose of the material investigations

The extensive laboratory studies programme of the research project was intended to investigate the binders and their amounts to be used in mass stabilization and the durability in use of the consolidated structure. Table 1 shows the tests carried out and their purposes.

Table 1. Tests made on test samples and their purpose.

Test arrangement	Purpose of test
• Uniaxial compressive strength	To use different binders and amounts to determine the best mix ratio for stabilized test samples.
• Frost-heave test	To determine the frost susceptibility of stabilized test samples, with the aid of their segregation potential.
• Freeze-thaw test	To determine the frost resistance of stabilized samples under cyclical freezing-thawing conditions.
• Thermal conductivity test	To determine the thermal conductivity of test samples in both a thawed and frozen state.
• CBR loadbearing test	To obtain a CBR loadbearing ration to assess the suitability of stabilized masses for road construction.
• Dynamic triaxial test	To determine the behaviour of stabilized test samples under dynamic loading.
• Water permeability	To estimate, on the basis of the rests, the susceptibility to frost of stabilized test samples and their suitability for various applications.
• Solubility (diffusion) test	To determine the environmental suitability of stabilized samples, using a Dutch solubility test.

2.2 Earth material and binders

The earth material studied was taken from a depth of 1,5–3,6 m in the Viikki - Latokartano area. The grading curve showed the earth to be frost-susceptible fat clay (Fig. 1), with a water content of 54...84%. The plasticity index (I_p) of the clay was 36,7%, its ignition loss 0,15%, and its pH 7,3. The selected binders were cement, a mixture of cement and lime, binder mixes: filler C, E1, E3, and E4 (Lohja Rudus Ltd.), and cement-activated blast-furnace slag.

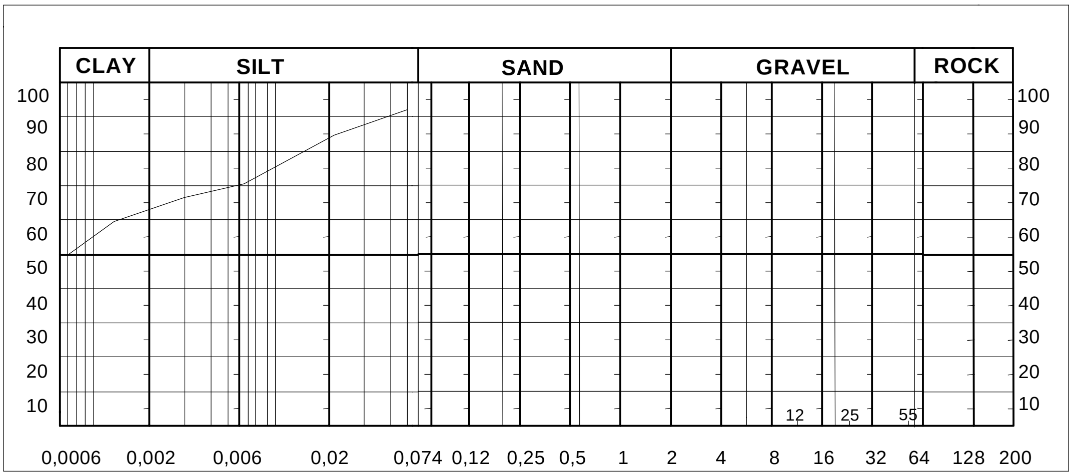


Figure 1. Stabilized clay grading curve.

2.3 Compressive strength, bearing capacity and thawing behaviour

The compressive strengths of the stabilized clay samples were determined using a uniaxial compression test. Table 2 shows the binders and amounts used. The consolidation times of the samples were 28 days and 60 days.

The change in the volume of test pieces kept on a capillary mat varied between 0...2,3%. During the test, water was absorbed into the materials by capillary action, which was shown by the increase in the test pieces' mass and weight by volume during the test. The compressive strengths of the samples varied between 95...372 kPa, except for the binder mix JMk + Se (70:30/12%), which had a compressive strength of 842 kPa. The compressive strength of this binder and amount was also considerably greater (897 kPa) than that of other binders. This shows that the consolidation reactions of cement-activated blast-furnace slag continue more strongly after the crushing and compaction of the material, than is the case with the other binders studied (Table 3).

Table 2. Compressive strengths and changes in the volume of the materials determined after the freezing-thawing test.

Binder/ (mix ratio)/ Amount of binder	Treatment of test pieces					
	Capillary mat		Freeze-thaw test piece 1		Freeze-thaw test piece 2	
	Change in volume ΔV (%)	Compressive strength S (kPa)	Change in volume ΔV (%)	Compressive strength S (kPa)	Change in volume ΔV (%)	Compressive strength S (kPa)
Binder C /30%	1,0	95	2,8 (1)	-	2,0 (1)	-
E1 /12%	0,0	187	2,3 (1)	-	4,6 (1)	-
E3 /12%	1,3	103	5,6 (2)	-	7,7 (2)	-
E4 /12%	1,0	273	18	39	16	45
Se+CaO (1:1) /12%	0,2	372	15	90	18	57
Se+CaO (95:5) /12%	1,7	234	20	69	5,0 (3)	-
Se / 6%	0,2	180	12 (11)	-	19	42
Se /12%	1,8	172	12 (5)	-	8,7 (4)	-
Se /18%	2,3	198	7,4 (3)	-	7,3 (3)	-
JMk+Se (70:30) /12%	1,3	842	16	67	17	45
E1 /12% B	1,8	149	4,3 (2)	-	9,8 (5)	-
Se+CaO (1:1) /12% B	0,6	363	1,6 (2)	-	16	56
Se /12% B	0,4	243	12 (5)	-	8,7 (4)	-
JMk+Se (70:30) /12% B	1,0	897	16	59	160	65

B = sample prepared according to method 1

Note: The number in brackets in the columns showing the change in volume is the number of the cycle in which the test piece failed.

Most of the samples in the freeze-thaw test (17/28 pcs) failed before the end of the test series. The compressive strengths of those remaining intact varied from 39 to 90 kPa, which means that, independently of the binder, the compressive strengths were considerably lower than those of the samples kept on a capillary mat. An increase in volume, which, in the case of the test pieces that withstood 12 freeze-thaw cycles, varied from 15 to 20%, was observed in all test pieces. The materials absorbed water by capillary action, increasing the masses of the test pieces during the test. However, the weight by volume of the materials simultaneously decreased, due to the materials' great freezing dilation (Table 2).

Evaluating and handling the materials between the freeze-thaw cycles was made difficult by involution of the surface of the test pieces and their fragile structure. Handling of the test pieces resulted in a loss of samples while some of the test pieces broke when being moved and measured. Due to the loss of samples, the changes in volume measured in the test pieces must be regarded as a minimum value for the expansion of the materials in the test in question.

Because the results of the compressive strengths in the freeze-thaw test were not promising, the bearing capacity of the stabilized clay samples was studied using the CBR (*California Bearing Ratio*) test. CBR values were determined for unfrozen and thawed samples. The freezing of the thawed sample took place under conditions corresponding to those in the frost-heave test. In the thawing stage, the temperatures of the upper and lower surfaces of the sample were +1,5°C. Once the samples had fully thawed, they were tested. According to the CBR-test the bearing capacity of the stabilized clay mass was adequate for the demands of road structures. This was also proven by a plate-loading test made during the constructing of the test road (see 3.6.2).

2.4 Frost susceptibility and freeze-thaw behaviour

Laboratory frost-heave tests were used to study the frost susceptibility of the stabilized clay samples. The frost susceptibility of the earth materials and the degree of susceptibility to frost can be assessed on the basis of segregation potential (SP), among other factors.

The frost-susceptibility tests showed all the samples investigated to be susceptible to frost. Clay stabilized with a cement/lime mix (95:5) with a binder proportion of 12%, and with cement using a binder proportion of 18% was slightly susceptible to frost (0,5 < SP < 1,5). Clay stabilized with cement-activated blast-furnace slag was averagely susceptible to frost (SP = 2,0). All the other samples investigated were highly susceptible to frost (SP > 3). Table 3 gives a summary of the frost-susceptibility test results.

Table 3. Frost-susceptibility test characteristics.

Binder/ (mix ratio)/ binder amount (%)	Total frost-heave 96h H (mm)	Frost-heave proportion z_{24h}	Frost-heave velocity v_{24h} (mm/h)	Frost-susceptibility index SP (mm^2/Kh)	Frost-susceptibility class, based on frost-susceptibility indices
Filler C /30% *)	7,7	0,13	0,26	5,0	Highly susceptible
E1 /12% *)	11	0,12	0,31	7,3	Highly susceptible
E3 /12% *)	11	0,14	0,34	4,5	Highly susceptible
E4 /12%	14	0,09	0,21	5,5	Highly susceptible
Se+CaO (1:1) /12%	10	0,06	0,19	4,8	Highly susceptible
Se+CaO(95:5)/12%	5.3	0,03	0,06	1,5	Slightly susceptible
Se /6%	16	0,10	0,26	6,5	Highly susceptible
Se /12%	9.8	0,04	0,12	3,5	Highly susceptible
Se /18%	3.5	0,01	0,04	1,0	Slightly susceptible
JMk+Se(70:30)/12%	6.5	0,04	0,10	2,0	Averagely susceptible
E1 /12% B	16	0,10	0,29	7,8	Highly susceptible
Se+CaO (1:1) /12% B	12	0,07	0,22	7,3	Highly susceptible
Se /12% B	8.7	0,05	0,14	3,8	Highly susceptible
JMk+Se (70:30) /12% B	16	0,11	0,30	6,3	Highly susceptible

B = samples prepared differently according to others
*) Duration of frost-heave test 45,5 h

2.5 Dynamic triaxial test

The result of a dynamic triaxial test is a dynamic modulus of elasticity (*resilient modulus*), the dependence of which on the stress state is often depicted by a power function. The tests were made on unfrozen and thawed samples. Freezing of the thawed sample took place under conditions corresponding to the frost-heave test. Thawing lasted at least 24 h.

3. Test structure studies

3.1 Design and dimensioning of the test structures

The sub-base layer of the test structure was made from stabilized clay, the estimated amount required being about 500 m^3rtr (Figure 2). The test structure was designed and dimensioned on the basis of the conclusions of laboratory studies at the University of Oulu. The dimensioning factor of the structure was frost resistance, which was to be controlled by the amount of binder. The dimensioning of loading resistance and the amount of binder were selected for a target bearing capacity of 136 MN/m^2. The layers of the test structure are shown in Table 4.

Table 4. Layers of test structure and reference structure.

Layer	Test structure		Reference structure	
	material	thickness	material	thickness
course layer	AC 20/100	40 mm	AC 20/100	40 mm
base layer	AC 2 x 30/150	120 mm	AC 2 x 30/150	120 mm
unbound base layer	crushed stone	200 mm	crushed stone	150 mm
sub base	stabilized clay mass	550 mm	sand / gravel	500 mm
insulation layer	sand	200 mm	-	-
	Total	1110 mm	Total	810 mm

The binders selected were E1 (Lohja Rudus Ltd.), a cement-lime mix (95:5), and cement-activated blast-furnace sand (70:30), according to which the test structure was divided into three sections of equal length. The designs of the E1 and blast-furnace slag/cement test sections included steel mesh in the bearing layers. The amount of binder used for stabilization was 14% of the wet mass of the clay.

3.2 Mixing equipment

The mixing method selected for this experiment was a new type of mass-stabilization device, developed by Ideachip Ltd. as an environmental geotechnical product development project. The mixer is attached in place of a shovel to a hydraulic excavator (Figure 2).

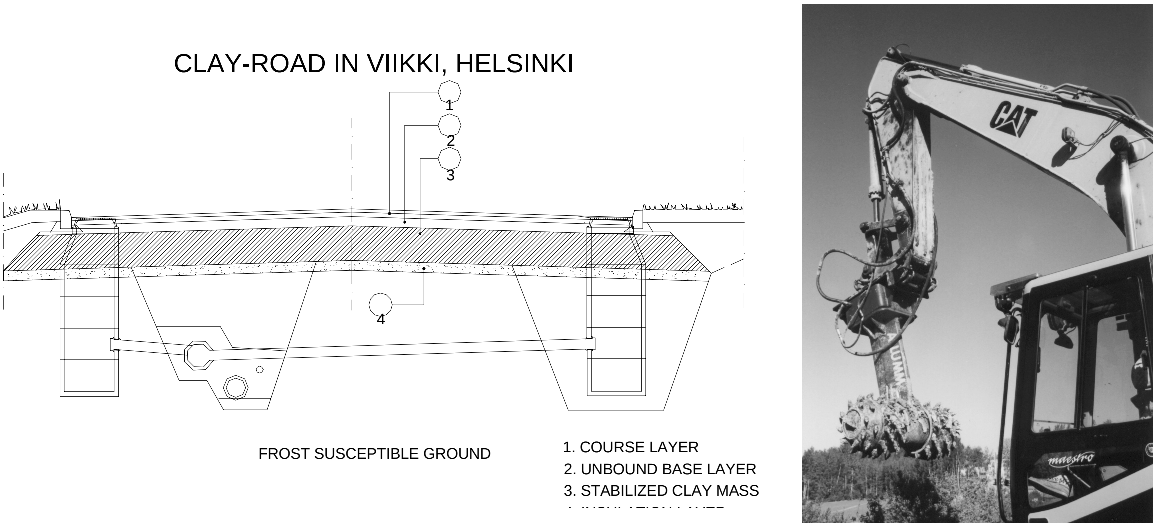


Figure 2. Cross-section of test structure and mixer attached in place of a shovel to a hydraulic excavator.

3.3 Clay material

The clay was excavated from a depth of about 1...2,5 metres in a field in Viikki. Technical difficulties during the work (reach of equipment etc.) and a weakening of the stability of the excavation ramps, limited the depth to a maximum of 2,5 metres. The assumed initial moisture content of the clay was about 50...60% by weight . On warmer days, the moisture content of the clay dropped, both at various stages of handling and as a result of moisture absorption by the binder, so that during mixing the stabilized clay became a stiff, dry mass.

3.4 Construction

The base of the test structure varied from clay to bedrock. In places, the bedrock had to be excavated and sections of soft ground had to be stabilized with pillars. The substructure of the test structure sections was embanked and compacted to a level of -1,10 from the grade line. On top of the embankment, a drainage and levelling layer about 0,2 m deep was made, in which subsurface drains were laid at both sides of the roadway. Fibre fabric was laid on top of the drainage layer. The drainage layer was intended to create uniform conditions in the different test sections, to facilitate comparison and ensure more reliable results. In hot conditions the surface of the clay mass was cracking (Figure 3a) so it was covered using plastic membrane (Figure 3b).

Mass-stabilization began in the summer of 1997. Binders were delivered to the site by tanker in batches of about 10...20 tonnes. The binder was blown from the truck to the base of the excavation under protective covers, to prevent dust spreading. 110 kg of binder was spread in 1 m^2 squares in a marked area. A clay layer 0,5 m thick was mixed at a time.

3.5 Construction costs

Cost monitoring of the test structure was carried out to the accuracy possible in the measurement of the construction materials and the work-hours spent on construction. The costs of the test structure do not correspond completely to the costs arising from the use of mass-stabilized clay in a normal construction project. Usually, the clay masses to be stabilized are greater than in the test structure, so that the amount of binder used will also increase while costs per unit of construction decrease.

In the future, the amount of binder required can be assumed to be 100…200 kg per cubic metre of clay, depending on the structural component. The price of the binder works out at about 6…18 euros, the cost of mixing at about 1...2 euros, and handling costs at about 2...5 euros per cubic metre of clay, giving a total cost of 8...25 euros/m^3, including finishing and overheads.

3.6 Clay road measurements

3.6.1 Settlement measurements

Settlement was measured from the tops of studs set in the surface of the pavement. The studs were set on both sides of the roadway at intervals of 5 metres, a distance of 1,75 m from the centre-line and on the centre-line. The measurements were made in winter, once frost had penetrated through the stabilized clay structure and in spring, once the entire construction had thawed.

Settlement averaged 5…10 mm. Total settlement (about 30 mm) was the greatest in an area in which 10 m of clay lay beneath the road structure. Taken overall, the frost movements were between 0…10 mm and were caused by the freezing of water and the subsequent expansion of the structure, and not by the occurrence of frost heave. Freezing expansion over the entire depth of the structure does not break the structure, as the formation of ice lenses in frost heave would.

3.6.2 Measurements of bearing capacity, made from the surface of the pavement

The bearing capacity of the thawing ground was measured with a plate-loading device (Figure 3d), once the stabilized clay layer began to thaw. Thawing of the stabilized clay layer (0,55 m) was estimated to take about 2 weeks. The results of the bearing capacity measurements showed, that all bearing capacity values obtained the road structure guideline values. Measured bearing capacities varied between 300…450 MPa.

On the basis of moisture and temperature observations, it can be concluded that only part of the water in the stabilized structure had frozen during the frosts of the winters of 1997–98 and 1998–99. Therefore, there was no significant freezing expansion in the structure. The bearing capacity in the spring was measured when the structure was weakest, having thawed completely but with its greatest moisture content. Values varied between 200…300 Mpa. Measurements of bearing capacity made in 1999 show that consolidation of the stabilized structure continued after the previous year's measurements.

3.6.3 Measurements of moisture in the construction

Ground moisture was measured using the TDR method, i.e. cable radar. Table 5 shows the results.

Table 5. Moisture contents measured in the test structure in 1997–1999. The structure was partly frozen in the case of the values in brackets.

Measurement points	Moisture contents, volume-% at the measurement points								
Year	1997		1998					1999	
Date	21.08	25.11.	13.2.	27.2.	22.4.	23.6.	13.10.	3.3.	21.4.
Test con. 1, 210	32,7	40,0	(21,1)	29,5	45,5	42,5	40,0	(30,2)	40,8
Test con. 2, 250	36,1	45,3	(31,7)	29,4	53,0	42,1	40,4	(30,1)	44,2
Test con. 3, 290	40,0	39,3	(36,4)	37,2	43,6	38,6	43,6	(34,6)	42,2
Reference con. 330	18,4	19,0	(-)	< 1	20,4	12,4	14,4	(3,1)	15,8

Moisture measurements made during 1997–98 show that the water in the stabilized clay structure froze only partly. The reason for this was the warm winter and the properties of the stabilized clay, so that freezing was complete only at temperatures of -5...-7 °C. There were no great changes from the previous year in the moisture measurements in the winter of 1998–99. Again, the stabilized structures only froze partly. The moisture measurements (Table 5) show that the unbound layers froze completely.

4. Conclusions

Altogether the utilization of stabilized clay mass was successful. The settlements varied between 5…10 mm, which was under limits. Also the bearing capacity values (300…450 MPa) measured using the plate-loading test obtained national standards.

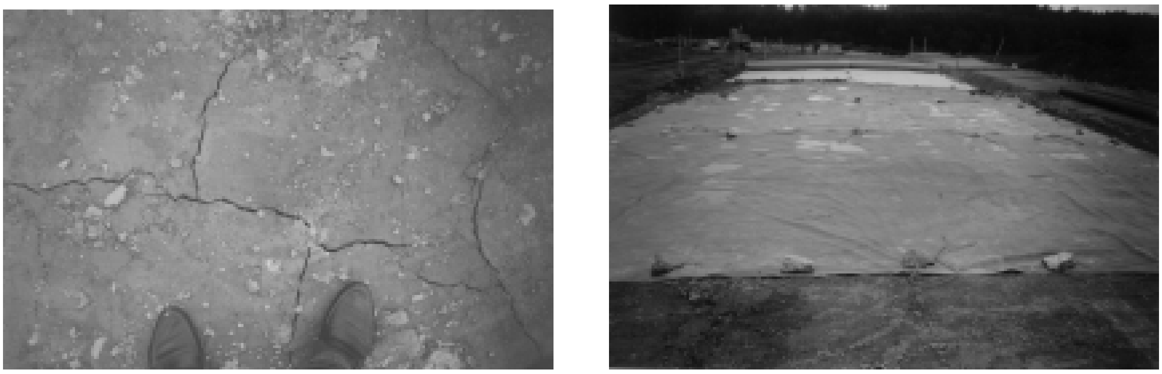
The strength achieved by stabilization is determined by the frost resistance and bearing capacity of the material, so that, as the strength increases, the values of the above material properties also increase. In addition, as strength increases, frost-susceptibility decreases.

If the binders used in this study are examined in terms of quality, the binder alternatives with the greatest potential for improving the frost resistance of a stabilized excavated mass appear to be the mixtures JMk+Se (70:30) and Se+CaO (95:5).

A precondition for the use of stabilized excavated masses in road construction is the limitation of water absorption, so that it can be assumed that there will be very little frost heave in the material. There is then also no change in volume. When dimensioning loadbearing capacity, an initial value of 150 MPa can be used, with a binder content of

12% when using Se+CaO(95:5) and JMk+Se(70:30) as binders, as the modulus of elasticity of the sub-base layer of a road built from a stabilized excavated mass.

The Viikki experiment shows that the competitiveness of clay construction will be affected substantially by a reduction in binder costs. The necessary amount of binder has a decisive effect on the strength and durability requirements of structural components, which depend on the location of the structural component, the class of the road, etc.



a) Cracks on surface of stabilized clay mass

b) Clay mass covered using plastic. membrane.

c) Constructing clay-road.

d) Plate-loading test.

Figure 3. Photos about road constructing in Viikki, Helsinki using stabilized clay mass.

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N.B. All the above publications are in Finnish.

Life cycle inventory analysis program for road construction

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ABSTRACT: The Finnish LCA-database and inventory analysis program for road construction was developed as a part of the Technology Development Centre's (Tekes) Environmental Geotechnology Programme. In the first stage of the study a life-cycle impact assessment procedure for the comparison and evaluation of alternative road and earth constructions was proposed. Additionally, a database containing the environmental burdens of the most significant construction materials and unit operations and the information required for the calculation of the data was constructed. In order to evaluate the applicability of the methodology the use of coal ash, crushed concrete waste and granulated blast-furnace slag was compared with the use of natural materials in corresponding applications.

All the work stages from material production to road management as well as the materials most commonly used in the structural courses of road constructions are covered in the analyses. The environmental loadings dealt with have been limited to those assessed as being the most important.

During the later phase of the work a practical calculation model based on the developed methodology and existing data was formulated. The data obtained in the first stage was also augmented to the extent necessary for this purpose. For example, leaching tests of natural aggregates were performed. The Excel-based life cycle inventory analysis program created is suitable for the routine calculation of the environmental loadings of the most common road constructions and for their comparison.

1. Development of the LCA-methodology

1.1 Background

About 70 million tonnes of natural mineral aggregates are used each year in Finland for road construction and earthworks. Depletion of the best materials, the need for resource conservation and lengthened transport distances have all increased the need to introduce substitute materials for natural aggregates. At the same time industry, construction and other similar activities produce large quantities of secondary products, which may be suitable for use.

One of the barriers to the wide-ranging utilisation of the secondary products of energy production and industry in road construction has been uncertainty about the environmental impacts. In order to prevent potentially hazardous effects it is important to identify all the positive and negative impacts of these materials. Life cycle impacts are also being increasingly used as a selection criterion for products and materials both in industry and in other activities.

Describing the total environmental impacts of activities and products reliably and in such a way that alternatives can be compared is no simple task. The ”cradle-to-grave” life cycle always involves numerous stages and activities that give rise to a number of different environmental loadings. In order to keep the amount of work within reasonable bounds, the assessments must always be limited and efforts must be made to identify the critical stages of the life cycle and those factors responsible for environmental loadings. This requires not only adherence to the basic principles of life cycle analysis but also knowledge of the product or activity in question.

1.2 Scope

The basic aim of the study was to provide a clear and functional procedure for the life cycle impact assessment of road constructions and for the comparison of alternative structural solutions. It was hoped that the assessment procedure would be so simple to use that it could easily be appliedd by road planners and designers. However, the assessment should cover the main life cycle phases of the constructions as well as the most important environmental impacts, and it should also meet the other basic requirements set for life cycle analysis. One premise was also that the assessment procedure should be applicable as a part of road planning, and that the results could be used as selection criteria for alternative constructions and materials.

The assessment procedure should also take account of the special features of road constructions, which are the large volumes of materials used, the long service lives of the finished products, the need to examine constructions as a whole rather than comparing alternative materials, and the significant effect of the constructions' longevity and need for repair on their life cycle environmental loadings.

The work was carried out in two stages so that in the first stage a proposal was made for a procedure suitable for the life cycle impact assessment of road construction (Eskola & Mroueh 1998, Eskola et al. 1999). In order to evaluate the applicability of the procedure, the use of coal ash, crushed concrete waste and granulated blast-furnace slag in road construction was evaluated in case studies. The use of these industrial by-products and waste materials was compared with the use of natural materials in corresponding applications. The necessary data was also collected during the studies. The aim of the work's second stage was to transfer the assembled data for utilisation as a practical model by creating an inventory analysis program to calculate and compare the life cycle impacts of the most common road constructions. The data obtained in the first stage of the study was augmented to the extent necessary for this purpose (Laine-Ylijoki et al. 2000, Mroueh et al. 2000).

1.3 Methodology

The basic phases of life cycle impact assessment are goal definition and scoping, inventory analysis, i.e. calculation of the material and emission flows, impact assessment and, if necessary, improvement assessment. In this study the life cycle assessment methodology was adapted to meet the requirements of road construction. The material and emission flows were determined at all stages of the life cycle, and the most important environmental impacts as well as their associated factors were identified. The following general procedural guidelines on life cycle assessment were applied: SETAC’s (Society of Environmental Toxicology and Chemistry) ‘Code of Practice’ (1993), Nordic Guidelines on Life-Cycle Assessment (Lindfors et al. 1995) and ISO standards (ISO 14040, ISO 14041).

1.4 System boundaries

1.4.1 Functions and work stages

The analysis included all the significant life-cycle stages covering the production and transportation of materials, their placement in the road structures and the use of the construction. The situation after the use of the construction was not included in the analysis because the structures most commonly remain in place after they have been withdrawn from service. The structures were examined as entities because in road construction the selection of a material often influences the quality and quantity of other materials used, the work methods employed, the need for upkeep, etc. Pavement and sub-grade structures were analysed separately and can be combined when necessary. The environmental loading data was calculated for each individual structural component and work stage, so that it is possible to examine flexibly the alternative constructions under study at any given time. The principal road construction and usage phases, which were taken into account when comparing structures and materials are shown in Fig. 1.

If industrial by-products are used in the constructions, the environmental burdens of landfill disposal can also be assessed, as an alternative to their use in road construction. This requires that landfill disposal is a real alternative to utilisation.

Those stages of road construction and use that have no significance for the comparison of constructions were ruled out of the analysis. These include: *site clearance*, *functions associated with road use* (e.g. lane markings, the installation and use of traffic signs and lights), *regular or seasonal maintenance* (e.g. snowploughing, road salting and sanding) and *traffic emissions*.

1.4.2 Environmental loadings

The environmental loadings assessed as being essential during the life cycle of road constructions were selected on the basis of the case studies for inclusion in the analysis. The included environmental loadings were the following:

1. *Use of resources*: natural materials, industrial by-products, energy and fuel consumption
2. *Atmospheric emissions*: carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), volatile organic compounds (VOC), particles and carbon monoxide (CO)
3. *Leaching into the ground*: heavy metals, chloride and sulphate
4. *Other loadings*: Noise, dust and land use

On the basis of a preliminary assessment of the quantity and significance, the following environmental loadings were excluded from the inventory: water use, discharges of COD and nitrogen to water, emissions of PAH, heavy metals and methane, ordinary and hazardous waste and accident risks.

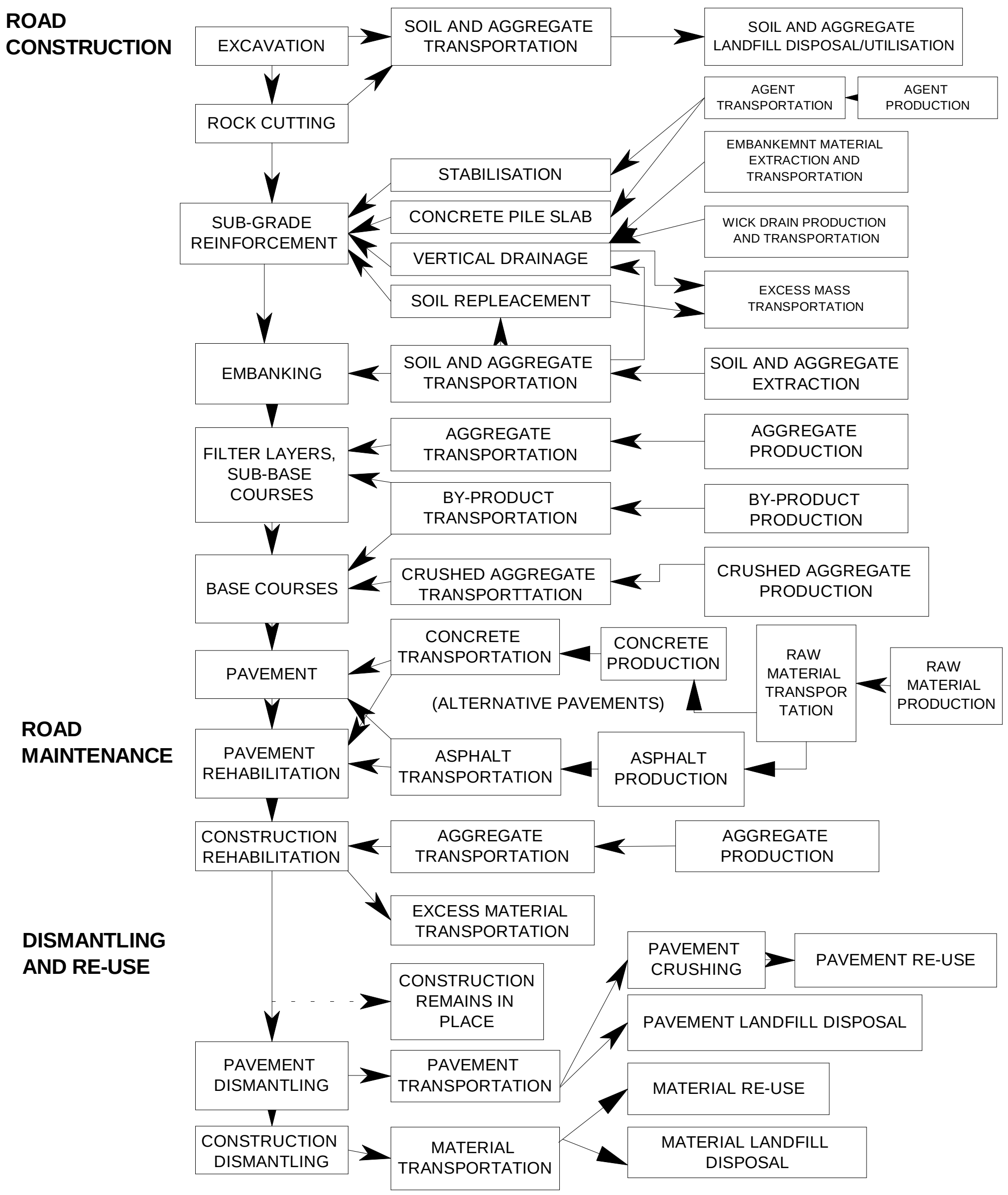

Figure 1. The principal road construction and usage phases.

1.4.3 Material production chains

The production chains of natural aggregates started from bedrock excavation or excavation from the ground. For cement and lime the starting point was extraction of raw materials and for rubber the production of crude oil. The production chains of industrial by-products were limited so that the environmental loadings of the by-product production process were not included in the analysis. By-products are defined in waste legislation as wastes for which no loadings are allocated in life cycle analyses. An alternative to the use of most by-products as recycled fill is disposal of the inert waste in landfills.

1.4.4 Other boundaries

<u>Functional unit:</u> When comparing constructions, the functional unit should always be structures of the same length that meet the same performance requirements and are

designed for the same site. In practical cases the entire construction can also be the functional unit.

Period of analysis: The period of analysis should include the entire life cycle of the material or product from raw material extraction to withdrawal from service and final disposal. In the life cycle assessment of a road construction the period of analysis must be sufficiently long to include the impacts of its service life.

Machines and equipment: The loadings caused by the manufacture of work machines and lorries and by the maintenance of machines were excluded from the analysis. The manufacture and transportation of blasting materials and fuels were also excluded.

Situation after use: It was assumed in the analysis that the construction would remain in service for 50 years. As road constructions usually remain in situ after use, no cases in which a construction was dismantled were examined in this report.

Landfill disposal: The program can give an approximate estimate of the environmental loadings avoided by using industrial by-products as recycled fills. The program calculates the minimum avoided loadings, i.e. the landfill volume needed for the inert waste and the emissions that would be released in transporting the material to the landfill site. The loadings caused by any sealing and covering of the landfill have not been included in the analysis because of their site-specific variability. Neither has leaching into the soil on the landfill site been assessed.

2. Environmental impact assessment

2.1 Significance assessment

The aim of the life-cycle environmental impact assessment is to convert the inventory results into a form that can be more easily interpreted and compared. The impact assessment procedure is performed in three stages: *classification*, i.e. sorting the environmental loadings into impact categories on the basis of potential impacts, *characterisation*, i.e. weighting the emissions and other environmental loadings within the category according to possible impact potential, and *valuation*, i.e. weighting the environmental loadings or impacts in relation to each other.

The advantage of the valuation methods is the simplicity of result interpretation. The final outcome is either one environmental loading index or an impact matrix of mutually comparable effect scores. Further exploitation of the results does not require any expertise on the part of the user.

The creation of significance factors that are as reliable and widely applicable as possible is one of the greatest problems of valuation. Effect scores generated by different methods also make it more difficult for the users themselves to assess the significance of the results. They often also arouse suspicion, because valuation means an increase in the influence of experts in decision-making, which some fear will lead to the influence of citizens being reduced and one-sided views being over-emphasised.

Several assessment methods have been proposed for the results of life cycle analyses, none of which can be regarded as being generally accepted or even applicable in all situations (Lindfors et al. 1995). The best known are the Swedish Environmental Priority Strategy (EPS) system, the impact categorisation method, which has been developed in Holland and Sweden, and the ecopoints method developed by BUWAL of Switzerland.

In this study the effect scoring was made on the basis of expert assessment. The environmental loadings of the constructions were converted into relative values using the reference construction made of natural materials as the base level. After the relative environmental loading levels had been calculated, the impact categories were proportioned to one another by multiplying the effect scores by the comparative scores obtained on the basis of expert assessment. Because the construction and the transport distances always affect the outcome of such comparisons, the results as such cannot be generally applied to the comparison of materials. When comparing the alternative constructions it is notable that in all respects the differences between the constructions are not particularly great, and that the differentiating factors act in opposing directions.

2.2 Data sources and uncertainties

Because of the local nature of the effects of road constructions, primarily local or material-specific data was used. Use was also made of general Finnish knowledge, which was supplemented by international sources of data where necessary.

The availability of data on by-products is limited by the fact that their utilisation is not yet well established. For this reason it is not always easy to determine the most usually employed working methods and the most general implementation methods of the work stages. As yet there is still relatively little experience- or measurement-based data on the work stages and their environmental loadings.

The release of dust emissions from materials during the different stages of production, transportation and construction is a significant environmental loading factor due to the comfort and heath risks that they pose. However, little measurement data on the release of dust emissions was found and its conversion into a comparable form was problematic. In practice, small particulate matter (SPM) can be more significant than dust particles. SPM emissions remain airborne for a very long time and are carried long distances by winds. Moreover, they pose a more serious health risk than dust particles. Because SPM emissions have attracted attention only recently, there is even less data available on them than on dust emissions.

The quantities of substances leaching out of secondary materials were simulated on the basis of laboratory-scale leaching tests. In practice, numerous factors affect leaching from construction materials. There can also be significant differences between the same material when produced under different conditions. Because there was no leaching data for natural aggregates, a few materials were tested during the project. The tests used were CEN pr EN 12457 (1996) and a pH-static test. The leaching of heavy metals from natural aggregates was found to be very small.

Because it is necessary to make many assumptions when assessing the environmental loadings, the uncertainties and ranges of the results are quite large. However, the fact that the same assumptions have been made when examining the various alternatives improves the reliability of the results.

3. The inventory analysis program

In the second stage of the project an Excel-based life-cycle inventory analysis program for road construction was created and the suitability of the program for calculation of environmental loadings of various constructions was tested.

3.1 Characteristics of the program

The inventory analysis program created on the basis of the developed methodology is suitable for the routine calculation of the environmental loadings of the most common road constructions, and for their comparison. Most of the data needed for calculations is included in the program. Only the dimensions of the construction, materials and thicknesses of the structural courses and transport distances of materials are required as input data.

The environmental loadings are presented in numerical form or using various standard graphical presentations included in the program. The program enables comparison of pavement structures as such, in relation to fixed reference construction or as effect scores.

The environmental loadings of constructions or structural courses (embankment materials, filter layer, sub-base, base course and pavements) can be presented by principal work stage or as total loading.

The pavement structure and the sub-grades are analysed separately and the results can be combined if necessary. The program includes the following alternative sub-grades: soil replacement, soil stabilisation, deep stabilisation, vertical drainage + drainage course + temporary loading berm and concrete pile slab.

If necessary the program can be extended to include new materials, structural components and alternative sub-grades.

3.2 Case studies

For testing of the life-cycle inventory program the environmental loadings of five actual road planning cases were calculated (Laine-Ylijoki et al. 2000). The calculation of environmental loadings of case studies proved to be a relatively simple and fast task. The use of the comparison worksheet enabled straightforward comparison of the alternatives and presentation of the results of calculations. An example of the graphical presentations included in the program is presented in Fig. 2.

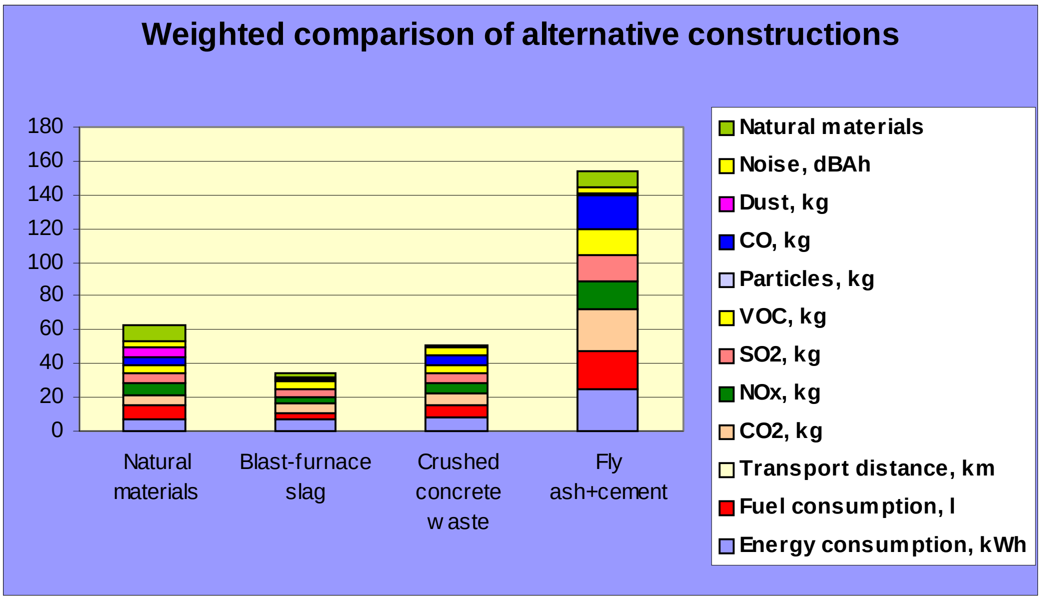

Figure 2. Example of the graphical presentations included in the program. Weighted comparison of alternative pavement constructions.

4. Conclusions

A life-cycle impact assessment procedure for the comparison and evaluation of alternative road and earth constructions was developed. The procedure focused especially on the comparison of industrial by-products and natural aggregates, but the assessment of other constructions is possible, as well. An Excel-based life cycle inventory analysis program for road constructions was developed on basis of the procedure. The program covers all the work stages from material production to road maintenance as well as the materials most commonly used in the structural courses of road constructions. The environmental loadings of the constructions and structural components made from the materials within the scope of the program can be calculated simply using only the dimensions of the construction, the thicknesses of the structural courses and trasport distances as input data.

The program is suitable for routine calculations of environmental loadings of different road constructions. The environmental loadings are presented in numerical form or using various standard graphical presentations included in the program. The environmental loadings dealt with in the program have been limited to those assessed as being the most important. However, the loading factors in question described the total environmental loadings quite well as long as the life cycle inventory pertains to complete constructions. The environmental loadings regarded as being the most important for road construction in the expert assessment made when creating the inventory analysis procedure were the use of natural materials, energy and fuel consumption, the leaching of heavy metals into the soil, and atmospheric emissions of NO_x and CO_2.

The simplicity of the inventory analysis program makes it suitable for use by structural designers and other groups not so familiar with LCA methodology. The program has an extensive basis database and extensions with new materials, structural components and sub-grades are possible.

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The quality control and the geotechnical properties of reclaimed concrete in earth construction

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ABSTRACT: Reclaimed concrete material is generated through the demolition of concrete elements and structures during building demolition operations. In this article the quality control and the geotechnical properties of reclaimed concrete have been studied.

The quality control of by-products is even more important than for "traditional" aggregates in order to have an acceptable material for utilisation in earth construction. The assorting demolition is a base for acceptable raw material for reclaimed concrete and the quality control secures the properties of the product. The geotechnical and environmental properties of reclaimed concrete have been studied in field on test roads and in a laboratory during several years. Both geotechnical and environmental properties of the crushed material indicate that the use of reclaimed concrete in road construction is acceptable.

On the basis of the field and laboratory studies and experiences user guidelines for the use of reclaimed concrete have been made for the Finnish National Road Administration (FINRA) and for the Association of Finnish Local and Regional Authorities. Also the quality assurance standard of reclaimed concrete is under work in Finland.

1. Introduction

Reclaimed concrete has been used in pavement construction since 1994 in Finland. Reclaimed concrete crushed by Lohja Envirotec Ltd is known by name Betoroc™-crush and it is classified to grades by the raw material and technical properties. In Finland Betoroc™ has been used in road and street construction mostly in sub base and base layers. Reclaimed concrete has shown favourable geotechnical properties in field studies on test roads and in laboratory tests and is thereby suitable for use in road construction. The quality control of by-product is important in order to have an acceptable material for utilisation. The by-product utilised in earth construction must have adequate technical and environmental properties and permanent quality. The Finnish quality assurance standard of reclaimed concrete will contain the quality control demands, methods and schedule of controlling for each phase from demolition operation to earth construction.

2. Classification of the Betoroc materials

Betoroc™ is classified to grades by the raw material and technical properties. A material can origin from building demolition operations or for example from hollow concrete production as waste, which have been abandoned due to manufacturing process requirements. The classification by the raw material is presented in Table 1. Table 2 presents the technical and environmental classification of the material.

Table 1. Classification of Betoroc™ by the raw material.

Grade	Raw material
BeM I	Pure reclaimed concrete, which origins for example from concrete element manufacturing.
BeM II	Reclaimed concrete, which origins from demolition of concrete structures and buildings. It may content some harmful materials.
BeM III	Reclaimed concrete, which origins from demolition of concrete structures. It might not have any self-hardening properties.
BeM IV	Reclaimed concrete, which origins from demolition of concrete structures. It has no self-hardening properties and it may be frost susceptible.

Table 2. Basic properties of Betoroc™ (a) and content of harmful materials and the use on the ground water areas. (b)

a)	Grain size distribution	Self-hardening properties	Frost susceptibility	E-modulus
BeM I	0–50 mm	Hardens	No	700 MPa
BeM II	0–50 mm	Hardens	No	500 MPa
BeM III	0–50 mm	Uncertain	No	280 MPa
BeM IV	Varies	No hardening	Varies	≤ 200 MPa*

* to be considered in each case

b)	max. content of bricks [weight-%]	Max content of other * materials [weight-%]	Leaching tests in crushing phase
BeM I	0	0,5	Not demanded
BeM II	10	1	Demanded
BeM III	10	1	Demanded
BeM IV	30	1	Demanded

* wood, plastics, etc. In addition of the weight-% demand there may not be harmful amounts of special light materials (such as polystyrene and other insulation materials).

3. Geotechnical and environmental properties

The geotechnical properties of the crushed reclaimed concrete have been studied both in laboratory tests and in test roads and streets. Table 3 presents some test results of crushed reclaimed concrete materials. The values shown present the variation of values of testing (the real variation of the properties may be larger). The design values of E-modulus are presented in Table 2a. The determination of the E-modules on the basis of the field and laboratory tests is presented in detail in the article Geotechnical Properties and Bearing Capacity of Reclaimed Concrete[Forsman & al. 2000].

The bearing capacity of the reclaimed concrete structures has been measured using plate load test or falling weight deflectometer (FWD). The first measurements have usually been done straight after compaction of the crushed reclaimed concrete layer and soon after paving. Later the bearing capacity has been measured in springtime and/or in summertime.

The E-modulus of the reclaimed concrete structure has been back-calculated on the basis of the field measurement data using both Odemark and APAS methods. APAS is a software developed by FINRA and Neste Ltd for analytical pavement design and it is based on NOAH (Nynäs Overall Approach) calculation module developed by Nynäs in Belgium [Pienimäki 1994]. Using this APAS-program it is possible to fit the calculated bowl to the measured FWD-bowl and that way back-calculate the E-modulus of road materials layer by layer.

Table 3. Geotechnical properties of reclaimed concrete based on some test results [Viatek 1999].

Property *	Unit	**Betoroc™ I** (hollow core slab waste)	**Betoroc™ II** (demolition waste)	Crushed concrete in general
Optimum water content	%	8…10	8…12	8…12
Maximum dry weight	kN/m^3	18…20	17.5…20.5	
Minimum dry weight	kN/m^3		12.7…14.5	
Specific gravity	t/m^3			2.55…2.65
Compression strength, 7 d	MPa	1.2…1.3	0.3…1.1	
Compression strength, 28 d	MPa	2.0…2.1	0.6…1.3	
Capillarity	m	0.25	0.20	
Permeability	m/s	1…7 $\times 10^{-5}$		
pH		12.7…12.9		≥ 11
Segregation potential	mm^2/Kh		0.11…0.28	
Heat capacity (unfrozen)**	Wh/m^3 K		485…590	
Friction angle	°			40
CBR-ratio	%			90…140
Los Angeles –ratio		23	28	

* E-modules used in dimensioning are shown in Table 2a.
** approximated from the field observations by back-calculation.

The environmental properties of Betoroc™ have been tested in Technical Research Centre of Finland (VTT) / Chemical Technology [VTT 1996; Wahlström et al. 1997]. The results from these chemical analysis and from tests made later show that Betoroc™ is environmentaly acceptable for road construction. On basis of the chemical analyses the target values for leaching from mineral demolition waste have been given (shown in Table 3). The target values shown in Table 4 concern the replacing class I (material can be used without limits in base layers). VTT Chemical Technology [1996] has also proposed recommendations for the quality assurance system for the utilisation of reclaimed concrete. The quality control will be done by the manufacturer.

Table 4. Target values for leaching from reclaimed concrete proposed by VTT [1996]. Proposed test method is CEN –batch leaching test with protocol 3 [prEN 12457 1996].

Element	Sulphate	Chromium	Cadmium	Copper	Lead
Target value (mg/kg)	750	0.5	0.02	0.4	1.0

4. Quality control system

In the case of by-product the quality control is even more important than with a "traditional" aggregate in order to have an acceptable material for utilisation in earth construction. Both the geotechnical and the environmental properties of the reclaimed concrete have to be studied by detailed quality control plan and with proper methods agreed in the user guidelines.

In Finland the quality assurance standard of reclaimed concrete [VTT 2000] is in progress to be created in co-operation of VTT, Lohja Envirotec Ltd and Viatek Ltd as a part of a wider quality assurance standard. The draft of quality assurance standard of reclaimed concrete contains the required quality controls and approved methods for controlling. The generation process and the quality controlling of reclaimed concrete is presented in Figure 1.

Main phases in processing reclaimed concrete are as follows: the delivering of raw material, transportation, receiving raw material at operating site, stockpiling of raw material, crushing, grading, stockpiling of crushed material and supplying material to utilisation site. In each phases the quality of the material is controlled. The studies the supplier does are grain size distribution, frost susceptibility (on the basis of the grain size distribution), maximum bulk density and optimum water content (if needed), compression strength, material purity and environmental qualifications.

5. Methods of quality control

5.1 Waste concrete

The first control of the waste concrete is visual checking of the material and its purity. The crushing stations of Lohja Envirotec Ltd have detailed guidelines for checking and classifying the received material. Materials containing harmful components such as PCB, creosote, asbestos, oil, heavy metals or sulphates are not accepted as raw material. The purity of the material is also checked visually through the manufacturing process from raw material till the utilisation site.

5.2 Grain size distribution and frost susceptibility

The grain size distribution is determined by grading (SFS-EN 933-1). One grading has to be done per every 2000 tonnes of material or at least twice a week. The grain size distribution curve must meet the requirements for the base layer grain size distribution presented in the FINRA’s guidelines [FINRA 1985]. Frost susceptibility of the material is determined by the grain size distribution. The frost susceptibility of the material is monitored with the same sampling interval as the grain size distribution. The reclaimed concrete in groups I, II and III (Tables 1 and 2) must be non frosting, in group IV the frost requirements depend on the case.

5.3 Maximum bulk density and optimum water content

If needed the maximum bulk density and optimum water content are determined by the improved Proctor test or the IC test. In the IC test the work pressure is 4.0 bar and the rounds are 160.

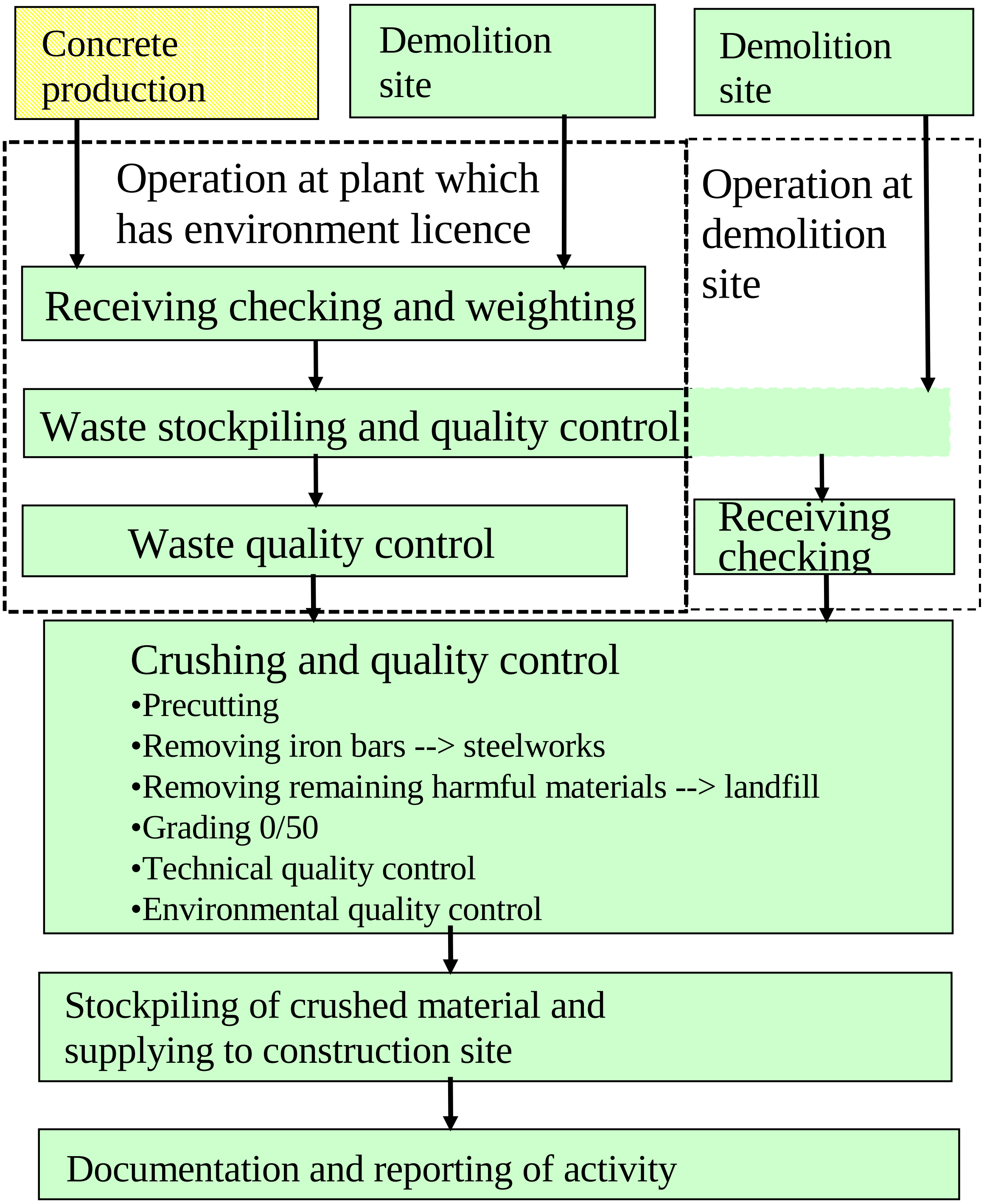

Figure 1. The generation process and the quality controlling of reclaimed concrete.

5.4 Compression strength

For determining the compression strength and to be able to follow the hardening, one sample set / 10 000 t or at least one sample set / crushed parcel is performed with specimens compacted the IC-tester equipment. One sample set includes 7 specimens. The specimens are prepared in the same way as the maximum dry weight is determined. The compression is done following the guidelines of BY 15 Concrete Norms 1993. Three specimens are compressed at the age of 7 days and three specimens are compressed at the age of 28 days. The seventh specimen is a spare sample which is compressed if needed. The specimens are kept at +20ºC covered with plastic foil.

5.5 Material purity

Material purity must be determined sufficiently often, at least at 20 000 t intervals. The determination of the amount of organic impurities (wood, plastic etc.) and the amount of bricks is done following the standard NEN 5942 (Nederlandse norm 1990) with the corrections as follows:

- The grains over #8 mm are divided approximately in three groups; concrete, bricks and others.
- The weight proportions (weight %) of each material are calculated from the total mass left on the #8 mm sieve.

The classification of the reclaimed concrete regarding impurities is presented in Table 2b.

The determination method of material purity has been developed by testing several methods and comparing the advantages and disadvantages of the different methods. Such methods as combustion, water weighting, photos and picking have been tested for determining the amounts of organic impurities and bricks. Combustion, floating, blowing and photos have been tested for determining the amounts of special light materials (such as polystyrene and other insulation materials).

5.5.1 Combustion

Combustion is a method which might be used for determining the amount of light materials but also for example wood etc. Combustion was done in an asphalt furnace at +500 ºC temperature. The problem was that at the temperature as high as used causes lost of water of crystallization in the concrete material and stones and the results are therefore unreliable. If combustion is used in determining the amounts of impurities it needs the correction curves done for the lost of the water of crystallization.

5.5.2 Water weighting and floating

The volume of the crushed concrete specimen was determined by sinking it into water. The specimen was weighted before sinking. The problem of this method was that the water intrudes into the concrete and brick grades and therefore the measured weight is not right. Another problem was the relative close density of concrete and bricks which causes difficulties specially in determining the amount of small proportions of bricks.

Floating is used for determining the amounts of special light materials (such as polystyrene and other insulation materials). When using floating, the material must be dehydrated after floating for further determining (amounts of bricks etc.).

5.5.3 Blowing

Blowing, like floating, is used for determining the amounts of special light materials (such as polystyrene and other insulation materials). Blowing loosen not only the special light materials but also cement from crushed material and is not therefore a reliable method for determining impurities.

5.5.4 Photos

Photos were taken of materials which were made mixing predetermined amounts of impurities into pure crushed concrete. The idea was to compare visually the crushed concrete specimens to the photos and determine the amount of impurities by the reference photos. Problem was that the small amounts of impurities gather on the surface of the pure concrete and the reference specimen looks less pure than it actually was. The method suits for rough estimation but not for exact determination of impurities.

5.5.5 Picking

In this method the impurities of the specimen are picked and sorted. The method was modified from the standard NEN 5942 (Nederlandse norm 1990). This method needs experienced examiner, but it is absolutely the most exact and reliable method and therefore is chosen as the used method. The method used will continuously be developed by Lohja Envirotec Ltd.

5.6 Environmental qualifications

The environmental qualifications are determined following the principles shown in the Figure 1. Before the crushing of the specimen the purity and the content of harmful materials is estimated visually.

Studied sample taken from the crusher run is crushed in grain size under 4 mm and then the sample is divided into laboratory samples (2 kg). The wideness of the testing depends on the raw material and the replacing site. The total content of harmful metals is determined using methods prEN 13657 or prEN 13656. PAH and PCB are recommended to be determined by using methods Nordtest recommends. The defining of metals in solutions are done following standards prEN 12506 and prEN 13370. The leaching of harmful compounds is determined by L/S relation 10 following test prEN12457-3 or using column test NEN7343 or NT ENVIR 002.

6. "User guidelines"

In Finland user guidelines for the use of reclaimed concrete and the guidelines for the quality control have been made for the FINRA and for the Association of Finnish Local and Regional Authorities by the financial support of The Finnish Technology Development Centre. The dimensioning parameters of reclaimed concrete and the construction procedures with reclaimed concrete have been studied on the basis of Finnish and foreign experiences. Dimensioning parameters have been reported in detail in a separate report "Design parameters of crushed reclaimed concrete" [Viatek 1999].

The bearing and the frost dimensioning parameters have been presented in the first part of user guidelines. The design considerations and ready-made dimensioning tables have also been presented. The E-modulus of reclaimed concrete (grade I…III) used in dimensioning has been 280…700 MPa depending on the properties of the material. By using high classic reclaimed concrete in some cases it is possible to make thinner bitumen bound surface layers. In the second part of user guidelines the construction procedures of reclaimed concrete pavements have been presented following the format of FINRA’s guidelines.

The user guidelines for the use of reclaimed concrete and the guidelines for the quality control made for the FINRA have been translated into English by Lohja Envirotec Ltd [Viatek 2000].

7. Conclusions

In the case of by-products the quality control is even more important than with "traditional" aggregates in order to have an acceptable material for utilisation in earth construction. Both the geotechnical and the environmental properties of the reclaimed concrete have to be studied by detailed quality control plan and with proper methods agreed in the user guidelines.

The assorting at the demolition site is a base for acceptable raw material of the reclaimed concrete. The quality control is needed when receiving the material at crushing stations. Also the whole process from crushing to delivering of the crushed material is under continuous quality control for securing the properties of the product.

Reclaimed concrete has shown favourable geotechnical properties in field studies on test roads and in laboratory tests. The reclaimed concrete, Betoroc™, has self-hardening properties (grades BeM I…II) and it is not frost susceptible (grades BeM I…III). The results from the chemical analysis show that Betoroc™ is environmentally acceptable for road and street construction outside the ground water areas.

Crushed reclaimed concrete has been used several years in street and road structures mainly in base and/or sub base layers. The structures made with Betoroc™ can be constructed by using normal road construction methods. The most important difference is the need to maintain the necessary humidity for hardening process of the concrete structure.

In Finland user guidelines for the use of reclaimed concrete have been made for the FINRA and for the Association of Finnish Local and Regional Authorities. The guidelines content material properties and classification of reclaimed concrete, dimensioning the structures with reclaimed concrete and guidelines for construction procedures. The quality assurance standard of reclaimed concrete is in progress to be created in co-operation of VTT, Lohja Envirotec Ltd and Viatek Ltd as a part of a wider quality assurance standard in Finland.

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The application of fly ash in Chinese freeway

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ABSTRACT: The applications of fly ash in Chinese freeways projections were explained in this paper. The using fly ash conditions, technology requests and economics, environment and social beneficial results in which fly ash be used on embankment, bases and cement concrete pavement of freeway were introduction.

Key words: Fly ash Embankment Bases Concrete Pavement

1. Introduction

In China on the great scale of freeway construction, in specially, we pay attention to protection of resources and environments, making to fly ash industrial solid waste as the resources of constructing highway to sufficiently utilize. In the embankments of freeway of Beijing to Shi jiazhuang, Shi jiazhuang to Anyang and Shanghai to Nanjing etc. the great amount of fly ash (25.05 million tons) in which is lower quality of its reservoir of power stations were applied. The number of freeway in III grade fly ash (6.5 million tons) adding cement or lime were used as the binder to stabilized graded sand and aggregate bases. The several cement concrete pavements of 460km (193.2 thousand tons) new constructed freeway in I, II grade fly ash in which to cement ratio 1/4-1/10 were used. It is protected ground resources, and decrease 25 thousand tons cement and reduce the equal amount CO_2 expelling to air. The total application of fly ash has 36.39 million tons, road total length is 3459.1 km, the 5943.2 hectares land has been saved. It has reduced 3.6 million tons fly ash flying into air. It is not only protected air and ground environments, but also the constructing fund about 1.881 billion RMB yuan of both freeway and power stations had been saved. It is realized sustainable development in Chinese freeway construction.

In this paper the using fly ash conditions, technology requests and economic environment and social beneficial results in which fly ash applied on embankments, bases and cement concrete pavement of freeway in China was introduction.

2. The application of fly ash on embankments in freeway

Because our populations and villages, towns are so much dense. The number of bridges and exchanges of Chinese freeway are more than abroad. The every 1 kilometer has 3 bridges, so the height of embankment in Chinese freeway is more than average 6 m. The amount of soil engineer is very great in the construction of freeway, we need to purchase so much soil to fill embankment of freeway. As our ground resources is very limited, the construction of freeway occupied great ground, to dig soil also ruined fertile land. At the same time, according our country policies we must recover arable land, protecting our limited fertile land resources.

In other hand, the area of building freeway is the more economic developing area, because of limited land resources, the soil price of using freeway is very expensive, in this area we had many coal power stations and so much fly ash waiting utilization. In this condition it is necessary that fly ash replaced valuable soil resources. The Chinese government encourages the utilization of fly ash in the highway engineering according to the economic sustainable development strategy. Under both the department of communications and electric power coordinately planed and guided, the application to highway projects of fly ash on storing its reservoir was encouraged from the country policy. The power stations provide economical subsidy and convenience of loading or transportation to highway constructing unites of using fly ash.

2.1 The specification of fly ash application to embankments

The ministry of communications in China issued and carried out "The Technology specification of design and construction of fly ash embankments in highway" JTJ016-93 in Dec. 1993[1]. It is included as follows:

2.1.1 The design of fly ash embankments in Chinese highway

The quality inspection of fly ash, design parameters, transverse form and shape of embankment, checking of stability, calculation of sinking, standard of rolling were included at this specification. The sketch map of fly ash embankment is shown as fig.1. The most important thought is that use soil to surround fly ash in embankment and protect fly ash to flying air and around environments in highway application process. The rolling density of fly ash embankments increased 90% to 93% as the height set up. The another method is separated layers of fly ash and soil. The last method is tested in experimental embankments, but nowadays it is scarcely used.

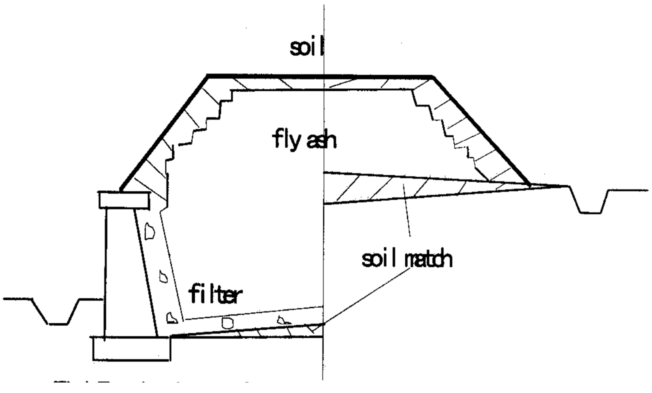

Figure 1. The sketch map of fly ash embankments.

2.1.2 The construction of fly ash embankments in highway

The construction of fly ash embankments is included its storing, transporting, paving, rolling, and curing etc. In the construction process of fly ash embankments it is need to solve the main problem: protecting fly ash to fly pollution into the surround air and vegetables, trees, crops and feed at near highway in its transportation. another problem is controlling the most suitable moisture of fly ash in rolling density process.

2.1.3 The quality management and inspection of fly ash enbankment

Its detailed regulation includes material test, inspection in construction process, completed inspection etc.. The technology rules are wide, density, slope, shape, altitude of transverse, smoothness, middle line error, value of load sinking, module of spring etc.. The inspection of the highway shoulder, side slope and ditch also definitely regulated.

2.2 The scale of constructing fly ash embankments

The technology of fly ash to fill embankments is utilized on which mainly several freeway had been finished in Chinese recently years. Author statistical results as table 1.

Table 1. The statistics table of fly ash application in freeway embankments.

Finished year	Freeway name	Used amounts of fly ash (million ton)	Length highway (km)	Saved lands (ha)	Remarks
1989	ShangHai-Jiading	0.20	1.30	10.0	test road
1993	Jinan-Qindao	0.40	3.625	20.0	test road
1994	Kaifen-Loyang	0.50	23.400	30.68	test road
1995	Beijing-Shijiazhuang	2.60	46.90	126.73	practice project
1995	Shanghai-HangZhou	1.00	28.20	46.0	practice project
1996	Shijiazhuang-Taiyuan	2.00	38.10	92.05	practice project
1997	Shanghai-Nanjin	6.25	119.60	282.14	practice project
1998	Shijiazhuang-Anyang	12.50	238.00	707.02	practice project
1989-1998	Freeway total	25.05	499.125	1314.62	
1990-1995	commonly highway	4.65	1500	2401.2	
	total	27.45	1999.125	3715.82	

In above table 8 freeways applied fly ash in embankments (this maybe not complete in all over country). We used total 25.05 million ton fly ash in freeway embankments. The length of constructing freeway is 499.125 km. It saved land 1314.62 hectares. Commonly highway used fly ash 4.65 million ton, the construction length of fly ash embankments is 1500 km, the saved land is 2401.2 hectares. The all highway embankments used fly ash 27.45 million ton, the construction length of fly ash embankments is 1999.125 km, the saved land is 3715.82 hectares.

3. The application of fly ash in freeway bases

The application of fly ash in freeway bottom bases is probable 6.50 million ton, the construction length of freeway is 1000 km. It is 20% of total finished freeway until 1997. We carry out “ Technology Specification of construction in highway bases” JTJ034-93[2]. In this specification the two stabilizing materials classes of fly ash plus lime and fly ash plus cement can be used to fixed soil, sand, sand and gravel, grade aggregates in freeway bottom base. Besides, we used various solid industry wastes, for example, slugs, steel slugs, Ti slugs, Ge slugs etc. As various chemical and physical properties of the kinds in industry wastes are very different, so they must be tested in application on highway bases. Here we only introduction the application of fly ash in freeway bases.

Beside of highway in Chinese municipal engineering the fly ash adding lime to stabilize gravel is major base form. The amount of fly ash in application of bases is about 5%-20% of its ratio to be stabilizing materials. The fly ash in application of bases is fly ash of III grade or below III grade. The chemical compositions and amount of fly ash being used to base on freeway are demanded that the total of SiO_2,Al_2O_3,Fe_2O_3 is more than 70%. The loss of burning of fly ash is not more than 20%. The ratio of surface area to weight is more than 2500 cm^2/g. The ratio of lime (cement) to fly ash is generally between 1:2 ~1:4. The proportioning of lime (cement) adding fly ash to soil, sand, grade aggregate is ordinary between 10:90 ~ 30:70. their proportioning is various so greatly, it depends on the materials fineness, character and chemical reaction activity. It is determined according to the testing compressive strength after it being soaked in water at 7 days. The base strength of lime adding fly ash is not less than 0.8Mpa. Its strength of bottom base is not less then 0.5Mpa. the compressive strength of fly ash adding cement in base is not less than 2~ 4Mpa, Its strength of bottom base is not less then 1.5Mpa. The construction methods of bases are two kinds. one is mixed in road bed, another is mixed in mixer machine. In our country standard of freeway rules must be mixer machine to blend, then it must be paving using asphalt pavement machine. Its rolling density is 96%.

4. The application of fly ash in cement concrete pavements

Owing to worry bout resistant wear and erosion is not enough after in the cement concrete pavements (CCP) adding fly ash. The fly ash is not be used in CCP in the past. in " The technology specification of design in highway cement concrete pavements" JTJ012-94[3] regulated a kind of portland cement with fly ash is not be used in freeway concrete pavements. Therefore, The application of fly ash in freeway CCP is researched in slipform concrete pavements after 1991.

We consider that in CCP adding fly ash is one of making high performance road concrete. In the research plan 85 of the national science and technology the ability of fly ash in certain mixtures to attain sufficient flexural strength and enough wear resistance was studied to ensure long-term concrete durability as well as protecting the environment through the recycling of by-product resources[4]. At the same time, in several freeway CCP projects were used fly ash in 460 km. The most length is 320 km Shenzheng to Shantou freeway in Guangdong province. Application of I, II grade of fly ash is about 193.2 thousand tons. It corresponds to save cement over 25 thousand tons. The CO_2 expelling to air decreased 25 thousand tons.

The application of fly ash in CCP consult to " The application technology specification of fly ash concrete" GBJ146-90[5]. According to our research the technology requests of application fly ash in freeway CCP as follow:

4.1 The technology demands

4.1.1 The quality of fly ash

The dry fly ash request to reach the technology quality indexes of I, II grade in Chinese

CCP. Its fineness (45 μ m screening remains)is ⩽ 20%; Its loss of combustion is ⩽ 8%; The ratio of demanding water is ⩽ 105%; the content of SO_3 is ⩽ 3%. The fly ash of III grade will not be used unless through experiment verify the strength, shrinkage and demand water etc. is suitable to make CCP. the moisture fly ash is not be used in CCP, due to combine lump of fly ash, it is not stirring to separate, it will not be well-distributed.

4.1.2 The volume of using fly ash

According author research[6], the proportioning of fly ash to portland cement is introduction between 1/4-1/10, the most volume of using fly ash at test project in CCP is 30%, but early flextural strength is less, there are the question of fracture board and curing time prolong, therefore we do not introduced so large contents of fly ash in CCP. Our guide thought is under the precondition of the all properties at freeway will be satisfied the application of fly ash in CCP. We do not pursue high contain of fly ash in CCP.

We must ensure the excellent quality of CCP. From cementitious theory in portland cement the gypsum and production $Ca(OH)_2$ of its reaction is mostly reacted with 28% of fly ash[7], if it is larger than this contain, the surplus of fly ash is not benefit for CCP. Another reason is in China our commonly portland cement has already contained 15% mineral cementitious materials. If we used 30% fly ash, the total mineral cementitious materials is larger than 45%. According above theory the best ratio of fly ash to cement, the surplus part of fly ash is not completely reacted with cement and obtain the responding to strength, under this condition the surplus fly ash will not only benefit but also be harmful to concrete quality as soil in mixture.

4.1.3 The design of proportioning of fly ash cement concrete

The design method of proportioning of fly ash cement concrete is overweight contain method[6], if I grade of fly ash the overweight ceofficent is 1.3; II grade of fly ash it is 1.5. surplus part of fly ash replaces sand and decrease sand content.

Through research in CCP we regulated the minimum cement content is not less than 250 kg/m³; The maximum content of fly ash is not more than 100 kg/m³; In China we usually used cement content 300-340kg/m³ with commonly portland cement 525#, the fly ash contain is 50-80kg/m³.

When we used entrained air admixture (we request compulsory application in CCP), the content of entrained air admixture will be double increased in fly ash cement concrete pavements. Other parameters of proportioning design in the fly ash cement concrete is the same as cement concrete materials.

4.2 The advantage and disadvantage

4.2.1 Improving workability of mixture

In the CCP adding fly ash make the total number of pozzolans in mixture proportions increases, The rich mortars get the shape of slipform pavement is more smoothness and rideability. The research determined that the fresh concrete mixtures of plus fly ash can decrease the vibration viscosity coefficient, it makes concrete mixture more easy to vibrated density. At the same time, the slump of adding fly ash into fresh concrete mixtures is also decreased, it is benefited to protect claps and slump in the slipform pavement edges. There is only the fly ash effects of micro glass balls, it can improve the workability and viscosity of concrete mixtures with fly ash. In usually conditions it is inverse proportion in both of vibration viscosity and slump. That they simultaneously reduce will be meted the contradiction demands of slipform rigid pavements construction technology. The properties of rheology in concrete mixtures is improved by the effects of micro glass balls of fly ash.

4.2.2 Increasing the flextural strength of long ages period

The modulus of rupture or flexural strength is the most important property of CCP. Though the early ages strength of the concrete with fly ash is not enough, its long ages strength can developed very high. The results are shown as table 2. The flexural strengths with fly ash at 28 days is more than 4.5Mpa, theirs at 90 days will be over 6Mpa, at 300 days will be more than 7Mpa. The more content of fly ash the more flexural strength increased. The most 300 days flexural strength is 8.1Mpa as fly ash content is 30%.

Table 2. The flexural strength development of CCP with fly ash.

Contents of I grade fly ash %		**The flexural strenght (Mpa)**			**Cement content (kg/m^3)**
CPC252#	**7 days**	**28 days**	**90 days**	**over 300 days**	**w/c=0.42**
0	**5.3**	**6.0**	**6.1**	**6.2**	**350**
10	**5.1**	**5.6**	**6.2**	**7.0**	**330**
15	**4.7**	**5.4**	**6.3**	**7.3**	**310**
20	**4.6**	**5.1**	**6.4**	**7.8**	**290**
25	**4.4**	**4.7**	**6.5**	**7.9**	**270**
30	**4.1**	**4.5**	**6.7**	**8.1**	**250**

Note: In this test the slump = 3–4 cm; gravel aggregate's D_{max}=30mm; river middle sand and the sand rate = 32%, with chemical admixtures.

4.2.3 Increasing durability

At first the resistance wearing is proportion to the strength at the same time in CCP. due to the flexural strength of the concrete with fly ash is eventually so high. The resistance wear at serviceability also very high. In the other hand, there are no chemical activity (alkali aggregate, sulfate, corrosion). There is more durability than the concrete with no fly ash.

4.2.4 Increasing dry shrinkage easy product plastic cracking

Due to the total cementitious materials in CCP with fly ash is more than the concrete with no fly ash. In generally, the cement content of 525# commonly portland cement in CCP is

300-350kg/m^3. The total cementitious content in CCP with fly ash is 350-400kg/m^3. the cement content of 425# commonly portland cement in CCP is 340-380kg/m^3. The total cementitious content in CCP with fly ash is 400-460kg/m^3. Its total content in CCP with fly ash is obviously more than concrete with no fly ash. In high cementitious is easy to cause the plastic crack at the summon windy job sites. The high proportion of cementitious concrete is not resistant cracking. We research has shown that the maximum cracking evaporation rate in Chinese CCP at these harsh environmental factors is not 1.0 kg/m^2hr, It is only 0.5 kg/m^2hr. The high cementitious concrete with fly ash must be applied 0.5 kg/m^2hr cracking evaporation rate to control plastic cracking in the structure of CCP.

4.2.5 The lower strength at early period easy to cause fractures of slab

The lower strength at early period easy to cause fractures of slab at CCP paving. In specially when slipform paving links another lane, due to before paved lane at longitudinal joint has already inserted the tie bars. The contract joints of which has in advance fracture through tie bars can transmit the fracture deformation from earlier to just new paving lane. This fractures of slabs be called the corresponding contract fractures of slab. There is disadvantage of CCP with fly ash, but we can in advance used soft cutting technology of sawing contract joints to effectively avoid and control their production.

4.2.6 Demand prolong curing time

The fly ash cement concrete demands prolong curing time, owing to its strength development is slower than others. This problem can be resolved, as the application of a sprayed-on curing compound. Its time of opening transportation will be postponed and protected curing compound membranes. The objective of prolong curing time can be reached.

5 Summary and conclusions

5.1 According to author's discomplete statistics, In several freeways 25.05 million tons of low quality fly ash was used to fill highway embankments. The freeway length is about 499.1 km. The 1314.62 hectares land have been saved. In some highways 4.65 million tons of fly ash was used to fill highway embankments. The highway length is about 1500 km. The 2401.2 hectares land have been saved.

5.2 The half-rigid bases of highway and freeways were applied 6.5 million tons III grade of fly ash plus lime or cement uses as the binder to stabilized graded sand and aggregate. The highway length is about 1000 km. The 1600.8 hectares land have been saved.

5.3 The several cement concrete pavements of 460km (193.2 thousand tons) new constructed freeway in I, II grade fly ash in which to cement ratio 1/4-1/10 were used. The 25 thousand tons cement and 10 million RMB yuan investments have been saved. It is meanings the 25 thousand tons CO_2 expelling in air has been reduced. These CO_2 for the air pollution has been protected to air environment.

5.4 The application of fly ash in highway bring the great environment and economic result effects(see table 3): In the highway constructions 1.335 billion RMB yuan investments have been saved. The power stations have saved investment 0.546 billion RMB yuan. In both highway and electric power 5943.22 hectares have been saved. We used fly ash replaced cement to product CCP. That fly ash flying at environment 3.6 million tons be reduced. It is great significance for Chinese in which the more populations and the less land resources and the more shortage construction investments.

Table 3. The total table of the application and effects of fly ash in Chinese embankments bases concrete pavements.

statistical year	kinds	used fly ash (million tons)	highway length (km)	saved lands (ha)	environment and economic effects
1989-1998	freeway embankment	25.05	499.1	1314.62	highway construction saved investment 1.335 billion RMB yuan
1990-1995	highway embankment	4.65	1500	2401.2	power station saved investment 0.546 billion RMB yuan
1990-1996	bases	6.50	1000	1600.8	reduce CO_2 expel in air 25 thousand tons
1994-1998	concrete pavements	0.1932	460	626.6	reduce fly ash flying environment 3.6 million tons
total		36.39	3459.1	5943.22	

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Ecological aspects of using utilized tires in building

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ABSTRACT: A great number of car and other tires with metalcord annually turn into waste. Keeping a great number of utilized tires causes fires and other disastrous effects. Utilized tires have original properties. Basing on those they have worked out the constructions of seismostable buildings, foundations, breast-walls, gabions, shore-strengthening walls, antierosional structures, drain constructions, mud stream protection construction, wave protection constructions and so on. Using utilized tires does not influence the longevity of the constructions for the tires are retained unspoilt for 50–60 years in the open air; and for 1500–2000 years in water.

1. Introduction

In the countries of the UIS (Union of Independent States) they annually recive about 5 million tons of car, aviation, tractor, motor-cycle and other tires being utilized because of their shabbiness.

It is jast the minority of tires stored, that is used in second processing. The rest of the tires end up in dumps.

There are huge cemeteries of utilized tires occupying large areas at many enterprises. The portion of metalcord tires is growing and nowadays has exceeded 50 per cent of the common volume of tires being produced.

Increasing five danger may be caused by keeping a great number of utilized tires. For instance, a dump of 6 million tires burnt in Weld, Colorado, the USA. There was a burning smell, around at 15 kilometers distance. In Virginia, the USA, 9 million tires burnt for 8 month in 1989. There was a great fire in the rubberwares in the town of Mingechevir, Azerbaijan.

After the appearance of mosquitoes in the city of Barnaul, Russia, in winter it was found out that those insects propagated themselves in a huge tyre dump under even such severe climatic conditions. It is evident that aimless keeping utilized tires causes serious ecological consequences.

The investigations have showed that tires let constructors get unique building constructures distinguished by cheapness and erecting simplicity.

2. Constructions of a seismostable building and steady foundations

2.1 Seismostable country building

They have designed the construction of a few-store yed building with seismostable frame made of utilized car tires with metalcord in the country for multiaimed use.

Vertical elastic elements are formed of piles of utilized tires which are set on the corners of the building on the ribbon foundation. Lower tires are attached to the foundation with anchor bolts. When attaching reinforcing ribbons of plastics or metallic net are fixed and attached for reliable cohesion with monolithicly laid clay wall of the building. A steel frame or a wire hauser done up in the foundation is passing through the pole elastic element.

The socle part of the building are made of limestone or river stone. Special undemountable elastic tubbing in which clay soil mixture is monolithicly laid and packed by a special roller is attached to tyre pole. Reaching the top of the building wall angle bar or channel cross-pieces are set on the elastic tyre elements-poles and linked to the steel frame or the wire-hawser in the middle being tightened by bolts making elastic vertical element properly rigid. Wooden purlins being attached to the available cross-pieces are set between vertical elastic elements to fix roofing.

The building construction worked out effectively perceive and extinguish seismoloads. During even a very strong earthquake there appear cracks on the walls, and the roof and the elastic carcass do not collapse. That permits to guarantee keeping people's and animals lives that are in such buildings during strong earthquakes.

2.2 The construction of round monolithic foundation

Monolithic reinforced foundation are most widely used beneath columns in industrial building. Round-shaped foundations are hardly even used because of the difficulty of maxing tubbing.

The author worked out the construction of a round monolithic foundation beneath columns and the technology of its making. Unremovable tubbing (fig. 1) for concreting the foundation consists of ring-shaped blocks 1 and 2 of the boot part and ring-shaped block 3 of the undercolumn. The ring-shapd blocks are utilized car tires with metalcord of different diameters. The blocks are linked to each other, fixed by vertical pintles 4. Holeformer 5 is attached to the tubbing. Blocks 1, 2 and 3 are concentricly set on each other. Metallic or plastics pintles 4 are set in the holes drilled on the surfaces of blocks 1 and 2 every 120° along the circles on the line of their touching blocks 2 and 3. These pintles prevent from horizontal relative displacements of the blocks. First steel frame is set and fixed in the cavity of ready tubbing, then emptyness-former 5 is attached over. After that the cavity is filled in with concrete mixture. Emptyness-former 5 is taken away after the concrete has hardened and the foundation is ready for further construction assembing.

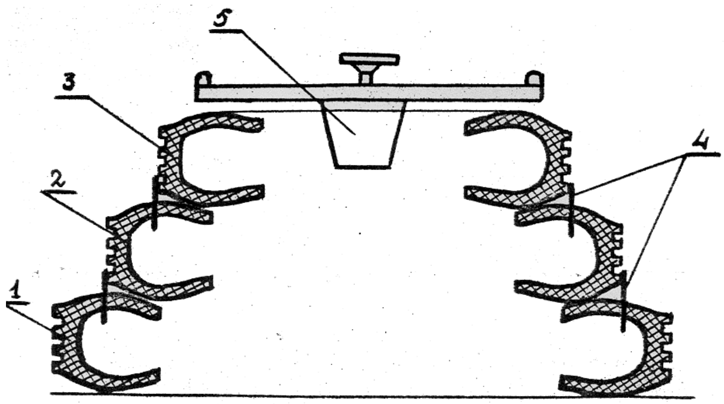

Figure 1. Round monolithic foundation.

When selecting utilized tires the area occupied by the lowest tyre must be determined according to the following inequality:

$$F \geq F_p = \frac{N_n}{H_c\left(R^N - \tilde{a}H\right)}, \tag{1}$$

here: $\boldsymbol{F}$ – area occupied by the lowest tyre; $\boldsymbol{F_p}$ – rated area of foundation foot; $\boldsymbol{R^N}$ – normal presure to the ground; $\boldsymbol{N_n}$ – reducted longitudinal rated force; $\boldsymbol{\gamma}$ - average volumetrical weight of soil; $\boldsymbol{H}$ – distance from the floor to the bottom of the foundation.

The effectiveness of the mentioned round monolithic foundation concludes in considerable reduction of expences for tubbing and using the tires in foundation as hydroinsulatioon. On the borders between shairs and on the foot of the foundation, there appear rubberreinforced layers which help to perceive and distinguish the energy of seismic vibrations.

2.3 Vibroisolated foundation

The auther has worked out the new construction of a vibroisolated foundation using utilized tires (fig. 2). This foundation consists of the casing of utilized metalcord tyre 1, filled in with dry substance 2, and boot 3, placed in casing 1 and partly deepened into the dry substance 2. Sade surface 4 of boot 3 is made bevelled where it is deepened into dry substance 2. The casing has flanges 5 over and beneath it.

The load is transferred by meas of the foundation ouing to bevelled side surfaces of the boot, then by means of the dry substance 2 to the lower part of the casing, to its side surface and butt-end flanges. That considerably increases the foundation bearing ability and results in effective perceiving and distinguishing vibration loads.

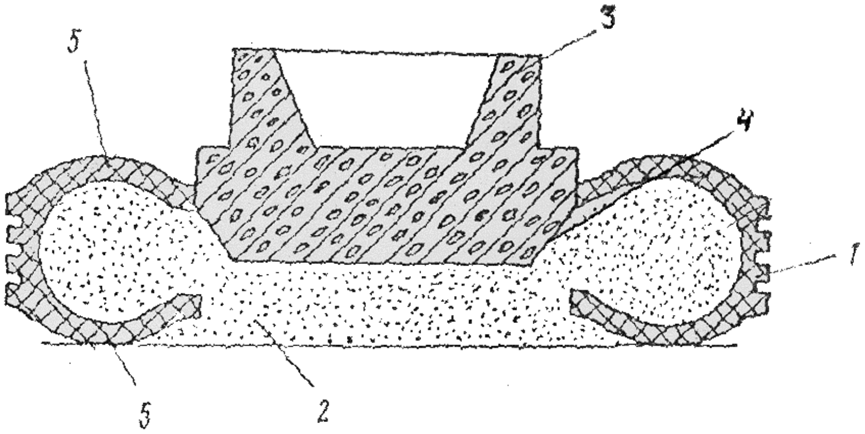

Figure 2. Vibroisolated foundation.

3. Hydrotechnical and natere protection construction

3.1 Drain muff

Different muff constructions are used as pipe drain. It is difficult to produce such muffs and to assemble a drain piping. Muffs can not often bear the stresses caused by ununiform displacement of the soil surrounding the pipe and destoyed.

The author has worked out a muff construction of a utilized car tyre with metalcord. Drain pipes 1 with special slots 2 at their ends are linked to a tyre-muff 3 (fig. 3). Perforated holes 4 are made in the muff beforehand.

The muff works as follows: the water enter into pipes 1 through perforation 4 and flows along the inclination to the collectors. The muff elasticity and constructional strength let it perceive swelling and settling of surrounding soil without destroying draing piping. The lower part of the muff serves to collect allwiums.

The elastic muff let to keep constant clearence between the trench walls and the pipes which is filled in filtering grainy substance.

3.2 Gabion

Gabion consists of horizontally placed cylindrical casing, filled in with soil. Cylindrical casings consist of car tires jointed to each other bound both with each other and adjacent casing by means of exclusive loops made of stretched steel ropes.

Gabions are made as follows: utilized tires of equal sizes are delivered to the ground. They are jointed to each other with butt-ends. Three casings are assembed at the same time, they let metalic ropes go in such a way that two linking loops which will tie the central casing and the two adjacent ones being in one row.

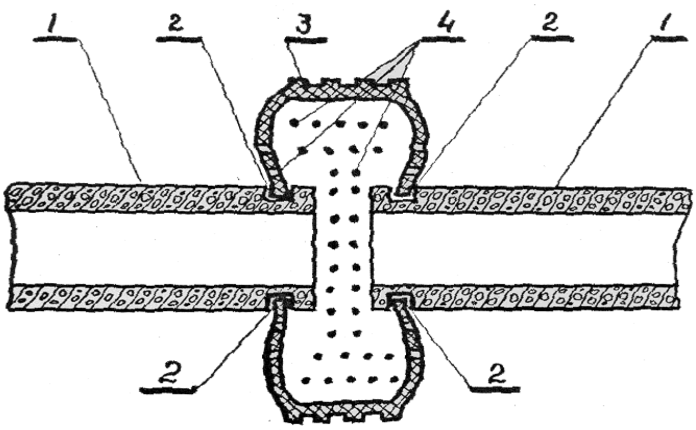

Figure 3. Drain muff.

The steel ropes are stretched and fixed by the knots on the front side of the casings. After that the backs of the casings are covered with a temporary cover and they are set in vertical position. Local soil is laid into the casings from above and condensed. The block of three casings is again set in a horizontal position, the cover is removed and the soil in the casings form natural slope. The blocks made in such a manner are set forming low and the following rows of a breast-wall or a protecting one.

3.3 Breast-wall

The author has worked out the construction of a breast-wall (fig. 4) that consists of utilized car tires 1 laid on each other. Pivot-piles 2 deepened into the ground are peaced along the central axis of cylindric casings formed. The casings are filled in with soil 3.

The distance between piles are selected so that the casing walls touch each other. The tires in the casing itself are linked along touching side muffs with crams.

The magnitude of the length of the pile deepened into the inmovable soil can be find out solving the following equation:

$$
\begin{aligned}
&a_1 P_{\max} h^3 + \left[2P_{\max}\left(a_1 h_1 + \frac{1}{2}a_2\right) - a_1 R_T\right]h^2 - \\
&- \left[R_T\left(2a_1 h_1 + a_2\right)\right]h - \left[2R_T^2 + 1{,}5\,h_1 R_T P_{\max}\right] = 0
\end{aligned}
\quad , \qquad (2)
$$

here: $\boldsymbol{h}$ – the magnitude of the length of the pile support in the unmovable band slide soil; $\boldsymbol{h_1}$ – vertical length land slide body at the point of setting the pile support; $\boldsymbol{R_T}$ – resultant landslide pressure to the pile support; $\boldsymbol{a_1}$ and $\boldsymbol{a_2}$ – specially determined coefficients; $\boldsymbol{P_{max}}$ – reactive soil compressing force on the border between land slide body and the soil laying under it.

The vertical height of the wall, excluding land-slide sliding over it are determined owing to the following formula:

$$h_c = \frac{\Delta T\left(\cos\frac{\text{è}}{2}\,\mathrm{tg}\,\varphi\right)\sin\frac{\text{è}}{4}}{\cos\frac{\text{è}}{2}-\left[\frac{1}{4}h_2\,\text{ã}\cos\left(\frac{\text{è}}{2}+\text{â}\right)\left(tg\,\varphi+tg\frac{\text{è}}{4}\right)\right]+\frac{C}{2\cos\frac{\text{è}}{4}}}, \qquad (3)$$

here: $\boldsymbol{h_2}$ – vertical length of land-slide body; $\boldsymbol{\beta}$ – the angle of incidence of sliding surface in the point of setting the pile post; $\boldsymbol{\Delta T}$ – the magnitude of land slide pressure in the point of setting the pile-post; $\boldsymbol{C}$ – soil cohesion force; $\boldsymbol{\varphi}$ – the angle of internal soil friction; $\boldsymbol{\gamma}$– volumetrical weight of land slide soil.

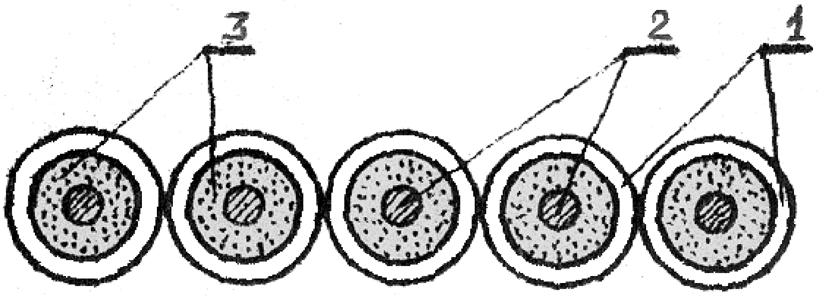

Figure 4. Breast wall (sight from above).

3.4 Mud stream protection construction

The new construction for mud stream protection consists of utilized tires with holes strung on the piles like circles on them forming horizontal through channels. The tires are fixed and attached to each other by washers and rigid pawls on the piles.

The construction works as follows: Its horizontal elastic elements (tires) perceive stroke from mud stream reduce the load and transmit in to the piles, and through them to the ground. The tires are hold from rising caused by vertical lifting component of the load owing to the pawls. The water and smaller fractions of mud in it lessen their speed and pass through the construction channels. Larger fractions which are bigger than through channels are detained by the construction. The rest of the mud stream may cover the construction, which has done its duties detaining large fractions of the mud stream and reducing its speed and stroke load.

3.5 Shore strengthening wave-protection construction

The construction protecting shore from wash-out by waves (fig. 5 a, b) consists of piles 1, placed at the equal distance. Utilized tires of the same size 2, which adjacent rows laid with joints tied up 3 assembling of the construction are made as follows. Piles 2 are hammered into the ground with equal step L, determined from the formula:

$$L = D(2K + B), \tag{4}$$

here: ***L*** – step formed by the axes of piles next to each other; ***D*** – tyre diameter; ***K*** – width of through ellipsis-shaped hole, which is formed when laying the tires with joints tied up of adjacent rows.

The cross-section of pile 1 must be ellipsis-shaped, identic with that of through hole.

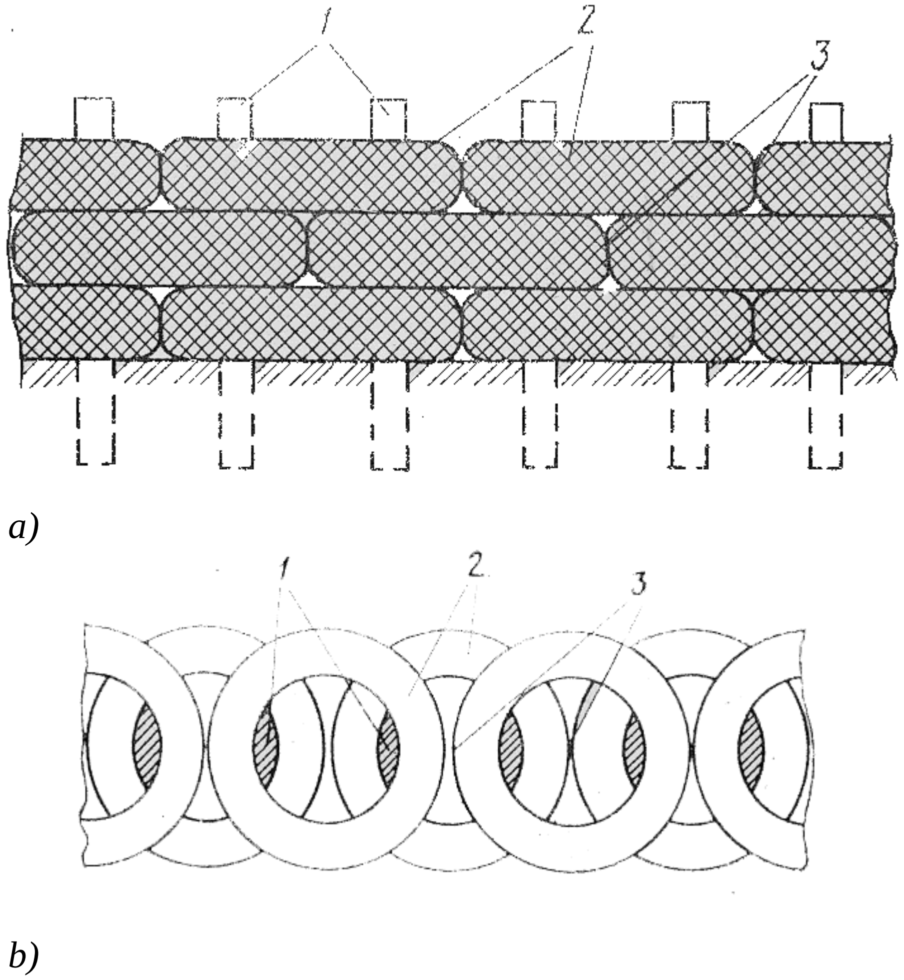

Figure 5. Shore strengthening wave protection construction:
a) front sight;
b) sight from above.

This construction perceive stroke influence of wind sea and river waves, more effective than reinforced concrete constructions at the same time its cost is 75–80% cheaper than theirs.

Using utilized tires in building does not influence the construction longevity, as tires are not spoilt for 50–60 years in the open air, and for 1500–2000 years in water.

The use of peat ash in earth construction

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ABSTRACT: This paper reviews the results of peat fly-ash utilisation of peat power plant in Rovaniemi. Peat ash has been tested as a filler material in asphalt pavement, as a sub-base material of a road structure and as layers of landfill cover structures. On the basis of the results obtained, peat ash is suitable for these applications in both technical and environmental aspects. At the moment peat ash is classified as waste and this retards the progress of extensive use of peat ash in earth construction.

1. Introduction

The Suosiola peat power plant of Rovaniemen Energia uses peat ash as its main fuel. In addition, also oil and wood chips are used. In August 1995, new modern combustion unit was taken into use. Approximately 13 000 m^3 of peat fly-ash is generated annually. At present, the peat ash is disposed 30 km away, at the Suksiaapa swamp.

The utilisation of peat ash in earth construction applications has been studied in several research and development projects, which have proceeded through the classification of material-related properties to designing and constructing test structures. At present in research, monitoring phase of the test structures is in progress. Because of the restricted availability of suitable natural raw materials in Rovaniemi and its surroundings, technical and economic needs to develop the utilisation of peat ash exists. Because of the geographical location, special climate conditions and, especially the freezing of the soil, has to be taken into consideration in structures and materials.

2. Environmental aspects

The basic precondition for extensive use of peat ash is the environmental qualification. In Finland, no such official standards exist which could be applied in evaluating the environmental impact of by-products applicable for earth construction. However, generally a three-step evaluating procedure is followed. In the first stage, the environmental impact is estimated on the basis of the composition. If the total concentration exceeds a certain maximum concentration, the environmental impact is evaluated on the basis of solubility and risk analysis.

Table 1. The total concentration and solubility of peat ash in maximum solubility test NEN 7341 and column test NEN 7343. The results are given in milligrams per one kilogram of dry matter (mg/kg dm).

Element	*Total concentration*	*Max. leaching test NEN 7341*	*Leaching test (Column test) NEN 7343*	*Guideline values for total concentrations*	
				Lower Value (mg/kg)	*Upper value (mg/kg)*
Al	47500	699.4	109		
As	54	20.7	0.04	13	60
B				5	50
Ba	142			600	600
Be				1	10
Ca	106000	29060			
Cd	4.3	0.99	0.004	0.3	10
Co	33	<5		50	200
Hg	-	<0.02			
Cr	212	<5		80	500
Cu	86	4.93	0.01	32	400
Fe	244000	<100			
K	1410	285.7			
Mg	12500	1132.9			
Mn	1700	51.2			
Mo	<5	<5		5	200
Na	1090	275.8			
Ni	85	<5	0.11	40	300
P	13200	492.6			
Pb	35	<10		38	300
S	9450	9851			
Sb		<50		5	40
Sr	353	89.6			
Ti	815	5.9			
V	356	18.7		50	500
Zn	126	9.9	0.76	90	700

< concentration is below the determination limit

The previously mentioned values are interpreted so that the by-product that has total concentrations below the lower value can be used without limitations to almost any purpose. Material that has total concentrations above lower value, but below the upper value, can be used with some limitations or with some protective precautions, but only in those applications that pose no risk for human beings. If the upper value is exceeded the use of material requires detailed risk assessment before use. This procedure is not, however, officially in use.

The total concentrations of the peat ash were determined by extracting it in nitrohydrochloric acid (3:1 hydrochloric acid : nitric acid 90^{o}C). The analysis was performed with ICP-AES- method. The concentration of the leaching elements were examined with maximum leaching test NEN 7341 and with leaching test NEN 7343.

The total concentration and the maximum leaching values and leaching values of peat ash are presented in table 1. Total concentration of all the elements are below the upper value. The lower value is exceeded by elements As, Cd, Co, Cr, Cu, Ni, V and Zn, but their solubility is slight according to maximum leaching test. In the leaching test (column test), the concentration of these elements was smaller than the maximum concentration when the placement criteria was group 1, i.e. application in an unisolated form.

3. The use of ash as asphalt filler

In the laboratory, the material properties of ash as filler, as well as the material properties of the bitumen-filler -mixtures and asphalt pavements that included ash were studied. On the basis of the laboratory results, a test pavement was constructed, where peat ash was used as filler for a SMA-12 pavement. In this research, PANK-norms (PANK 1995) that correspond the European standards were applied.

3.1 Laboratory phase

The peat ash fulfilled the requirements of the filler, except for the voids content, that was higher than the maximum value presented in PANK-norms. Because the fine aggregate of asphalt pavement generally includes a mixture of sand and crushed rock as fine aggregate, the voids content in the fine aggregate is smaller than that of the peat ash alone. Hence the norm requirement can be achieved. To fulfil the norm requirement, an individual estimation of each case is required. The peat ash that was examined met the PANK-norm requirements considering grain size distribution and ignition loss for the additive filler.

The effect of peat ash on the stiffness of the pavement was studied by determining the softening temperature of bitumen (B120) and filler mixtures for aged and unaged samples. According to these results, the softening temperature of mastic that included peat ash as filler was clearly higher than the softening point of the mastic that included lime or a mixture of lime and peat ash. On the basis of the softening temperature, it can be estimated that when using peat ash as additive filler, the modulus of stiffness is greater than when lime filler is used. However, using only peat ash as filler is limited by the voids content that can raise the total amount of mineral aggregate voids content in asphalt mass to be too high.

In laboratory experiments, pavement type AB 16 was used. Bitumen B 120 was used as binder. In the test pavements, peat ash was used as additive filler. For the reference pavements, lime powder was used as additive filler. According to the determinations, the optimum binder content of those pavements that included peat ash, is 0.6...0.8% higher than that in the reference pavements. The increase in binder content is apparently caused by the higher voids content in the ash. The modulus of stiffness of the test pavement was higher than that of the reference pavement, for example, in +20°C 1.45 times higher value was achieved. The deformation values of the test pavements represent the deformation class I in 1995 Asphalt norms. All test and reference pavements were easy to compact.

3.2 Field results

The test asphalt pavement is located in the centre of Rovaniemi, at Lapinkävijäntie road. The proportional class that is determined on the basis of the traffic flow, is B. SMA 12 test pavement included peat ash 9% of the total mass of mineral aggregate. In the reference pavement, lime powder was used as filler. Core samples were taken from the test and reference pavements, and the mass density, the void content, indirect tensile strength and sensitivity for deformation were measured. The void values of the test pavement, which included fly-ash, varied slightly more than the void values given in 1995 Asphalt norms. On the basis of the tensile stress (-2 ºC), the test pavement is classified to the highest freeze-proof class. On the basis of the cyclic creep stress test, the test pavement is classified to deformation class II, which corresponds to the proportional classification (table 2).

Table 2. The material properties of the test and reference pavements (SMA 12) at the Lapinkävijäntie road site.

Pavement	Pavement density kg/m^3	Mass density kg/m^3	Voids %	Indirect tensile strength (kPa)		Creep test %
				-2 ^{o}C	+10 ^{o}C	
Reference	2410…2566	2566…2604	4,1…5,2	2060…2491	1018…1488	
Test	2460…2482	2586…2618	0,9…6,1	1819…2491	1068…1163	2.7…3,1

4. The use of ash in sub-base layers

Peat ash reacts with water in a pozzolanic manner. This property is viable in structures that require high bearing capacity, such as road, street and yard structural layers. On the other hand, problems caused by the strength gain of the material have to be taken into consideration, for example in municipalities' technical maintenance work. In order to strengthen the structures as far as possible, peat ash should be stored dry and moisturised only immediately before the constructing or during the work. Repeated freeze - thaw cycles decreased the compressive strength of peat ash.

In the test structure (figure 1) peat ash replaced the 900 mm thick sub-base layer of crushed rock or gravel crush. The compacting of peat ash was done in November 1997, as the temperature was -7 ^{o}C. Compacting succeeded well with ash that was still warm after the burning process. Peat ash was moisturised at the power plant immediately before transportation to the construction site. The base course and the pavement layers above peat ash were constructed during summer 1998. At the same time, monitoring equipment was installed and samples were taken from peat ash layer. More information will be obtained from the freeze-thaw weakening, relation between thermal conductivity and the water content, and the frost susceptibility of ash, when the behaviour of the structure is observed in situ conditions. This information and other material parameters (table 3) are essential requisites for establishing instructions for the use of peat ash in the future.

The results of laboratory tests of the samples taken from the test structure are presented in table 3. Significant in these results is the low frost susceptibility (segregation potential), which indicates that when ash is well compacted and its strength is increased, the material is classified as non-frost susceptible.

Maximum depth of frost during winter 1998–1999 was 156 cm, and during winter 1999–2000, 138 cm. The freezing index was 36 300 Kh and 30700 Kh, respectively. In reference structures, the frost depth during winter 1998–1999 in the Rovaniemi region was approximately 250 cm. The insulation effect of peat ash is clearly illustrated in the temperature gradient (figure 2). During wintertime, peat ash retards frost penetration and the temperature decreases in the top part of the base course. On the other hand in springtime the layer of peat ash slows down the thawing process. Both low thermal conductivity and high heat capacity affect the frost behaviour of ash.

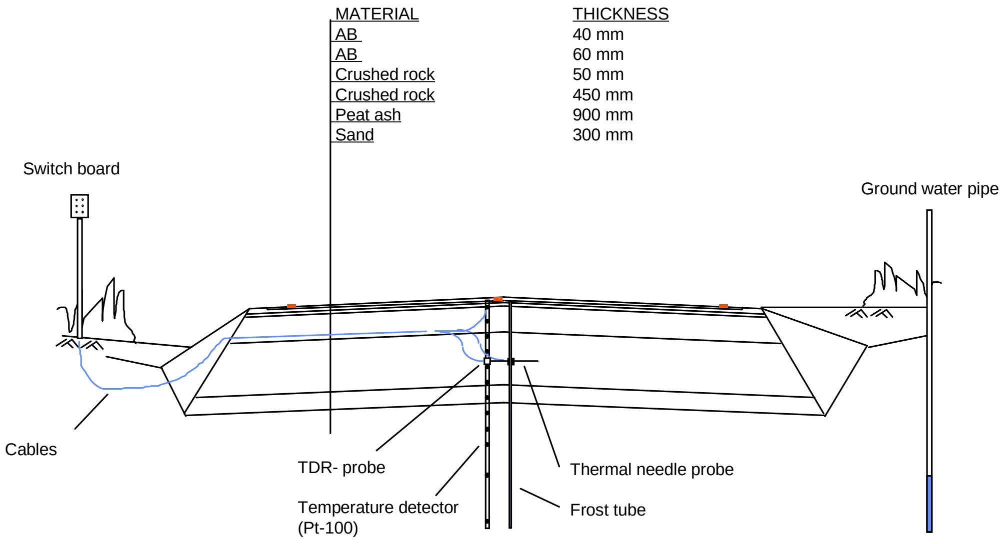

Figure 1. Cross-section of the peat ash test structure of Rovaniemi Teollisuustie.

Table 3. Material properties of peat ash layer of Rovaniemi Teollisuustie.

Properties	Value	Unit
Density*	1.59	kg/m^3
Water content*	35	%
Porosity*	61.9	%
Compressive strength*	1.14	MPa
CBR-value	34.8	%
Segregation potential	0.2	mm^2/Kh
Thermal conductivity (+20^{o}C)	0.75	W/mK
Hydraulic conductivity	$10^{-6.1}$	m/s

* *Average values of the samples*

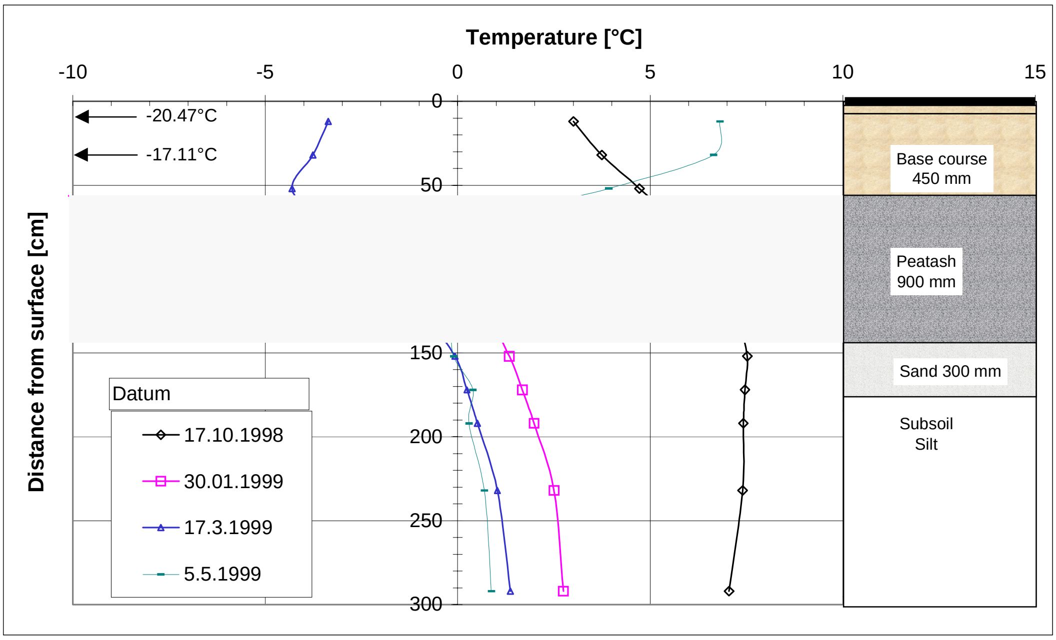

Figure 2. The temperature profiles of the Teollisuustie peat ash structure in Rovaniemi, winter 1998–1999.

5. Utilisation of peat ash in landfill structures

The cover of Mäntyvaara landfill was chosen for test constructing purposes. In laboratory, the peat ash index properties, compaction properties, frost susceptibility, freeze - thaw behaviour, air permeability and erosion properties, as well as mechanical, hydraulic, and thermal properties were studied. In addition, the amount of water infiltrating through the test structure was estimated by numerical modelling. On the basis of this research material, a plan for the test structure was made. The plan includes two test structures. In the thinner structure, the idea is to allow the frost to penetrate the hydraulic barrier, and to determine the effects of frost for the material properties of the hydraulic barrier, as well as for the functioning of the whole structure.

The monitoring of the test structure includes measuring the amount and quality of the water infiltrating through the structural layers, the settlement, temperature and the peat ash water content measurements (figure 3).

The settlement of the test structures during June/99-May/00 were between 0.22...0.32 m. In both test structures, the greatest settlements were in the middle of the structures. In test structure 1, the maximum frost depth was approximately 0.8 m in February, when 0.6 m of the peat ash surface layer was frozen. During November-April, a significant temperature gradient (approximately 5...7 ^{o}C) in the peat ash surface layer was noticed. The temperature difference is related to the low thermal conductivity, which is about 0.35...0.55 W/Km with the present density and water content (Jauhiainen, 1999). The temperature of the waste fill during the period varied between 6.5...14.4 ^{o}C (figure 4).

In the test structure 2, the maximum depth of frost was approximately 0.8 m in February. At the time, the 500 mm thick peat ash surface structure was completely frozen. The temperature of the waste fill in test structure 2 during the period varied slightly more, being between 4.8...14.1 ^{o}C than the temperature of the waste fill in test structure 1 (figure 4).

No significant changes occurred in the volumetric water content of the peat ash layers in test structures 1 and 2. In both test structures the volumetric water content of the hydraulic barrier (46…48%) was higher than the volumetric water content of the surface layer (32...42) during the observing period June/99-May/00.

In December, it was observed that through the surface structure of the test layer 1, about 0.5 l of water had infiltrated. In other lysimeters no water was noticed during the observation period. The rainfall during June-December was 454 mm altogether in Rovaniemi. On the basis of the analysis, the pH of the water was high (11.97). Concentration of heavy metal of the infiltrated water were extremely small (table 4).

Table 4. Results of the analysis of water infiltrated through the surface layer.

Properties	Value	Unit
pH	11,97	
Electrical conductivity	766,0	mS/m
Copper	267	µg/l
Arsenic	0	µg/l
Nickel	45	µg/l
Chrome	649	µg/l
Zinc	4	µg/l
Cadmium	0	µg/l

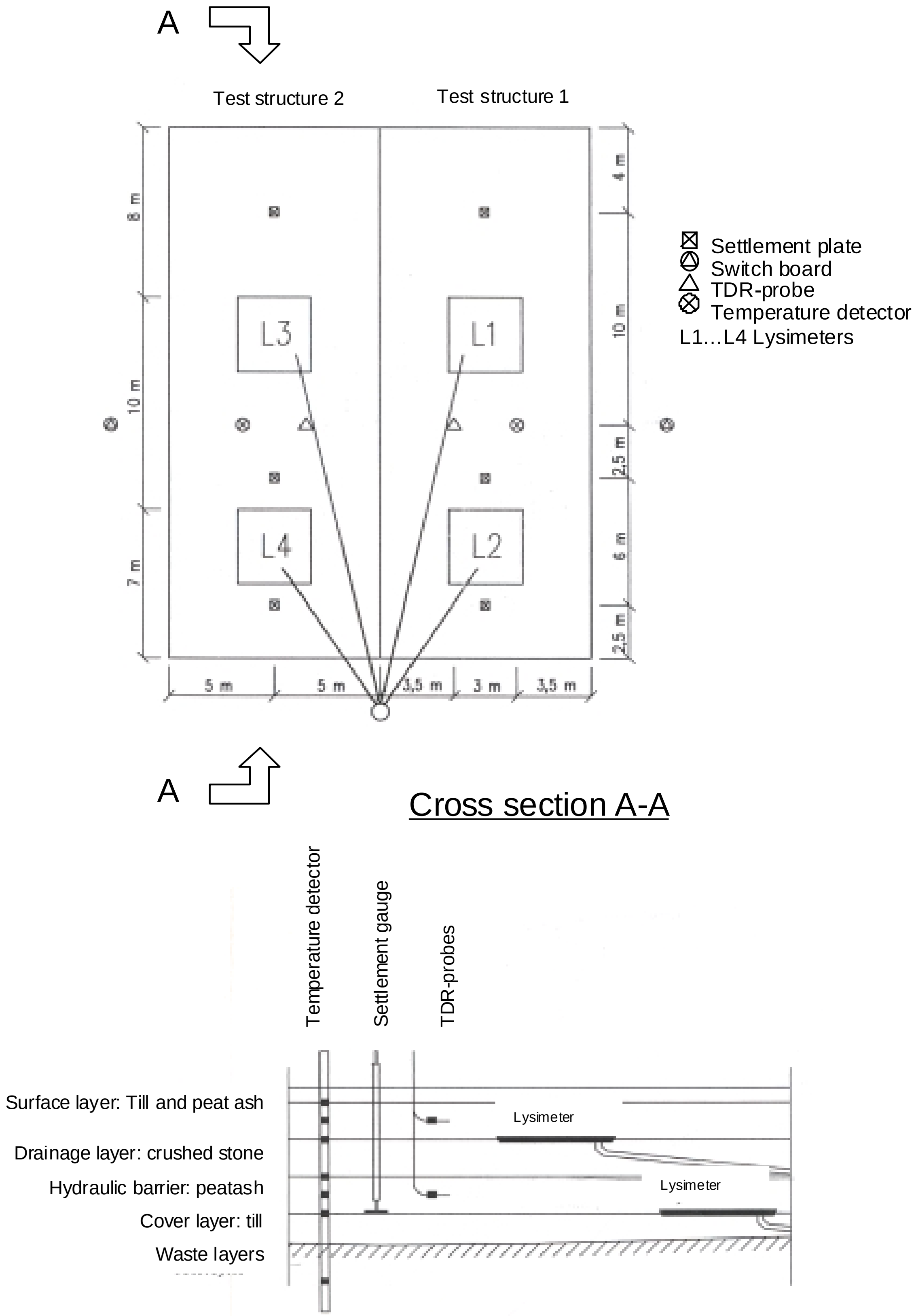

Figure 3. The instrumentation of the test structure.

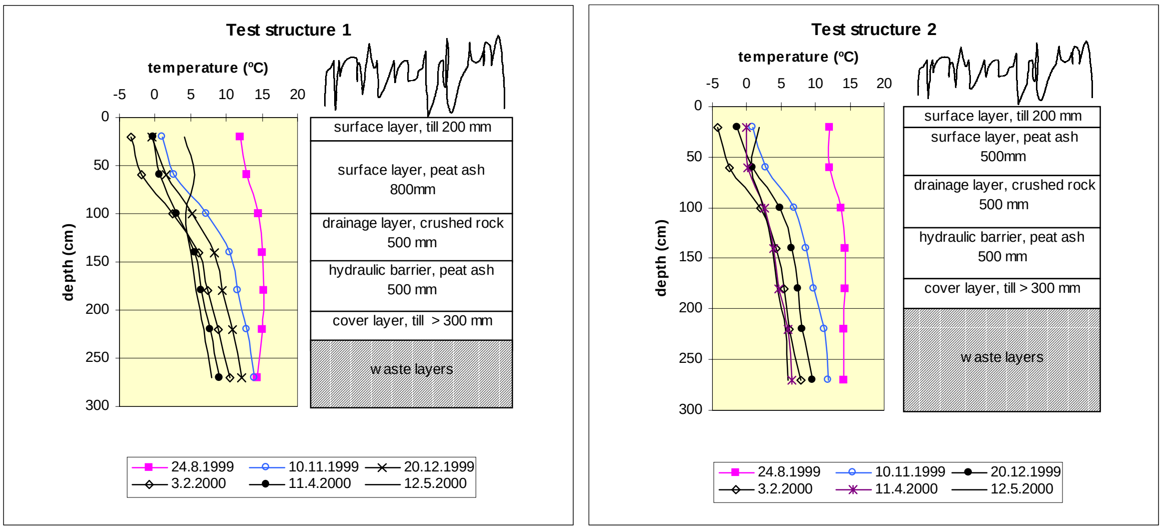

Figure 4. Temperature profiles of the test structures 1 and 2 during the observation period.

6. Conclusions

On the basis of the results and experience obtained, both technical and environmental properties enable peat ash to be used in the tested applications. In order to determine and ensure the long-term durability, continuing the monitoring of the test structures is essential. The long-term behaviour of peat ash in different applications will finally determine the application-specific life cycle costs, which determine the technical and economical competitive ability of different utilisation alternatives.

According to the present environmental legislation in Finland, peat ash is classified as waste. The research and development projects implemented, as well as the monitoring measurements in progress will enable analysing the physical and chemical functioning of the structures with numerical models. The analysis of the water infiltrated through the peat ash layer showed that the solubility of heavy metals *in situ* was very low. To help decision making, risk analysis can be made on the basis of these preliminary results and experiences.

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Design of soil structures using Crushed Stone Wool insulation

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ABSTRACT: Crushed Stone Wool is a recycled by-product from the production of stone wool insulation. Stone wool insulation is made of natural minerals by melting at high temperature (1500°C). The geotechnical properties of Crushed Stone Wool are similar to natural sand, but the thermal conductivity is considerably better and the density extremely lower than for sand. The grain size of the material varies between 0…100 mm depending on crushing method. According to the environmental qualification test the total amounts of all chemical compounds in Crushed Stone Wool are below the permitted limits set for soil materials in construction in Finland. The recycling possibilities have also been studied at construction site conditions by crushing demolition stone wool waste. The amount of demolition stone wool waste is predicted to increase remarkably in the future. Crushed Stone Wool may be utilized in numerous soil structures in different manners: as an insulation layer in yards, parking places, bicycle and pedestrian tracks in frost-susceptible subsoil or as a light material filling in embankments and noise barriers situated in soft subsoil (clay). By using Crushed Stone Wool in soil structures several benefits may be achieved, like good insulation against frost damage, lighter soil structures in soft subsoil and a reduced amount of demolition waste.

1. Introduction

Crushed Stone Wool is a recycled by-product from the stone wool industry, which may be utilized in many different soil structures. Alternative recycling possibilities have also been investigated at construction sites by crushing demolition Stone wool waste using different methods. The amount of demolition stone wool waste is estimated to increase notably in the future and also the new waste law decrees to recycle demolition waste more effectively in Finland.

The project started in 1998 when the Master’s thesis about the geotechnical properties of Crushed Stone Wool (Höynälä, 1998) was completed at the University of Oulu. Also the environmental qualification test for the material was committed. The next step was a test road section in Raahe where the material was used in an insulation layer. At Helsinki University of Technology a study was performed on the bearing capacity of packed Crushed Stone Wool. Based on all this research information and experience, the design and dimensioning instructions and also the general work descriptions and quality requirements were established. The latest case of Crushed Stone Wool utilization was the unloading station of Metsä-Tuomela in Nurmijärvi where the material was used as a lightweight material filling in 1999.

2. Stone wool insulation production

Stone wool insulation is made from natural minerals by melting raw materials in a melting furnace at high temperature (1500°C). In the fibering process and in the compression and heat treatment the molten mineral mixture is transformed to stone wool insulation mass. The stone wool industry by-products are generated in the cutting process where the edge trim is separated and crushed after cutting [Figure 1]. The total amount of annually produced edge trim is about 3000 tons.

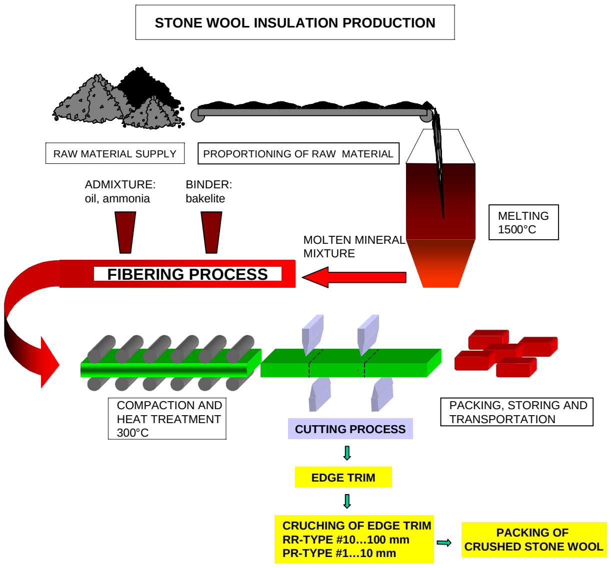

Figure 1. Stone wool insulation production and produced by-products.

The grain size of the by-products may be controlled by changing the crushing method. The edge trim is possible to crush into the two different fractions: RR-type grain size # 10…100 mm [Figure 2a] and PR-type grain size # 1…10 mm. The technical properties of the material do not differ notably according to the grain size. Crushed Stone Wool is also possible to pack in bags which considerable improves the compressibility of Crushed Stone Wool [Figure 2b].

At construction sites stone wool demolition waste may be crushed by mobile crushing equipment. Some tests have been performed and the results have been very promising. The grain size of the waste pieces is similar to industrially produced Crushed Stone Wool. In the future the utilization of stone wool demolition waste at construction sites is expected to grow. In 1996 the amount of demolition stone wool waste was 900 m^3 and it is estimated to increase to 14 000 m^3/year between 1996 and 2010.

a) *b)*

Figure 2. a) Loose and b) packed Crushed Stone Wool.

3. Technical properties of Crushed Stone Wool

3.1 Chemical properties

Stone wool insulation is manufactured from natural minerals and its chemical composition may be compared with natural sand and stone. The binder content of stone wool insulation is 0.7…4.5%. The binder is phenol formaldehyde resin modified by urea. Oil is used as an admixture to improve the water-repellent properties of stone wool insulation. The main components of Stone wool insulation are silicon oxide (SiO_2), aluminum oxide (Al_2O_3) and calcium oxide (CaO) and iron oxide (FeO) [Figure 3].

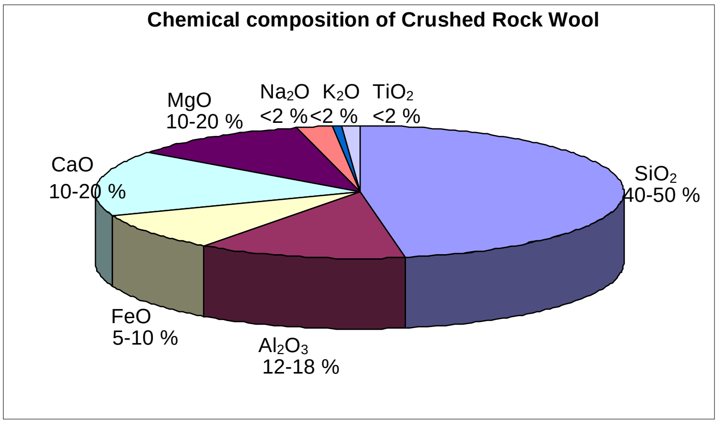

Figure 3. Main components of stone wool insulation.

3.2 Physical properties

In factory conditions the edge trim separated straight from the product line is very dry (water content < 1 weight-%). In the ground conditions the normal water content settles between 20…25 weight-%. The other physical properties of Crushed Stone Wool to a considerable degree depend on the loading above the Crushed Stone Wool layer. Table 1 shows how the technical properties change with increased loads. The thermal properties of the material convert according to loading and water content, but as a dimensioning factor for thermal conductivity the value 0.10 W/mK may be used.

Table 1. Technical properties of Crushed Stone Wool according to loading.

Loading [kN/m^2]	Volume Weight [kN/m^3]	Settlement [%]	Water Permeability [m/s]	Capillary Rise [m]
10	1.6	25	$10^{-4}…10^{-5}$	0.07…0.10
20	2.0	37	$10^{-4}…10^{-5}$	0.07…0.10
30	2.2	45	$10^{-4}…10^{-5}$	0.07…0.10

3.3 Environmental aspects

The University of Oulu and VTT (the Technical Research Centre of Finland) have made environmental qualification tests for Crushed Stone Wool and stone wool products. According to the test results stone wool does not emit any substances into soil or water to the extent that would endanger the quality of soil or water. The content of all the analyzed components in stone wool were well below the guidelines or limit values applied to building land.

4. Design of insulated structures using Crushed Stone Wool

4.1 Design principles

The design principles are based on existing instructions and regulations referring to insulation materials and methods in Finland but also the investigation results of Crushed Stone Wool are taken into account. The thermal properties of Crushed Stone Wool are considered when designing insulated soil structure.

4.2 Insulated soil structures

The insulation of soil structures will enable the reduction of frost heave damage when the subsoil is frost-susceptible. The most potential insulated soil structures using Crushed Stone Wool are lightly loaded soil structures like:

- Bicycle and pedestrian tracks
- Transition structures beside buildings and
- Yards and parking places (no heavy traffic).

In Raahe, Crushed Stone Wool was tested as an insulation material in a bicycle and pedestrian track. The asphalt pavement of the old road structure was badly damaged because of frost heave. The new structure was improved by building an insulation layer of Crushed Stone Wool, with a final layer thickness of 100…200 mm depending on the thickness (400…800 mm) of the superstructure above. The type picture of the structure in presented in Figure 4. The overall length of the test road was 100 m.

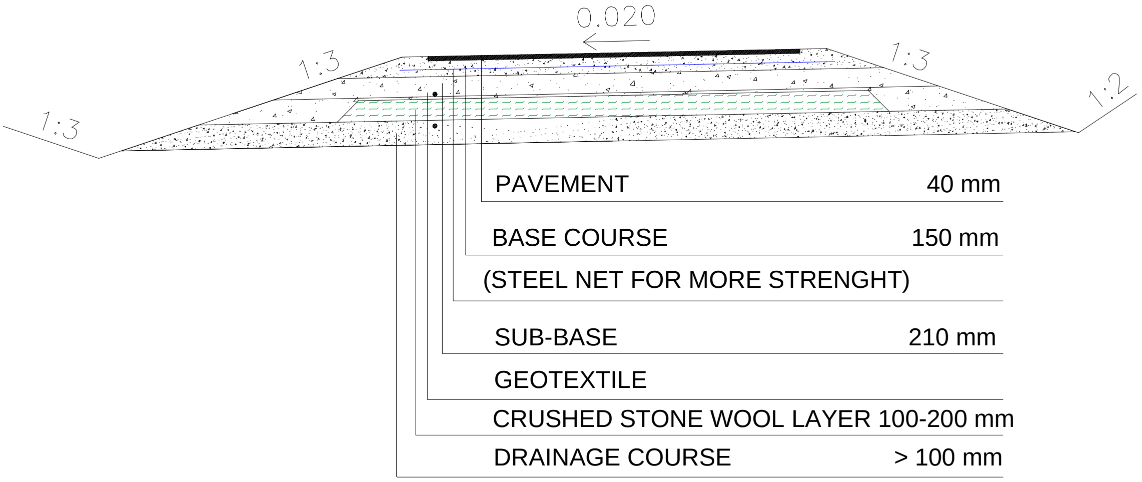

Figure 4. Cross-section of the bicycle and pedestrian track in Raahe where Crushed Stone Wool was used as an insulation material in very frost-susceptible subsoil.

Inside the test structure sensors were installed to measure the water content, the temperature and the thermal conductivity of the Crushed Stone Wool layer. The temperatures of the superstructure and subgrade (up to 2 m from the asphalt surface) were also measured. The measurings have been executed for two years back and the test road has served as planned. No damage has appeared such as longitudinal pavement cracking caused by frost heave. No uncontrolled settlements have arisen so far even though this was a risk due to the soft nature of Crushed Stone Wool. According to the temperature measurements the Crushed Stone Wool layer efficiently prevents very frost from penetrating under the superstructure to the frost-susceptible subsoil. The deviation of temperature above and below the insulation layer is 4…5°C degree during the coldest time of the winter.

5. Design of lightweight earth structures using Crushed Stone Wool

Crushed Stone Wool may be utilized as a lightweight material filling in different kinds of soil structures. The dimensioning value varies between 2.0…2.5 kN/m^3 according to the purpose of utilization. Figure 5 presents a case where an old waste water settling pool was modified to a new waste water treatment plan in the unloading station of Metsä-Tuomela in Nurmijärvi. Extra earth filling around the new waste water treatment plan would have caused additional settlements which was why lightweight Crushed Stone Wool was used to replace natural soil. The total amount of Crushed Stone Wool was approximately 280 tons. The volume of the pool was about 770 m^3 [Figure 5].

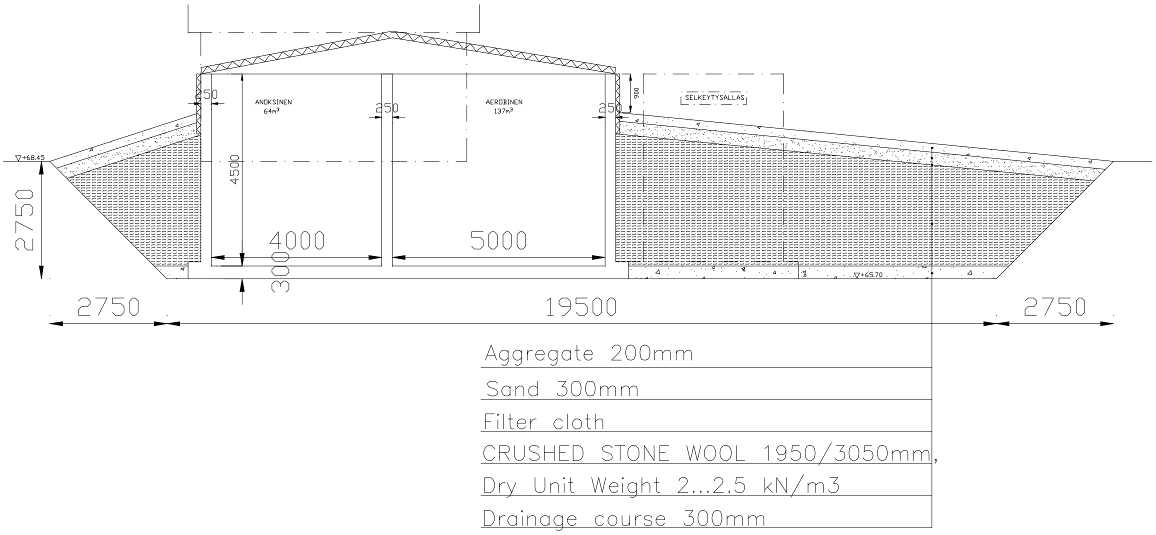

Figure 5. Cross-section of waste water settling pool in Nurmijärvi. Crushed Stone Wool was used as a lightweight material filling to eliminate settlements.

In embankments and noise barriers the lightweight property of Crushed Stone Wool may be utilized when situated in soft subsoil. The packed material [Figure 2b] may be the most suitable to build these kind of structures. The amount of material as a material filling in a noise barrier varies between 1000…3000 m^3 for every 100 meters. The density of packed Crushed Stone Wool varies between 185…220 kg/m^3 depending on loading. For the dimensioning the unit weight value 2.0 kN/m^3 may be used for packed Crushed Stone Wool.

The compressibility of packed Crushed Stone Wool is not remarkable when the height of the noise barrier is < 3.0 meters. All expected settlements inside the Crushed Stone Wool structure take place immediately during the construction. Under the noise barrier a drainage course should be planned because of a capillary rise of ground water (clay subsoil) is to be expected. It is necessary to make small holes (∅=50 mm) in the bottom side of the bags to ensure the leakage water to flow through the structure. If water remains inside the structure, the weight of the material filling and the whole structure increases and which may cause uncontrolled deformations and possible collapse of soft subsoil. Figure 6 presents a type structure of the noise barrier with the packed Crushed Stone Wool as a material filling.

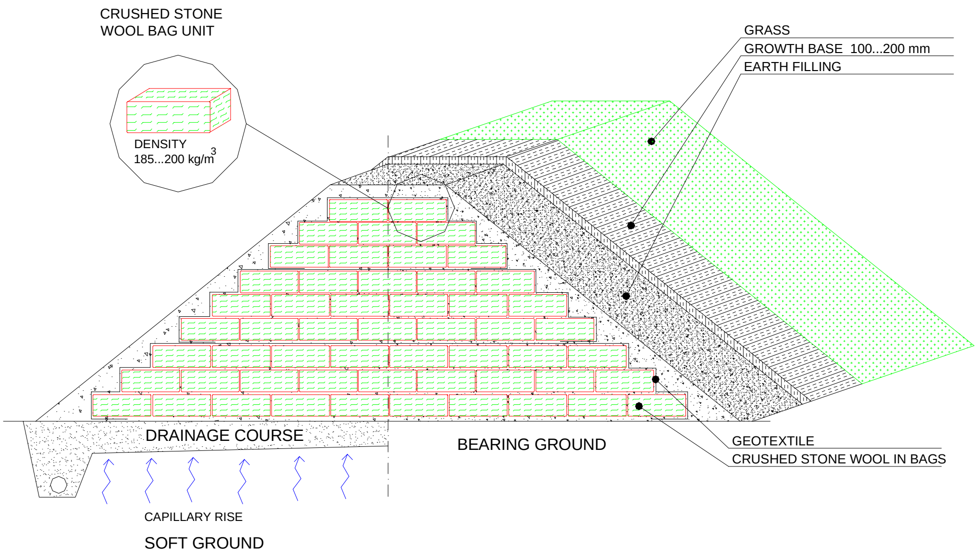

Figure 6. Noise barrier using packed Crushed Stone Wool as a filling material. The size of one bag is length ~ 0.8 meters, width ~ 0.4 meters and height ~ 0.3 meters.

6. Conclusions

Both the laboratory investigations and the experiences from the cases in Raahe and Nurmijärvi have been promising and the results positive. The utilization of Crushed Stone Wool gives a lot of benefits to soil structures such as good insulation against frost damage, lighter soil structures and reduced amount of demolition waste. The monitoring of the structures continues and all the new experiences gained are analyzed and noticed in planning new structures in the future. The aim is to take the utilization to a level where almost all produced stone wool insulation by-products and the main volume of demolition stone wool will be recycled.

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Testing of long-term geotechnical parameters of by-products in laboratory

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ABSTRACT: The properties of four by-products were determined in this research project. These by-products were cement stabilised fly ash, blast-furnace slag sand, mixture of fly ash and de-sulphuration product and cement stabilised wood or peat ash. The properties considered critical in relation to long-term stability were determined in the laboratory. The results obtained were compared against the requirements set on by-products used in road construction. One of these tested materials has also been used in a test section built before these tests were started.

All materials tested are in principle capable of producing adequate compressive strength and stiffness to be used in road construction. In practice some problems may arise especially concerning the choice of parameters for design due to poor environmental durability. In other words stabilised or self-strengthening materials do not necessarily last as intact the repeated freeze thaw cycles. Although the stiffness of stabilised material decreases significantly do to structural failure it may still possess reasonable large stiffness to be used in sub-base of a road structure.

1. Introduction

The properties of four by-products were determined in this research project. These by-products were cement stabilised fly ash, blast-furnace slag sand, mixture of fly ash and de-sulphuration product and cement stabilised wood or peat ash. The properties considered critical in relation to long-term stability were determined in the laboratory. The results obtained were compared against the requirements set on by-products used in road construction. One of these tested materials has also been used in a test section built before these tests were started. This research project has been one project in the Tekes Ecogeotechnology R&D -programme.

2. Test materials

The tested materials were cement stabilised fly ash from Fortum's Meri-Pori power plant, SKJ's blast-furnace slag sand, mixture of fly ash and de-sulphuration product from Helsinki Energy and cement stabilised wood or peat ash from UPM-Kymmene's Kaipola factory. Blast-furnace slag sand was opposite to other materials studied as granular unbound material. The properties and behaviour of slag sand are well known and it has been used as a reference material for the test methods in this study. The test results obtained with slag sand are not presented in this article. Cement stabilised fly ash from Fortum's Meri-Pori Power plant has been used in a test road section in Pori area built under the test construction programme of Ecogeotechnology R&D programme.

Typical gradation curve of fly ash of Fortum's Meri-Pori Power plant is presented in Figure 1. This fly ash was used in the sub-base layer of the Pori test road. Also shown in Fig. 1 is the typical gradation curve of the bottom ash, which was used as one component in the base layer of the test road.

Typical gradation curves of fly ash from Helsinki Energy are shown in Figure 2. Typical gradation curves of peat ash created by burning mixed peat, wood and waste wood at the UPM Kaipola factory are shown in Figure 3.

The mix ratios, quantities of additives and optimum water content together with maximum dry densities determined for mixtures are presented in Table 1.

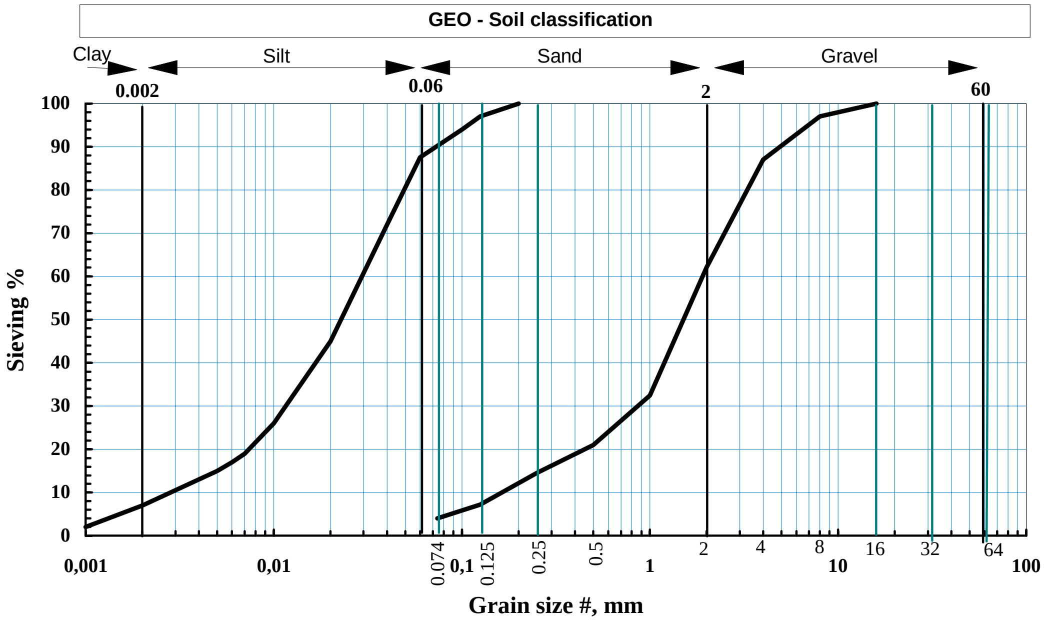

Figure 1. Typical gradations of fly ash (finer) and bottom ash (coarser) of Fortum's Meri-Pori power plant.

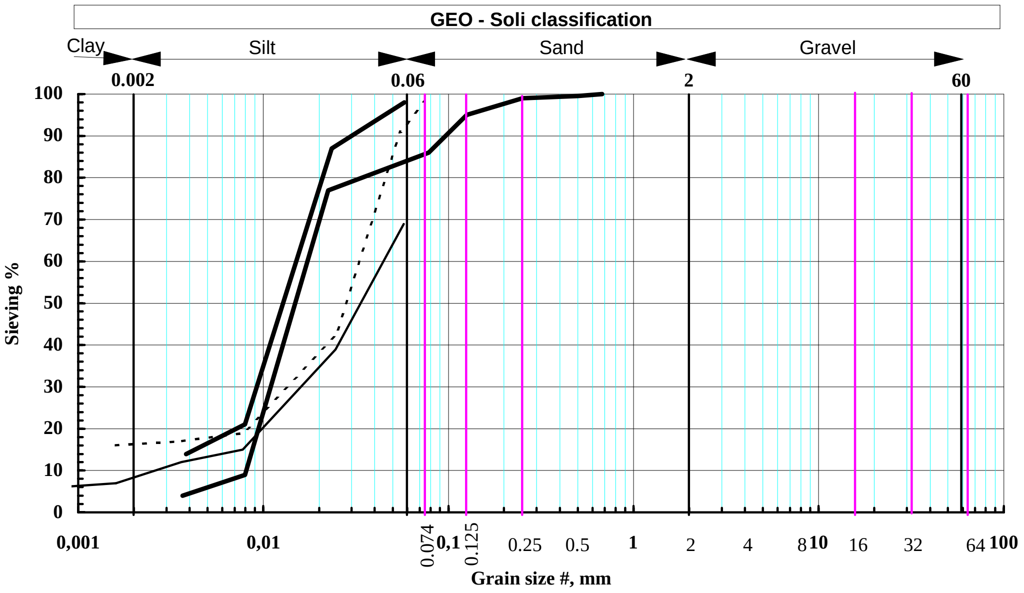

Figure 2. Typical gradation curves for fly ash from Helsinki Energy. The gradation of dry fly ash (thick lines, samples taken 26.3.97–7.5.98), de-sulphuration product heaped 30 days out of doors (broken line) and fly ash heaped 180 days out of doors (thin line).

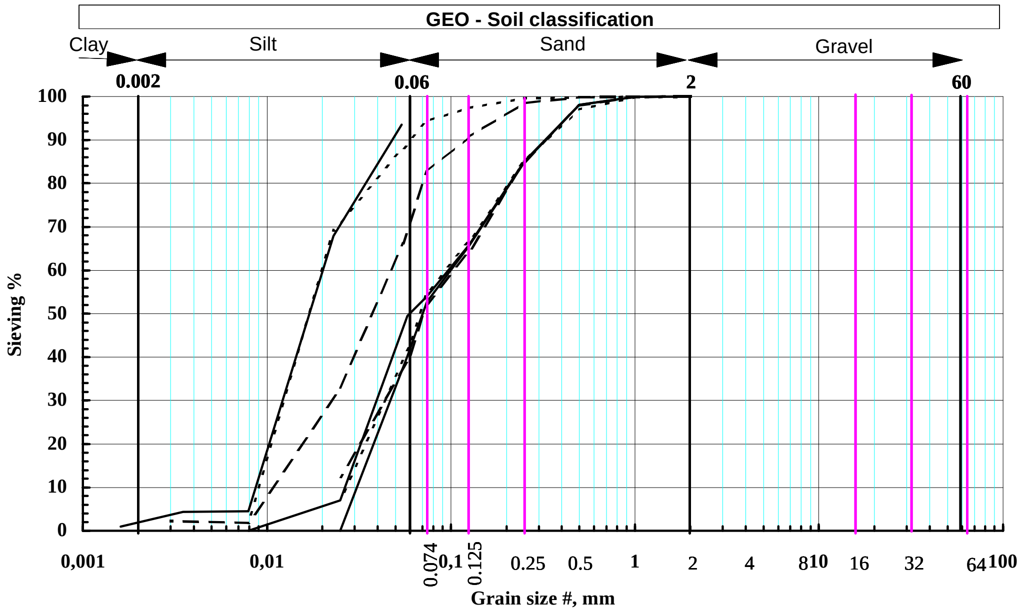

Figure 3. Gradations of Kaipola wood ash. The finer samples are dry ashes and the coarser (four lines nearly on top of each other) heaped ashes.

Table 1. Materials, mix ratios and basic properties.

Property	Stabilised fly ash	Fly ash / de-sulphuration product	Stabilised peat ash
MIX RATIO OR CEMENT CONTENT, %	6%	50% / 50%	4%
w_{opt}, %	25.0	25.0	36.2
$\gamma_{d\ max}$, kN/m^3	12.9	13.3	11.6
Design relative density, D, %	90	95	92

3. Testing program and test results

The testing program /2/ included the determination of dynamic stiffness modulus, compressive and tensile strength, thermal conductivity and permeability together with freeze thaw durability and frost heave parameters. In addition a specific forced bending test with beam specimens (h * b * l : 100mm*100mm*500mm).

The test specimens used in the tests were compacted under the optimum water content specific to each material to the desired densities. These densities are presented in Table 1. The stabilised fly ash specimens were manufactured to correspond to the density obtained in test road. The specimens of other materials were manufactured to correspond to the designed use of the material. The specimens were usually tested at the age of 28, 90 and 180 days.

The test results are presented in Table 2. Table 2 contains also the requirements submitted to materials used in the upper part of the road section. The requirements submitted to by-products with their complete justifications are presented in reference 2.

Table 4. Test results for each material and requirements in the upper layer of road section.

Property, parameter	Stabilised fly ash	Fly ash / de-sulphuration product	Stabilised peat ash	Requirement
Stiffness modulus, MPa (water content at compaction / saturated)				> 300
28 d	1400 / 2100	1100 / 700	4800 / 3300	
90 d	- / -	1200 / 2700	2300 / 3700	
180 d	2300 / 2300	2300 / 1000	- / -	
Compressive strength, MPa (wc at compaction / saturated)				> 1.5
7 d	1.5 / -	1.7 / 1.1	3.1 / 3.0	
28 d	2.2 / 2.5	2.6 / 2.0	5.4 / 4.8	
90 d	3.2 / -	3.5 / 3.1	8.5 / 9.6	
180 d	3.5 / 2.4	4.8 / 2.9	- / -	
Tensile strength, kPa	290	247	715	-
Freeze thaw durability, cycles (end cycles)	3	2	12 (30)	≥ 12
Frost heave parameters SP (2 kPa), mm^2/Kh	0.9…1.1	0.05	0.0	< 0.5
Water permeability, m/s	$2.0*10^{-7}$	$1.1*10^{-8}$	$1.2*10^{-9}$	$> 3*10^{-7}$
Bending capacity, R_{min}, m	94	108	84	$R_{longt} < 300$ $R_{shortt} < 150$
Thermal conductivity, W/Km, recommendation (frozen / thawed)	0.69 / 0.76	0.55 / 0.95	0.57 / 0.89	< 1 / 1

4. Review of the results

All materials fulfilled the compressive strength and dynamic stiffness requirements at the age of 28 days both under optimum water content and saturated state submitted for the upper part of the road structure.

Also the beam specimens of all materials sustained the required long-term and short-term bending test.

On the other hand none of the materials (excluding the slag sand) fulfilled the required permeability value/criteria.

Stabilised fly ash

The value of frost heave parameter, the segregation potential (SP), did not fulfil the requirement submitted for the upper part of the road section. The requirement submitted for lower part (SP < 1.5 mm^2/Kh, depth > 1.0 m) was on the other hand fulfilled.

The specimens did not survive the freeze thaw test due to specimen failure after the third cycle. Also the permeability value determined failed to fulfil the required value.

Mixture of fly ash and de-sulphuration product

The value of segregation potential determined passed the required value for upper part of the road section but the specimens failed to pass the freeze thaw test due to specimen failure after the second cycle. The permeability value determined failed to fulfil the required value.

Cement stabilised peat ash
The value of segregation potential determined passed the required value for upper part of the road section. The specimens also passed the freeze thaw test, which was carried out until 30 cycles was reached.

5. The estimation of long-term durability of materials

5.1 Stabilised fly ash

According to the test results the cement stabilised dry silo fly ash is capable of developing reasonable compressive strength and high stiffness value. This leads to good structural bearing capacity and better thermal insulation properties than can be found with natural materials.

Saturation was found to decrease the compressive strength and static stiffness modulus value.

The stabilised fly ash appeared to be low frost susceptible in the frost heave test made according to the test programme and it also failed to pass the freeze-thaw test simulating the climatic effects. Based on these results the long-term stability of the cement-stabilised fly ash in question appears to be poor. Due to this the properties do not remain constant but they may change considerably when the structure fails. This result means that it is not possible in the pavement design to use the high stiffness level measured (of the order of 2400 MPa). One must estimate the structural modulus value level, which can be reached for the failed material. The modulus value of the layer of failed bound material may still be of the same order as in similar layers built with natural materials.

The properties of bound materials are always strongly dependent on the internal alteration of quality of the product. The test specimens were compacted to the density obtained in the test road. Before the test road was constructed a set of preliminary laboratory tests were carried out. In these tests material did not possess frost heave problems (larger degree of density) and it passed the freeze thaw tests although loosing some of the compressive strength. The properties of fly ash studied during the test program and during the preliminary tests differed to some extent also in relation to compactability properties.

5.2 Mixture of fly ash and de-sulphuration product

The mixture of fly ash and de-sulphuration product was behaving almost like the cement stabilised fly ash. The mixture was found to be non-frost susceptible but it failed to pass the freeze thaw test simulating the environmental impact/stress.

5.3 Cement stabilised peat ash

Cement stabilised dry peat ash can produce very high compressive strength and good stiffness value. At the age of three months the level of compressive strength is 8…9 MPa and the value of dynamic stiffness modulus varies between 2000…4000 MPa. The effect of saturation on these properties is small and inconsistent. Material is non-frost susceptible and it passed the freeze thaw test simulating the environmental impact/stress. Based on the test results one can estimate that the long-term durability and also the bearing capacity stability is reasonable good. The thermal insulation properties of material are better than with natural materials.

It remains a slight problem to foresee the behaviour of material are due to quality variations (proportion of wood and peat) and at least in this case the extreme reactivity of used peat ash. Due to the latter property the ash behaved as a binder. At most the ratio of stiffness values of comparable specimens was up to 7. This strong strengthening property was not observed during the earlier studies. If one wants to make use of the good properties of this material one must check and verify the properties of material and construction process with dry material case specifically. Even a small amount of moisture beforehand reflects strongly to the strengthening of the material and a long-term moisturising alters also the other material properties to large extent. The permanent strengthening property disappears and the peat ash may change to frost susceptible.

6. Experience gained from the fly ash test road

The stabilised fly ash test road (Mt 272 Ämttöö-Poikeljärvi) has been monitored widely since the construction phase. The subject was one of the test road structures constructed under the test construction programme of Tekes's Ecogeotechnology R&D -programme and it is currently being monitored under TPPT test road project. The results obtained since spring 2000 are presented later in this document and are based mainly to this ongoing monitoring work /1/. This monitoring has included sampling, surveying, measuring of evenness (IRI) and bearing capacity determinations.

Cement stabilised (6%) fly ash from Fortum's Meri-Pori power plant was used in sub-base layer of this test road. Based on preliminary tests the stiffness modulus value of this stabilised fly ash in design was 400 MPa. The relative density was planned to be D = 92%. The amount of binder was chosen to produce a compressive strength of 3 MPa at the age of 28 days to limit the effect of freezing of the material. According to the preliminary tests the fly ash was non-frost susceptible. The bearing capacity requirement for the final fly ash structure was 416 MPa and the bearing capacity requirement for the reference (traditional structure) structure was 263 MPa.

The densities required in design were not fully achieved. The mean relative density of sub-base layer was ca. 90%. One reason to lower density was probably the variation in fly ash properties during the construction phase compared to the fly ash used in preliminary tests. The maximum dry density of fly ash varied between 12.8 …15.8 kN/m^3 and optimum water content between 17.2…28.2% during the construction. The variation in compactability properties of fly ash may especially in lower relative densities reflect to other geotechnical properties of the material. The optimum water content of the material used in preliminary tests was 15% and the compacted specimens (D = 92%) were non-frost susceptible. In the laboratory tests made after the construction (this project) the optimum water content of fly ash was 25% and relative density D = 90%. In this case the material was slightly frost susceptible (SP = 1 mm^2/Kh).

In spite of lower relative density than planned the bearing capacity measured on top of the fly ash layer in-situ the gave modulus values between 700…800 MPa. Samples taken in autumn before the freezing season gave compressive strength of 3.1 MPa.

Surveying

During winter 1997–98 frost heave values of 40 … 50 mm were monitored on the fly ash sections. These measured values corresponded well to the calculated frost heave value of ca. 40 mm determined based on winter's freezing index (9500 h°C) and laboratory and in-situ parameter values. The calculated frost depth (61 cm) corresponded reasonably well to the measured values (39 … 49 cm) from the road shoulder.

During winter 1998–99 (freezing index F = 14789 h°C) the maximum frost penetration 1.09 m was reached in April 1999, at which time the frost had penetrated through stabilised both fly ash layer (500 mm) and underlying filter sand layer (300 mm) into the subgrade. The frost penetration depths varied between 1.36 … 2.00 m in the reference structure.

The maximum frost heave of the fly ash structure varied between 28…88 mm. The largest frost heave 88 mm was measured at pile number 750 on the right shoulder on March 1999. At that time the frost had just penetrated through fly ash layer, which means that the frost heave measured is due to frost heave of the stabilised fly ash itself. The frost heave has been unevenly distributed in the section and the road shoulders have larger frost heave than the central part of the road. The frost heave values of the reference structure varied between -10…11 mm.

The surveying results at pile number 750 are shown in Figure 4. From the cross-section one can deduce that the largest frost heave values appear to happen at the shoulders. The smallest frost heave values appear within 1.5…2 meters from the centre line partly at both sides where they form depressions collecting water. Pooling due to uneven frost heave of the stabilised fly ash is shown in Figure 5.

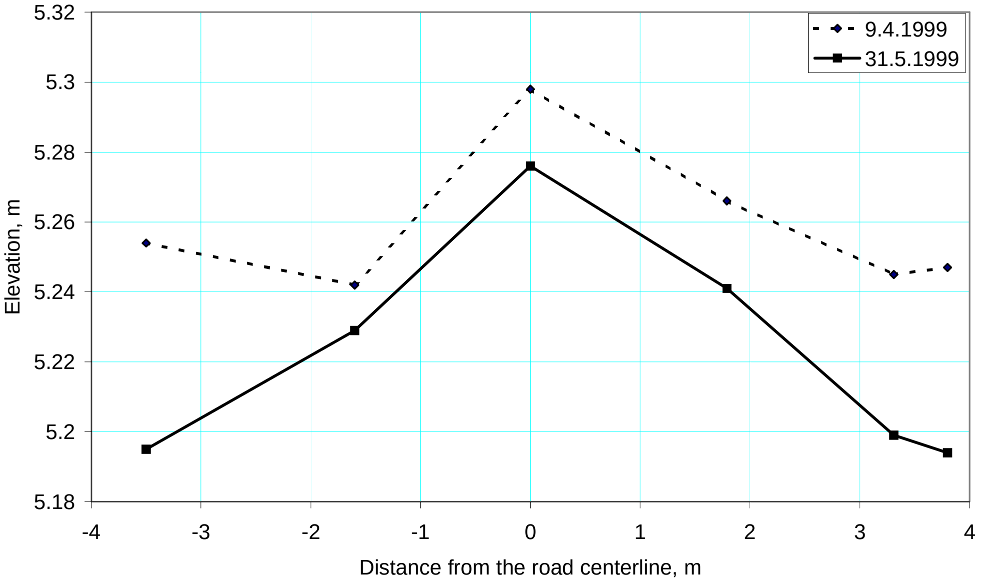

Figure 4. Cross-section surveying at pile number 750 during the maximum frost heave period in spring 1999 (9.4.1999) and early summer 1999 (31.5.1999).

Figure 5. Pooling due to uneven frost heave of fly ash structure in spring 1999.

In-situ samples

A second set of samples was bored in autumn 1998 at the same pile number as in autumn 1997. The age of the material was ca. 14 months when the samples were taken. Visual inspection revealed plenty of cracks and disintegration of stabilised material. The most intact specimens were chosen for laboratory tests.

Compressive strength, density and water content in in-situ condition were determined from these samples. Between the samplings (ca. 9 months) the compressive strength of the intact parts of sub-base layer decreased from 3.1 MPa down to 2.1 MPa. The in-situ water content also increased with 4…8% -units.

The third set of samples were bored, and this time from frozen layer, on March 1999. The samples were taken at pile numbers 460 and 900 from the right lane. The lengths of these samples varied between 25…110 mm.

Water contents were determined from all samples and the compressive strength from two specimens (the only ones long enough). In addition to that a thaw settlement and frost heave tests were carried out with the longest specimen. The compressive strength had decreased down to 25…50% of the value determined autumn 1997. The average values of compressive strength as a function of time has been shown in Figure 6 together with the average compressive strengths determined in laboratory.

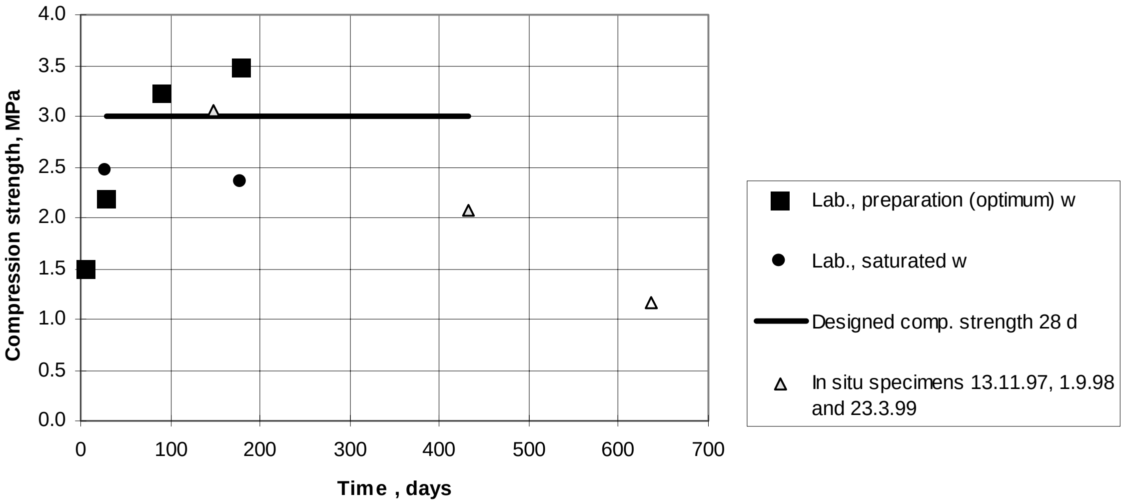

Figure 6. The compressive strength (average values) of specimen taken from test road at different times and the compressive strength (average values) determined at different ages in the laboratory.

A thaw settlement test was carried out with specimen taken from pile number 460, which had been taken as frozen from the depth of 0.32–0.43 m. This depth corresponds to the upper part of the sub-base layer. The settlement of the specimen was ca. 2%. After the thaw settlement test a normal frost heave test was carried out, which gave the segregation potential of SP = 0.5 mm^2/Kh for the fly ash specimen.

Segregation potential value SP = 1.0 mm^2/Kh was determined earlier for laboratory compacted stabilised fly ash specimen. Using temperature, frost depth and frost heave values measured during winter 1998–1999 as input the back-calculated segregation potential value for the stabilised fly ash structure varied between 0.5…2.0 mm^2/Kh depending on the absolute in-situ frost heave. According to the frost susceptibility criterion based on segregation potential SP the material is lightly frost susceptible if SP varies between 0.5…1.5 mm^2/Kh and medium frost susceptible if SP varies between 1.5…3.0 mm^2/Kh.

The bearing capacity

In autumn 1998, about one year after the construction, the average bearing capacity level at the road surface of the fly ash structure measured with FWD was 476 MPa. The average bearing capacity of the reference structure was 430 MPa. The average bearing capacities for both structures were in excess of the design value.

In spring (May) 1999 the average bearing capacity of fly ash test structure was 415 MPa, which corresponded with design value. The average bearing capacity of the reference structure was 430 MPa. The bearing capacity values for reference sections are well above the design values (263 MPa). The results of these FWD measurements are shown in Figure 7.

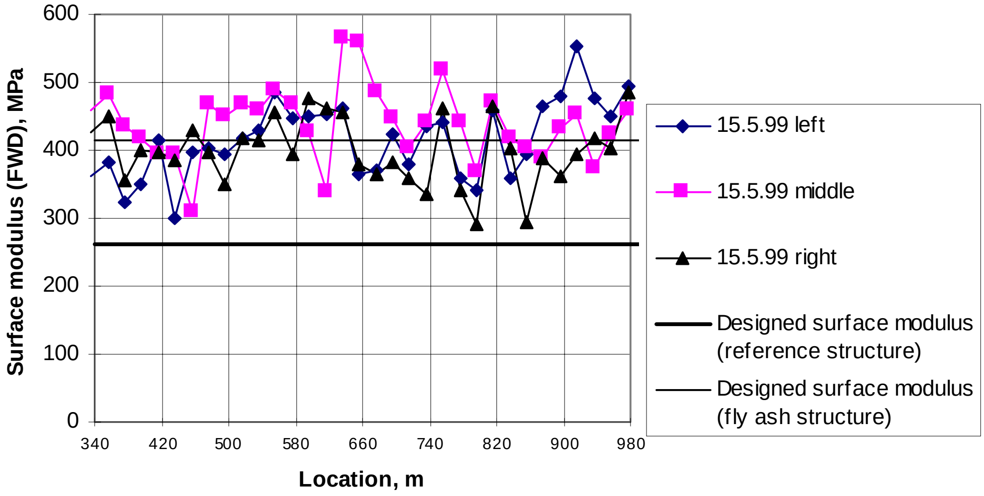

Figure 7. Temperature corrected FWD results, May 1999.

Wearing course damages

The first longitudinal crack was observed after the first winter 1998–1999 between pile numbers 442.4–445 on the centre line of the road. The width of the crack was ca. 5 mm. In spring 2000 there were found to be five cracks in separate places along a 70 m length. In addition there was one 5–10 mm wide crack on the left lane at 2 m distance from the centre line. The frost behaviour during winter 1999–2000 was quite similar to that during the previous winter.

Summary of the test road

As a summary of the behaviour of the fly ash structure one can conclude that the structure as a whole has behaved reasonably well despite the unevenness and pooling during late springtime. In spite of uneven frost heave, cracking of stabilised fly ash and decreased compressive strength the fly ash structure still had the design bearing capacity during spring 1999 and the bearing capacity was better than that of the reference structure. Frost heaving, material cracking and decrease in strength probably even down to less than half of the design value had no detrimental effects on the bearing capacity of the stabilised fly ash layer. This badly cracked stabilised fly ash layer behaves similarly to unbound crushed aggregate.

If the modulus value of the other layers are in agreement with design values then the modulus of stabilised fly ash is also in line with the design value (400 MPa). This value is only 19…15% of the dynamic modulus value determined with saturated intact specimens at the age of 28 and 180 days. In previous studies with cement stabilised glacial till it has been found out that the average dynamic modulus values of broken specimens are ca. 16…17% of that of corresponding intact specimens. With moist, broken stabilised glacial till the modulus value is ca. 21% and with saturated and broken specimen ca. 13% of the modulus value of the corresponding intact specimen.

7. Summary

All materials tested are in principle capable of producing adequate compressive strength and stiffness to be used in road construction. In practice some problems may arise especially concerning the choice of parameters for design due to poor environmental durability. In other words stabilised or self-strengthening materials do not necessarily last as intact the repeated freeze thaw cycles. Although the stiffness of stabilised material decreases significantly do to structural failure it may still possess reasonable large stiffness to be used in sub-base of a road structure.

The second phenomenon affecting strongly on the use of by-product is the internal variability of properties of by-products. These variations are mainly due to variations / changes in origin and composition of fuel used in relatively small power and production plants. This variation in quality causes uncertainty about the properties obtained in structural layer in two ways. The material used in laboratory test may differ sometimes quite remarkably from the material used in the actual structure. Also the variation during construction phase makes it difficult to carry out the compaction control.

By-products can be successfully used for road construction as long as the special properties and precautions of these materials are taken into consideration in testing, planning and construction.

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The use of steel melting slags in earth construction

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ABSTRACT: The problem of secondary metallurgical industry products/wastes utilisation is closely associated with the environmental protection. And whereas the problem of utilisation of blastfurnace granulated slags is completely solved, the steel melting slags are used in small amounts and are collected in dumps in huge amounts, in particular, in Ukraine. The difficulties of their utilisation come from considerable variations of their chemical-mineralogical composition. That's why the only appreciable use of steel melting slags is to use them in road construction. Basing on the established peculiarities of regulating the structure formation processes of the alkaline binding systems the more efficient way of steel melting slag utilisation has been developed- in the production of effective types of cements. The study's results including those of investigation of structure formation process, properties and principles of regulating properties are reported and discussed in details.

Intensive researches aimed at creating a principally new class of cementitious materials- the alkaline cements/binders which are themselves a blend of alkalies of the 1st group of the Periodic Table and aluminosilicates of natural and artificial origin (slags, ashes, slurries, etc.) are being conducted at the Kiev National University of Construction and Architecture since 1957 (in 1957 the Problem Laboratory of Earth (Soil) Silicates was founded (now, the V.D.Glukhovsky Scientific Research Institute for Binders and Materials).

The idea of using the above systems as cementitious materials was supported by the following: first- the geological data that the earth crust is widely represented by sodium, potassium, sodium-potassium-calcium aluminosilicates side by side with the calcium ones and the first listed compounds are characteristic of the better stability and resistance to atmospheric reagents, second- by the experimental studies performed by a scientific school of Professor V.G.Glukhovsky (1959) who put forward the idea that alkalies and alkali metal salts creating an alkaline reaction in aqueous medium, under condition of their high concentration, come into interaction with clay minerals, aluminosilicate glasses and crystalline substances of natural and artificial origin to form as a result of this interaction the water resistant alkaline and alkaline- alkali-earth aluminosilicate new formations analogous to natural minerals of the zeolite and mica type.

Among a great variety of these alkaline cements , according to classification given in Krivenko (1997), the most investigated are the slag alkaline cements/binders (Figure 1).

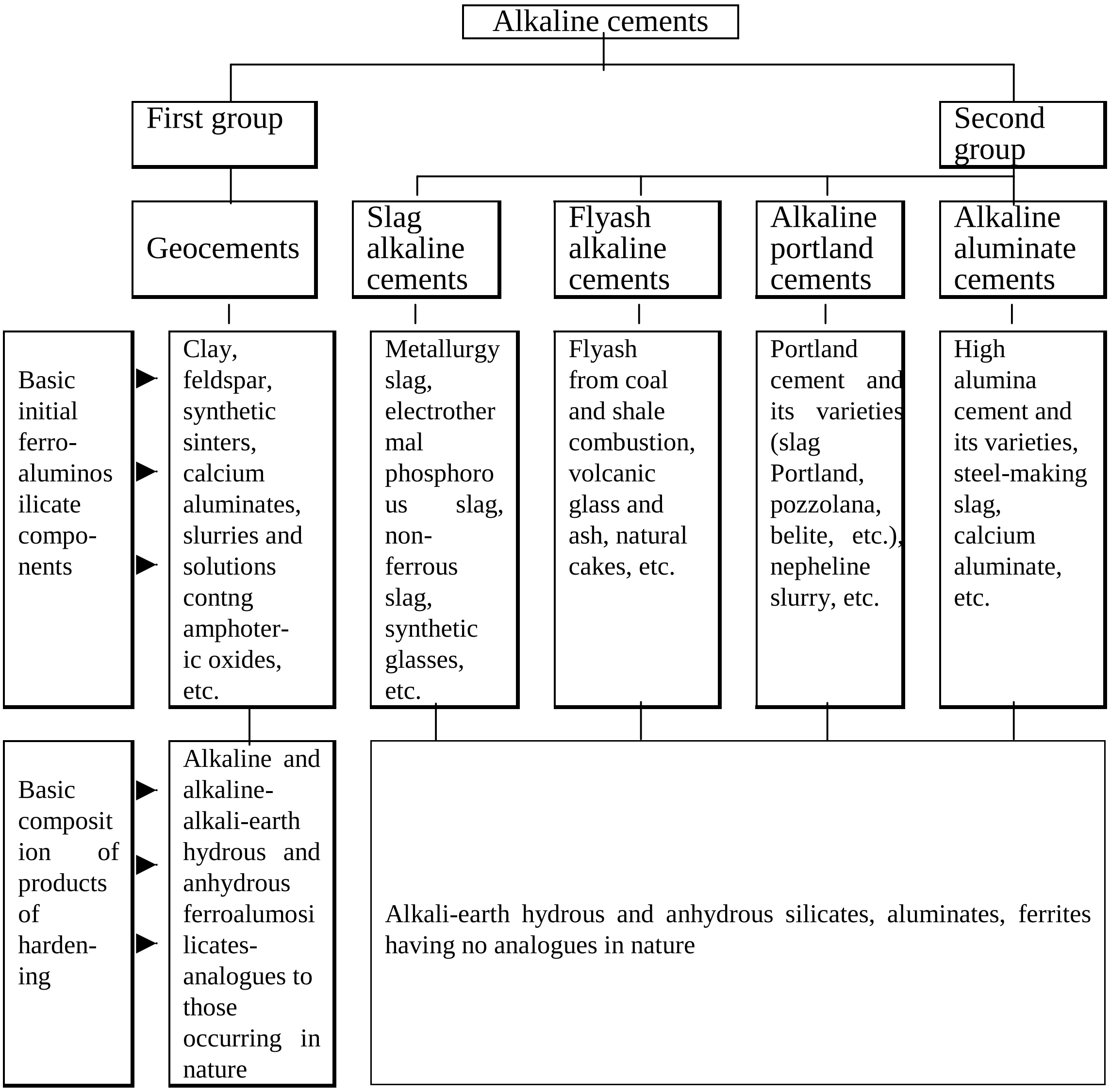

Figure 1. Classification of alkaline cements.

The investigation of activity of this group of cements on model glasses CaO-Al_2O_3-SiO_2 (Figure 2) showed that the fields of the highest activity are situated, not depending upon type of alkaline component and hardening conditions, in the field of compositions containing 15–20% Al_2O_3 and 40–50% CaO. The majority of metallurgical, in particular, blastfurnace slags, fall just within these compositions.

As it was established, an ability of slags to perform a hydraulic activity depends in case of alkaline cements upon a complex of physical-chemical, mineralogical and structural peculiarities that are similar for both glassy and crystalline slags. Taking into these peculiarities suggested to develop a wide range of highly effective slag alkaline cements with the use of slags not meeting the requirements of optimal constituent composition similar to blast furnace ones. To such slags may be referred a wide range of steel melting slags (open hearth, cupola, converter), from welding, ferroalloy, electric thermophosphorous as well as slags from non-ferrous metallurgy (nickel, lead, copper).

A chemical-mineralogical composition of steel melting slags varies within wide ranges, due to this the use of these slags in the building materials industry is of small practical value. Meanwhile, the application of new principles of control of structure and properties of slag alkaline cementitious materials, in particular, a selection of optimal ratio of glassy crystalline phases of the aluminosilicate component allowed to produce effective cementitious materials using a wide range of steel melting slags.

Chemical composition of these slags is given in Table.

Table. Chemical composition of steel melting slags.

Slag	Oxide content, % by mass						Mb*
	SiO_2	CaO	Al_2O_3	MgO	FeO+ Fe_2O_3	MnO	
Open-hearth	13.9–26.2	24.7–43.6	2.8– 5.2	6.9–11	11.4–26.3	2.9–10	0.8–1.5 >1,5
Converter	16.3–16.7	44,9–46,7	1,9–4,8	3,5–5,5	18,4–25,9	4–4,6	>1,6
Electric furnace steel melting	18,8–19,8	39–43,9	3,1–7,6	15,7–16,7	10,8–20,8	1,2–2,8	0,8–1,5 >2
Cupola	38,3–48,2	26,1–31,5	10,6–11,3	4,3–5	3–4,9	2,7–11,5	• 0,8
Silico-mangamese	42–45	20–22	12–15	2–3	-	16–18	• 0,8

NOTE: *- Modulus of basicity (Mb)= CaO+MgO/ Al_2O_3+ SiO_2

Analyzing a chemical- mineralogical composition allowed to divide the interaction of steel melting slags with alkali-metal compounds in three groups: low-basic glassy akermanite- melilite composition (cupola and silicomanganese with Mb=0.8); basic crystallized monticellite-mervinite and monticellite-diopside composition (open-hearth and electric furnace steel melting with 0.8‹Mb= 1.5; high-basic crystallized orthosilicate (open-hearth and converter with Mb = 1.6)(Figure 3).

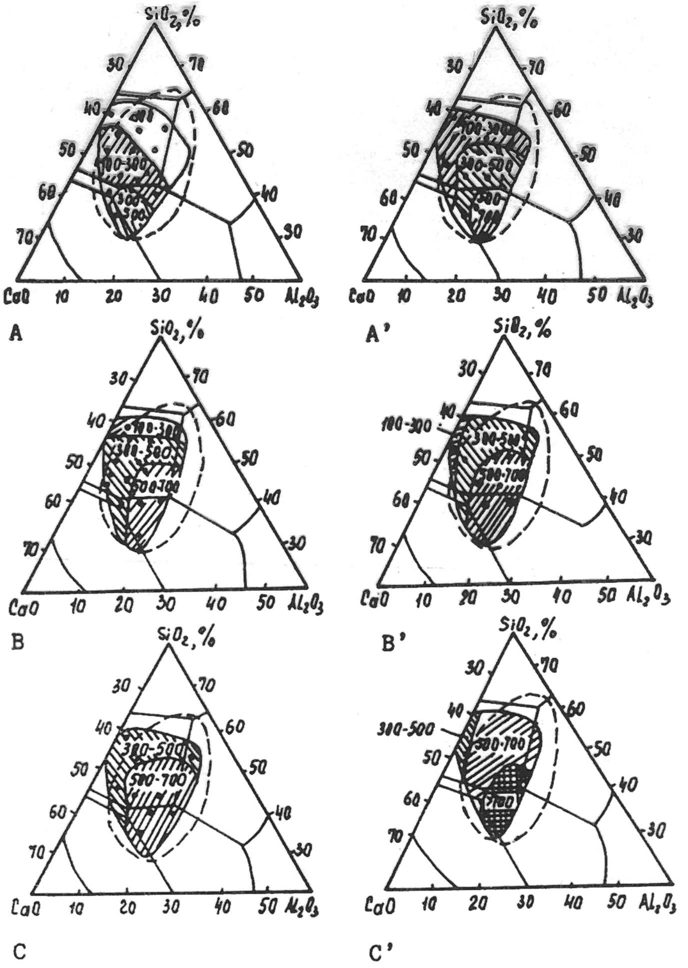

Figure 2. Activity fields of the cements from synthetic glasses of the system CaO- Al_2O_3- SiO_2 in combination with soda solutions (• =1180 kg/cub.m) (A and A1), sodium hydroxide (• =1180 kg/cub.m) (B and B1) and sodium metasilicate (• =1300 kg/cub.m)(C and C1):
A,B,C- hardening in normal conditions;
A1, B1, C1- hardening under steam curing (2+6+2hrs at T=368+/-5^{o}C) .

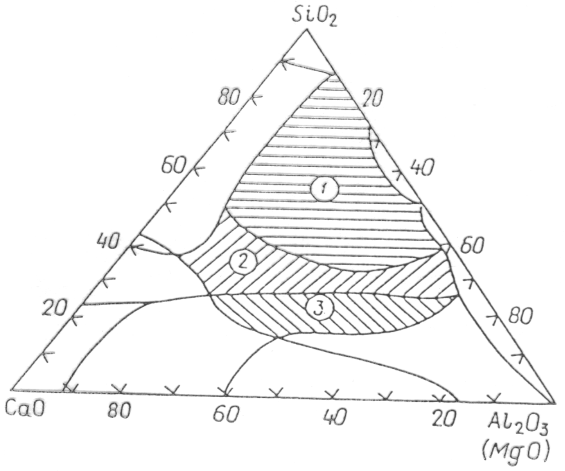

Figure 3. Crystallization fields of the slags under investigation:
1-orthosilicate field;
2-monticellite-mervinite and monticellite-diopside field;
3-akermanite- melilite field.

The processes of heat evolution during hardening of the alkaline cements are reported by Usherov-Marshak, Krivenko and Pershina (1998). A specific feature of the processes of hydration and hardening of the cements made from high-basic crystallized steel melting slags of orthosilicate composition is high intensity of heat evolution and contraction during first 1–3 days (Figure 4) accompanied by quick thickening and setting of the binding system. The binder activity determined on paste of normal consistence in 1 day age is 6–9 MPa (made with soda) and 10–15 MPa (made with sodium metasilicate) depending upon slag basicity.

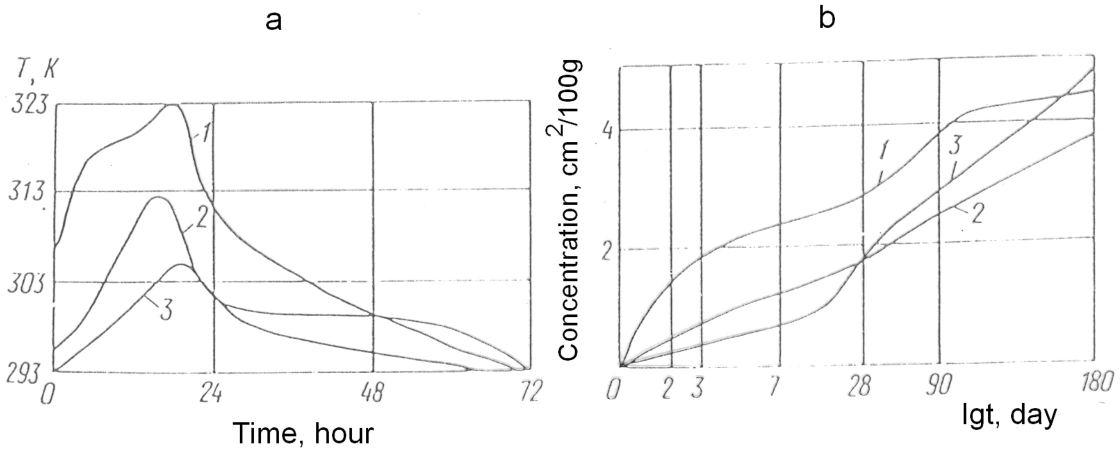

Figure 4. Heat evolution of contraction (a) and (b) of the cements made with sodium metasilicate and slags:
1- open-hearth (Mb=2.65);
2- open-hearth (Mb=1.1);
3- cupola (Mb=0.75).

Further development of hydration processes is characterized by lowering the intensity of contraction phenomena and strength gain (Figure 5). Strength of the specimens at an age of 28 days of normal hardening is 20–25 MPa (within soda) and 38–45 MPa (with sodium metasilicate) and those steam-cured- 22–30 MPa and 35–50 MPa, correspondingly.

Phase composition of the products of hydration and hardening of the cements made from steel melting slags of orthosilicate composition of both normal hardening (at an age of 28 days) as well as after stem curing is represented, mainly, by changes in the hydration products in the direction of formation of low-basic calcium hydrosilicates- CSH(B), afwillite, foshagite, xonotlite, highly siliceous hydrogarnets and mixed sodium-calcium hydrosilicates of pectolite type. The strength of cements was found to be 45–60 MPa (with soda) and 65–75 MPa (with sodium metasilicate) and by 4 years reached 55–70 and 81–87 MPa, correspondingly (Figure 5).

The processes of hydration and hardening of the cements from basic crystallized steel melting slags of monticellite-mervinite and monticellite-diopside compositions are accompanied by less intensity of heat evolution and contraction (Figure 4); there was fixed in the graphs a shift of extremums at the later ages as compared with cements from slags of orthosilicate composition. The development of such hydration processes is a reason of very low strength of the cements at an age of 1 day: 0.2–3 MPa with soda and 3–6 MPa with sodium metasilicate.

Further development of the processes of hardening is accompanied by some increase in rate of contraction, which, is considerably lower compared to the cements made from slags of orthosilicate composition.

The activity of cements made from basic steel melting slags under normal hardening at an age of 28 days was found to be 15–20 MPa with soda and 20–30 MPa with sodium di- and metasilicate, whereas the strength of those steam cured- 10–20 MPa and 25–40 MPa, correspondingly. The appreciable strength characteristics are gained by such cements in later ages of hardening (1–4 years). As reported in Petropavlovsky (1987), after 1 year of hardening, the strength of specimens was 30–42 MPa with soda and 46–58 MPa with sodium metasilicate, after 4 years- 40–50 MPa and 60–70 MPa, correspondingly (Figure 5).

The phase composition of the products of hardening of these cements is represented mainly, by by a poorly expressed X-ray detected low-basic calcium hydrosilicates of tobermorite composition as well as by calcite and the compounds of calcium- manganese-iron containing composition of julgoldite, orientite, and carpholite. The degree of hydration of these cements even by 1 year of hardening does not exceed 14%.

A specific feature of the processes of hydration and hardening of the cements made from low-basic glassy steel- melting slags is low activity of heat evolution and, particular, of contraction (Figure 4) in early ages of hardening (up to 15 days).

These cements are characteristic of low activity: at an age of 1 day- their activity is almost and only by 3 days of normal hardening it corresponds to a 1 day-strength of the cements made from basic slags, and by 14 days- 1 day-strength of the cements made from high-basic steel melting slags.

However, by an age of 14 days, the processes of hydration and hardening of these cements intensify (Figure 5) and by 28 days age of normal hardening the strength is 10–15 MPa with soda and 30–40 MPa with sodium metasilicate; by an age of 1 year- 62–75 MPa with soda and 90–98 MPa with sodium metasilicate, what is by 1.1–1.4 times higher the strength of those made from high-basic steel melting slags and by 1.5–2 times higher than that of the cements made from basic steel melting slags.

It was established, that hydration rate of the slag alkaline cements from glassy slags over the whole period of hardening exceeds that of the cements from crystallized steel melting slags, what is a characteristic of high rate and intensity of chemical interaction of alkali and glassy slag constituents as compared to the crystalline ones. Worthy mentioning is that these cements attain high strength characteristics after steam curing, their strength is 1.5–10 times higher than strength of similar binder samples from crystallized slags and is 38–50 MPa with soda and 87–105 MPa with sodium di- and metasilicate.

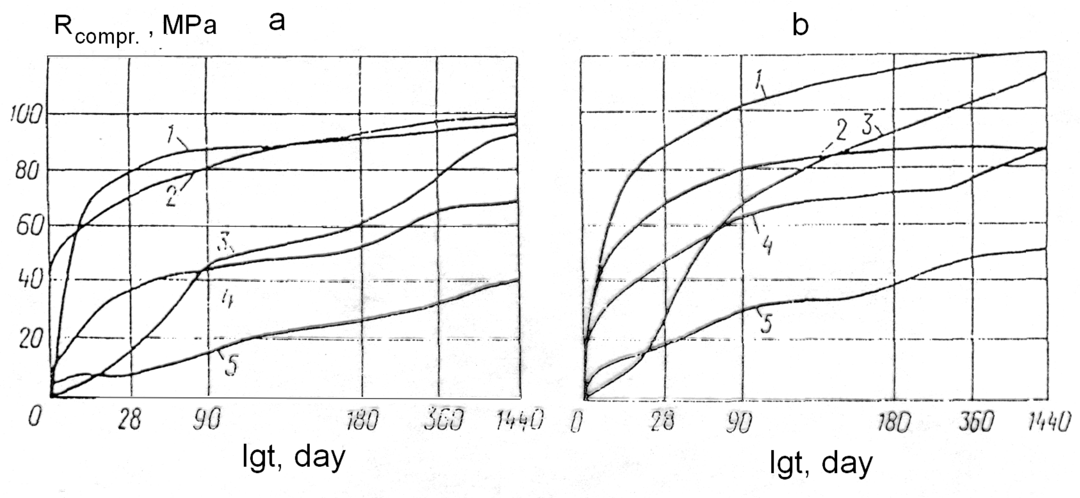

Figure 5. Change in activity of the cements (paste of normal consistency) on soda (a), metasilicate (b) and the slags:
1- blastfurnace granulated slag (Mb=1.13);
2- portland cement with water;
3- cupola (Mb=0.75);
4- open- hearth (Mb=2.65);
5- open-hearth (Mb=1.1).

Phase composition of the products of hardening of the cements made from low-basic glassy slags is represented, mainly, by a gel phase of tobermorite composition, low-basic calcium hydrosilicates, calcite and alkline hydroaluminosilicate- paragonite.

Hence, the crystallized steel melting slags have no practical value as independent binder constituents that meet the existing standards. The cements made from high-basic slags are characteristics of rather high rate of cation-exchange processes resulting in a quick setting of the cementitious system and preventing the formation of strong structure of the artificial stone.

The cements made from slags with the lower basicity (Mb= 1.5) are characteristic of not high rate of cation-exchange processes, however, a poor chemical interaction of the alkali and crystalline slag constituents does not allow to create a strong structure of the artificial stone. These cements obtain rather high strength in late ages of hardening (1–4 years), these values are comparable with those of the cements, but are 1,5–3 times lower the strength of the slag alkaline cements as well as the slag alkaline cements from low-basic glassy steel melting slags.

As stated by Petropavlovsky (1987), the cements on low-basic glassy steel melting slags in early ages of hardening (28–90 days) perform low strength caused by a weak intensity of the cation-exchange processes in the system reducing their efficiency. They gain a practical interest only when they are steam-cured because reach strengths that are compatible to those obtained with the use of blastfurnace slags.

Thus, an assumption may be put forward that it is possible to develop effective slag alkaline cements that would contain a blend of glassy and crystalline slags.

That's why below are given the results of studies of the alkaline cements, an aluminosilicate constituent of which is represented by compositions "crystallized steel melting slag- blastfurnace granulated slag" and ""crystallized steel melting slag- glassy steel melting slag".

As it was established as a result of studies on the processes of hydration and hardening of these binding compositions reported in Krivenko, Petropavlovsky, Pushkarjova and Maliarenko (1989) the combination of blastfurnace and high-basic crystallized slags provides the decrease in intensity of heat evolution and contraction as well as more smooth development of these processes what is accompanied by the extension of setting times of the binding system. Low-basic calcium hydrosilicate predominate in the hardening products phase composition, the quantity of the gel phase increases (as compared with the cements made from high- basic steel melting slag without additives), and the iron-containing phase is more saturated with silica which provides a predominant synthesis of a hydrogarnet- andradite.

The mixed cements from basic crystallized slags are characteristic of the occurrence in the heat evolution curves of additional effects, the increase in rate of development of the contraction, what corresponds to the increase in chemical interaction of slags with alkali-metal compounds. The increase of the gel phase is fixed in the phase composition of these cements.

By introducing into the slag alkaline cements made from low-basic glassy slags of high-basic crystallized steel melting slag, the rate of heat evolution and development of contraction phenomena increase. The phase composition of the products of hardening is characterized by increase in volume of hydrate formations. Strength of the mixed cements under normal conditions at an age of 28 days was found to be 1.5 times as high as that of the additive-free cements.

The optimization of mixed cements compositions was conducted using a numerical planning of experiment. The regularities revealed were similar to these characteristic of slag alkaline cements from blastfurnace slags with Portland cement clinker additive. However, due to more stable structure and less basicity of slags as compared with clinker, the optimal content of crystallized steel melting slags is higher; it depends upon both basicity and composition of these slags and basicity of glassy binder constituent and varies within 5–50%. The optimal content of crystallized steel melting slags in the compositions made from acid blastfurnace granulated slags 1= Mb=0.89), basic blastfurnace granulated slags (1.13=Mb=1) and ultra-acid steel melting slags (0.75=Mb=0.42) is 10–26.5; 5–15 and 20–50%, correspondingly.

The introduction of optimal quantities of crystallized slags into the cements allows to decrease the consumption of alkaline component (by 10–20%) without changes in strength characteristics or to increase strength of the cements by 1.1–1.5 times under steam curing and by 2–3 times under normal hardening at an age of 28 days with the same content of alkaline component

The mixed slag alkaline cements from blastfurnace granulated slags with Mb=0.89 and high-basic crystallized steel melting slags may be referred to as quick-hardening cementitious materials (compressive strength at an age of 3 days- 52–62 MPa, 7 days- 66–80 MPa, 28 days- 90–110 MPa).

The mixed slag alkaline cements made from the glassy low-basic steel melting slags with optimal content of high- basic crystallized slags (25–35%) are characterized by high strength (50–65 MPa after steam-curing with soda and 90-120 MPa with sodium di- and metasilicate, after 28 days of normal hardening- 40–50 and 89- 96 MPa, correspondingly.

The building technical properties of the mixed slag alkaline cements can be regulated within wide ranges due to changing a ratio in them of slags of glassy and crystallized structure. As reported by Rostovskaya, Petropavlovsky and Blazhis (1984), the normal consistency of paste is within 19–26%, setting times may vary within the following ranges: initial setting time- 4–260 min., final setting time- 10–520 min. The ways of how to slow down the initial setting of quick-hardening cements by introducing additives (LST, LST+NaOH, etc.) have been developed and it was established that the investigated additives allow not only prolong the initial setting but also promote a considerable increase in binder strength (by 10–15 MPa).

Long-term observation (360 days) of self deformations of the slag alkaline cement stone suggested to conclude that the shrinkage deformations of the mixed slag alkaline cements are considerably lower than those of the additive-free slag alkaline cements and fall within the values of shrinkage of portland cement. It was established that it is possible to keep these values under control and vary them within wide ranges up to producing by varying a quantity of crystallized steel melting slags within the mixed cements up to producing low-shrinkage and shrinkage-free cementitious systems. So, the shrinkage-free cements have been developed based on high-basic open-hearth and converter crystallized slags and soda, which have shrinkage 0.01–0.35% at an age of 28 days.

Thus, the application of the principles of directed formation of phase composition of the hydration products of the alkaline cements suggested to develop effective cements and concretes with the use of variety of steel melting slags. The results of these studies extends considerably raw materials base of the slag alkaline cements and promotes the cleaning of environment since they open the way of utilisation of practically all steel melting slags collected in dumps.

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ALT-MAT-project, Finnish national report

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ABSTRACT: The environmental aspects strongly necessitate more extensive utilisation of the alternative materials. This utilisation needs more information of the mechanical and leaching properties, functional requirements and long term stability of the materials. The European ALT-MAT project defines methods by which the suitability of alternative materials for use in road construction can be evaluated under appropriate climatic conditions. The Finnish national work in ALT-MAT project concentrated on the development of the climate chamber test. The purpose of these test was to simulate the field conditions of road structures (miniembankment) without a pavement. The test consisted of 20 wetting-drying and freezing-thawing cycles. Miniembankments were wetted with salt solution. The leaching of contaminants due to these accelerated climatic cycles and salt solution was studied. The tested materials were two slags: ferrochrome and blast furnace slag. The test results exhibited that the leached amounts of many metals were very low, usually below the limit of detection. These results were verified with other leaching test results. All test data showed that the leaching of contaminants for both slags is very moderate. The climate chamber test proved to be a good, but expensive method to test the environmental suitability of alternative materials.

1. Introduction

Every year the Finnish steel industry produces over one million tons of by-products, mostly different kinds of slags. These slags have mechanical properties that satisfy ideally the material requirements of road construction layers. In some cases, such as lightness, stress- and deformation durations, slags are even better than natural aggregates. During last few decades, part of the annual production of blast furnace and ferrochrome slags has been utilised as road construction materials. This utilisation has occurred mainly in the vicinity of steel factories. The growing awareness of environmental aspects and the lack of high quality road materials in some regions has increased the interest in utilising slags more efficiently.

The greatest obstacles to more efficient utilisation of slags lie in the uncertainties of environmental impacts. The environmental impacts of by-products are normally studied with leaching tests. To study varying climatic conditions and their effect on the leaching, we developed a new test method called the climate chamber test. The aim of climate chamber tests is to simulate field conditions of a road construction without a pavement. This method provides opportunities to overlap the difference in small-scale laboratory experiments and full-scale trial embankments. The test is designed to study the release of contaminants (leaching) due to accelerated climatic cycles and salt solutions used for winter maintenance in Finland.

The development of the climate chamber test method is a part of the ALT-MAT project.

The main objective of the ALT-MAT project is to define methods to evaluate the suitability of alternative materials in road construction. The methods evaluate the suitability under appropriate climatic conditions. We also compared the results of the climate chamber test with other leaching test results to exhibit leaching under various circumstances.

As test materials we selected ferrochrome and blast furnace slag, because their general use as road construction material is always subject to a special permission from the Finnish Environmental Institute.

2. Materials and methods

2.1 Test materials

The two materials studied are blast furnace (BFS) and ferrochrome slags (FCS). The chemical compositions of them are displayed in table 1.

Blast furnace slag is a by-product obtained in manufacturing of pig iron in a blast furnace. Blast furnace slag is formed by the combination of the earthly constituents of the iron ore with the limestone flux. Because the constituents of slag are important for the function of blast furnace, so they must be kept as steady as possible. The quality of slag produced in a particular steelwork is highly consistent and its variability matches that obtained in the exploitation of conventional aggregates (Lee 1974). The production sites of BFS in Finland are steel factories in Raahe and Koverhar.

The temperature in the blast furnace is over 1 300 °C. Lighter slag floats on pig iron. Slag is conducted apart from pig iron to the cooling process. There are two possible cooling methods: air- or water-cooling. In the air-cooling method the melt slag is poured out to a cooling embankment where it cools slowly. Because the cooling is slow, mineral has time to cristallyze. In the water-cooling method a high-pressure water jet cools slag. This rapid solidification produces a granulated glassy material. The internal structure of this glassy slag is more broken, which means that it is more reactive than air-cooled slag. Nowadays, most of the BFS produced in Finland is water-cooled.

The major components of BFS are silica, sodium and magnesium oxides (together 83%). The main minerals of BFS are melilite, oldhamite, mervinite and some glass.

Besides of the chemical composition, the glassy structure of BFS affects its binding properties. BFS binds hydraulically, but considerably slower than cement. The addition of cement or mincing of grain size accelerates the binding reaction. The binding reaction happens on the surface of grain. After crushing binding starts up again on a new surface. Then, this crushing in structure is self-reconstructive in the long-term.

The cooling method affects the mechanical and chemical properties of slag. The water-cooled BFS (granulated) is porous, slowly binding material and it looks like sand. The bulk density of BFS is low, l1–13 kN/m^3, which means that it can be used as a light-weight material. The air-cooled BFS is a little heavier and its grains are bigger than water-cooled slags. The hydraulic, deformation and strength properties of both BFS are excellent, and they fulfil ideally the material requirements of unbound road construction material. The thermal properties of BFS are very good, therefore it is natural that BFS is also used as a thermal insulating material.

Ferrochrome slag is a by-product obtained in the manufacture of refined steel in Tornio. The manufacture process resembles that of the BFS. Correspondingly, FCS can be cooled with air or with water. The mechanical and chemical properties of FCS are quite similar to BFS. Yet, there are two important differences: the abrasion values of FCS are much better than BFS's and FCS does not have the capability to bind itself.

The major components of FCS are silica, aluminium and magnesium oxides (together 77%). FCS includes 6.5% chrome, which exceeds the total recommended concentration of chrome (table 1).

Table 1. The chemical composition of ferrochrome and blast furnace slags.

Ferrochrome slag (water cooled) (aqua regalis) (%)	Typical analysis of ferrochrome slag (%)	Blast furnace slag (air cooled) (%)	Blast furnace slag (water cooled) Koverhar (%)	Granite, Teisko (%)
CaO 3–8	CaO 2.1	CaO 37	Mg 9.41 XRF	CaO 2.4
SiO_2 27–29	SiO_2 28.6	SiO_2 35	Al 6.14 XRF	SiO_2 69.7
Al_2O_3 23–28	MgO 24.3	MgO 11	Si 15.0 XRF	MgO 0.9
MgO 22–27	Al_2O_3 27.0	Al_2O_3 9	P 0.006 XRF	Al_2O_3 15.4
S 0.1	Ti 0.29	TiO_2 2.5	S 1.79 XRF	K_2O 3.3
Cr 6.5	Mn 0.15	MnO 1.0	K 0.43 XRF	Na_2O 3.8
Fe 4.0	K 0.08	K_2O 1.0	Ca 24.0 XRF	Fe 2.6
	Na 0.02	Na_2O 1.0	Ti 1.12 XRF	Ti 0.2
	S 0.16	S 1.5	V 0.057 XRF	Ba 0.074
	Fe 4.5	FeO 0.5	Mn 0.12 XRF	Mn 0.062
	P <0.0005	P 0.003	Fe 0.63 XRF	P 0.042
	Ba 0.01	Ba 0.038	Cr 0.004 XRF	S 0.029
	C 0.12	Ce 0.012	Ni 0.001 XRF	Sr 0.018
	Cr 7.7	Cr 0.003	Sr 0.047 XRF	Zr 0.016
	Cu 0.01	La 0.006	Zr 0.015 XRF	Cr 0.013
	Co 0.03	Sr 0.042	Nb 0.001 XRF	Zn 0.008
	V 0.020	V 0.030	Mo 0.000 XRF	V 0.004
	Zn 0.010	Zr 0.017	Sn 0.001 XRF	Cu 0.003
	Sn <0.0010	Sn 0.002	Ba 0.056 XRF	Ni 0.002
	Li <0.01	Nb 0.001	La 0.006 XRF	
	Ni 0.03	Ni 0.001	Ce 0.009 XRF	
	Mo <0.01	B 0.004 2	Ca_{ASTM} 39.7	
	Sb <0.001	Cu 0.000 8	Ca_{pH5} 6.9	
	As <0.001	As 0.000 67	Fe_{met} 0.3	
	Bi <0.001	Zn 0.000 2	F 0.1	
	Pb < 0.001	Pb < 0.000 05	Zn 0.000 4	
	Cd < 0.001	Cd < 0.000 005	As 0.000 5	
	Hg < 0.000 002	Hg < 0.000 002	Cd <0.000 005	
			Pb <0.000 01	
			Hg <0.000 005	
			B 0.0487	
			Cu 0.000 08	

2.2 Test methodology

The climate chamber test boxes were constructed to bear stresses from compacting, moving and freezing during the test. The width and length of a box were 700 mm and its height was 300 mm. The body of a box was made of plywood and its inside was covered with a plastic membrane of HPDE. A filter cloth was placed between the specimen and the plastic membrane. In the bottom of the box there was a lead-through for draining and leachate collection. The boxes were placed on movable carriages. Figure 1 illustrates the construction of the miniembankment.

SKJ-Yhtiöt LTD delivered both slags to us. The tested materials were: air-cooled ferrochrome slag and water-cooled blast furnace slag.

The test material was compacted to the box to the 95% density of maximum density value of Proctor compaction test. We had two concurrent specimens of both materials. Totally, we had four specimens. The technical data of these specimens are in table 2.

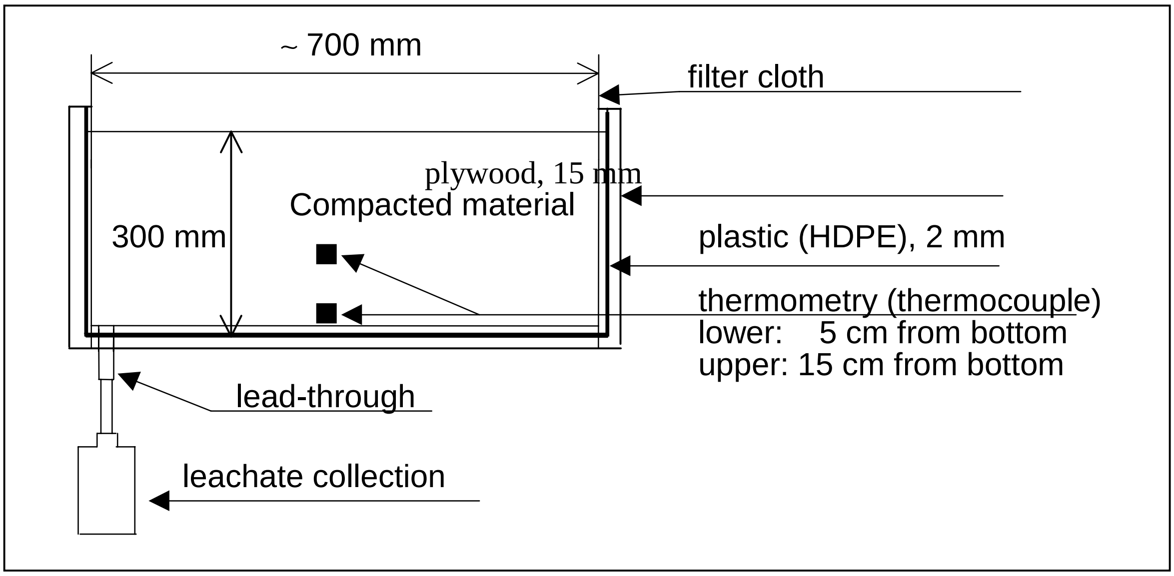

Figure 1. The construction of the miniembankment.

Table 2. The technical data of specimens.

Data	Ferrochrome slag		Blast furnace slag		Remarks
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	
Volume (cm^3)	152.70	150.37	152.799	159.312	
Dry density (g/cm^3)	1.83	1.83	1.37	1.37	95% of Proctor density
Weight (kg)	294.72	290.21	209.335	214.147	

The climate chamber test (CCT) consisted of three main phases: wetting – drying cycles, freezing – thawing cycles and leachate collection. The liquid, which is in contact with solid, is referred to here as leachant and the liquid leaving the solid is referred to as leachate. The flow chart diagram of the whole CCT leaching test is illustrated in figure 2.

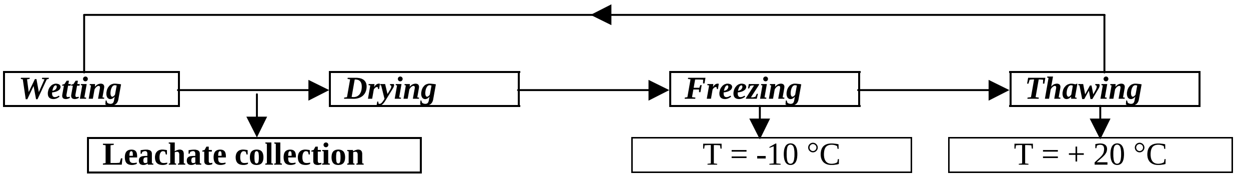

Figure 2. The flow chart diagram of the CCT test.

First, the specimens were wetted with a salt solution (leachant) composed 10% of salt used by Finnish National Road Administration and 90% of normal tap water. The typical chemical composition of salt is shown in table 3. The total quantity of salt solution was about 25 kg in each wetting cycle. The wetting happened in a normal room temperature +20 °C. During the wetting, leachate was collected from the specimens into glass bottles.

Leachate samples were analysed in the laboratory of VTT Chemical Technology. Leachate was collected:

- before first freezing
- after 2 freezing – thawing cycles
- after 10 freezing – thawing cycles
- after 20 freezing – thawing cycles

After the wetting and leachate collection, the specimens were dried for 1 day. Then, the lead-through was closed and carriages were moved to a cold room, whose temperature was -10 °C. The temperature of the specimens during the freezing was monitored from two thermometers. When the whole specimen was frozen to -10 °C, the specimens were taken to the thawing room (+20 °C). Totally, the specimens were treated with 20 freezing - thawing cycles.

Table 3. The chemical composition of salt.

Component	Percentage (%)
NaCl	98.82
Ca	0.27
Mg	0.02
K	0.09
SO_4	0.80

In the beginning freezing – thawing cycles took at least 8 days each, thus to run all 20 cycles would have taken about five months. Since that was too much, the temperature of freezing room (-10°C) was be lowered to -30 °C and the temperature of the thawing room raised to +40°C. With these test arrangements, one test cycle time could be lowed to 5 days. In spite of these accelerations, the climate chamber test is a very time-consuming test. In ideal conditions one whole test takes at least 3 months.

3. Results

3.1 Mechanical behaviour

We visually followed the behaviour of specimen during the test. The surface of the specimens cracked and heaved during freezing. These cracks and frost heave were due to the enlargening of the freezing water. After thawing some compaction happened, but the structure did not get back to the original compaction ratio. The grain size distributions of specimens were tested before the first freezing and after the whole test (figure 3) to see whether any weathering had happen during the test.

3.2 Chemical behaviour

We had two concurrent specimens of both slags. The leachates were collected four times, so the total amount of analysed leachates was 16. We discussed with the chemists and chose together the most interesting elements from the environmental point of view to be analysed. The analysed elements were: Ca, Na, K, Al, As, Cd, Cr, Cu, Mo, Ni, Pb, Zn, Fe, Mg, Mn, sulphate and vanadium from blast furnace slag. The values of pH, conductivity and redox - potential were also measured. The concentrations of Ca, Na, K, Al, Cr, Cd, Mo, Zn, Fe, Mg, Mn and V were analysed with atomic spectrometric technique (ICP-AES). The concentrations of Cu, Ni, Pb and As were determined with GRAAS-technique and the concentration of sulphate was determined with chromatograph - technique (FINAS T44/A1/95). The concentrations of many analysed elements were under the limit of detection. The accuracy of results varied from ± 10% to ± 30% depending on the analysis technique.

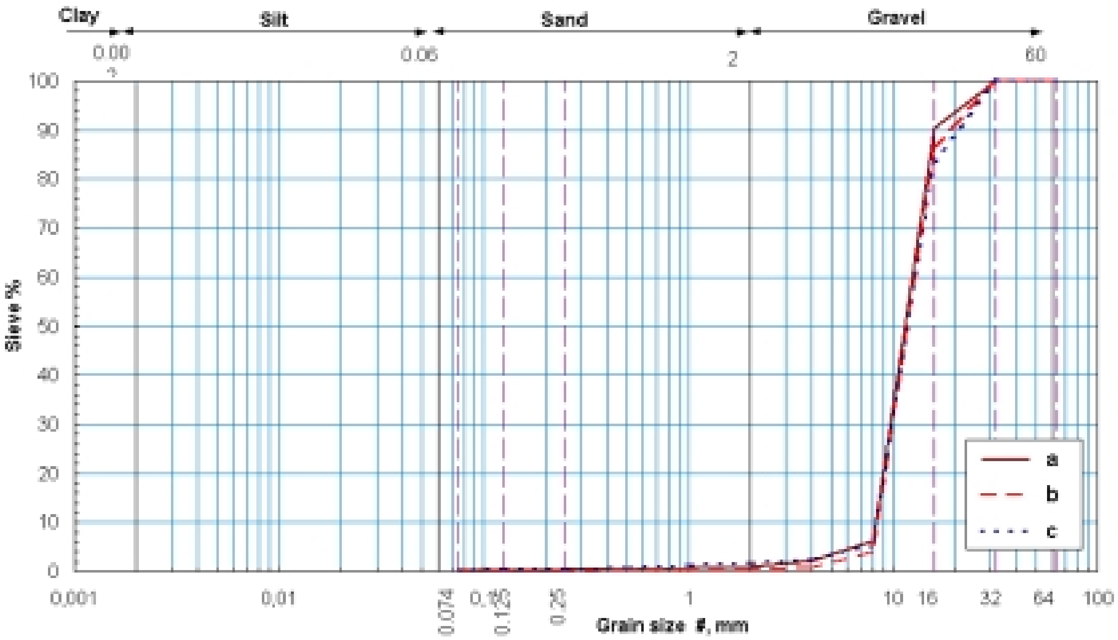

Figure 3. The grain size distribution of air-cooled ferrochrome slag (a = before test sample 1, b = before test sample 2 and c = after climate chamber test).

4. Discussion

4.1 Mechanical properties

The grain size distributions of the slags before and after the test cycles differ only a little. The biggest grains crush a bit during the test (figure 3). The visual observations during the test cycles exhibit some loosening and frost heave.

4.2 Leaching of blast furnace slag

The leaching of blast furnace slag is very moderate in climate chamber tests. The test results indicate that freezing – thawing cycles and the use of salt solution do not accelerate the leaching process of any analysed element. Vanadium and sulphate, which are possibly the most harmful elements of blast furnace slag, stay in indissoluble form. Even though their total constituents are quite big, they leach very moderately in climate chamber tests. We verified CCT test results with many other leaching tests successfully (figures 4 and 5). All test results confirm the impression that the leaching of blast furnace slag fulfils environmental requirements.

We changed all leaching test results to L/S-ratios, where L means liquid (the amount of used leachate flowing through a solid) and S is for solid (the amount of alternative material). The use of L/S-ratio makes it easier to estimate leaching in relation to time, because the amount of liquid flowing through the solid increases with time. In many tests more than one L/S-ratio was analysed, so we summed up all these concentrations to get the cumulative concentration (mg/kg).

Most of the verification tests were different kinds of parametric tests, but we also included some simulation tests like climate chamber, lysimeter, column and permeameter tests. In a parametrical test only one parameter, like some leachant, is tested in ultimate conditions. Simulation tests, on the other hand, try to simulate the whole leaching process.

That is why parametrical tests tend to overestimate real leaching. Leaching usually decreases with time, because the easily dissolvable elements leach first. Thus, many illustrated test results, included climate chamber tests, exhibit a lower slope, when L/S-ratio is greater than 1 (figures 4 and 5).

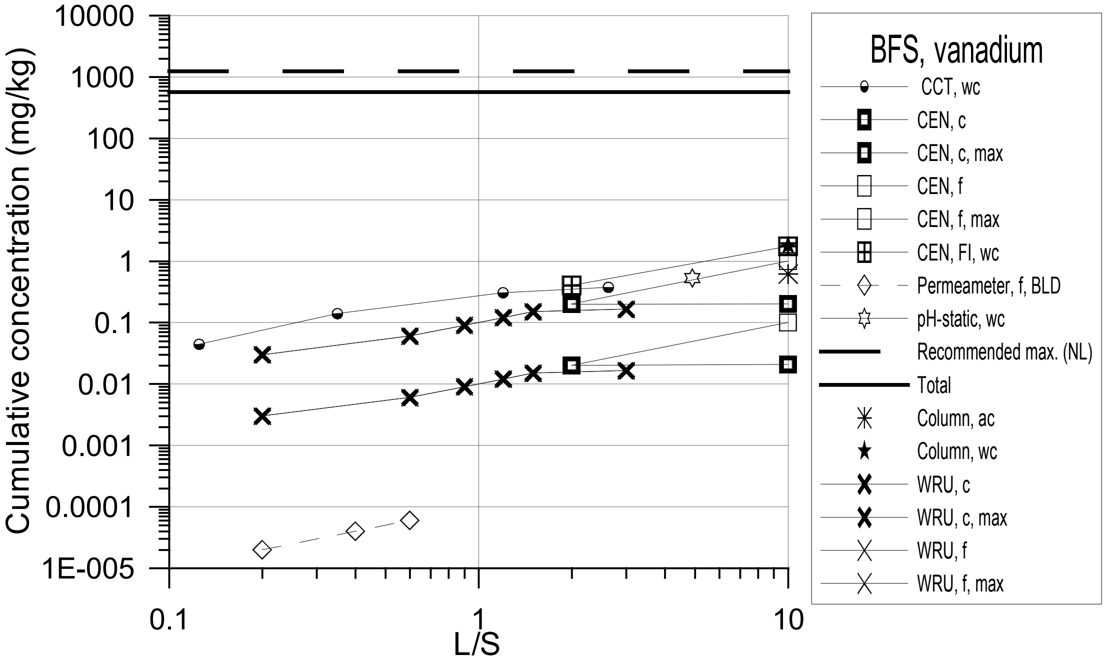

Figure 4. BFS. The leaching of vanadium.

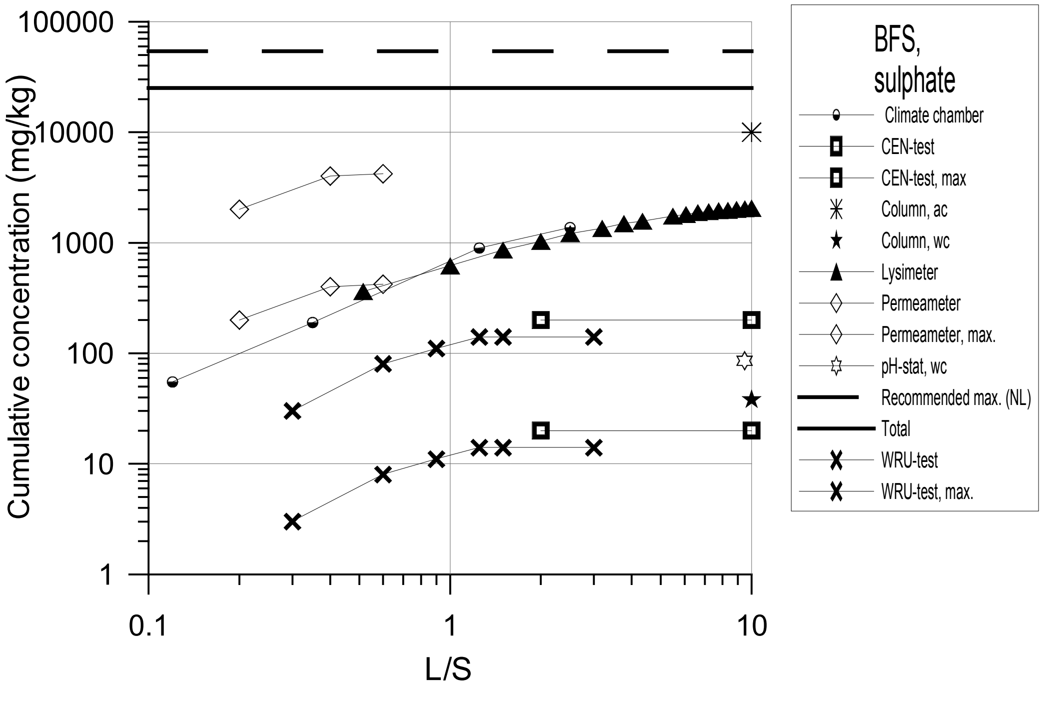

Figure 5. BFS: The leaching of sulphate.

The cooling method affects some leaching properties, especially to the leaching oh sulphate (figure 5). The leaching of sulphate of air-cooled (ac) slag in a column test is more than hundred times bigger than leaching of the water-cooled (wc) slag (ac: about 10 000 mg/kg;

wc: about 30 mg/kg). When slag is cooled with a high-pressure water jet, it is probable that sulphate components leach with the cooling water. The leaching of sulphate in climate chamber tests increases up to 1000 mg/kg, even though the slag is water-cooled. This is because the salt solution contained sulphate and a great part of leached sulphate originates in salt solution.

4.3 Leaching of ferrochrome slag

The most interesting elements of ferrochrome slag from the environmental aspect are chrome and aluminium. The total constituent of chrome is 6.5%, which is many times bigger than the total concentration recommended by Dutch authorities. Because Finland does not have its own environmental recommendations yet, the Finns usually comply with Dutch directions. The chrome of FCS are mainly Cr^{+++} or Cr^{++}, which are both difficultly soluble. Hence, it is not surprising that no great leaching was detected from the climate chamber test (figure 6). Even though the recommended total constituent of chrome is exceeded, the leaching is very moderate and fulfils Dutch recommendations for a covered material. The other elements also leach moderately and fulfil Dutch recommendations. The most essential method to mitigate environmental impacts of alternative materials is to decrease the amount of infiltrated water. Covering and bounding are common, effective and economical mitigation methods.

Wahlström and Laine-Ylijoki have studied widely the leaching of FCS in laboratory tests. Figure 7 shows their test results of different kinds of leachants as a function of pH. The climate chamber test data agree with their test data. Ferrochrome slags natural pH is over 10, but acid rain water decreases pH gradually. Yet, according to these test results, the leaching increases significantly only after the pH is less than 6. Wahlström and Laine-Ylijoki have estimated that time needed to neutralise a 0.3 m thick layer of ferrochrome slag from pH 10 to pH 7 takes 270 years. pH in the climate chamber test is about 7.5.

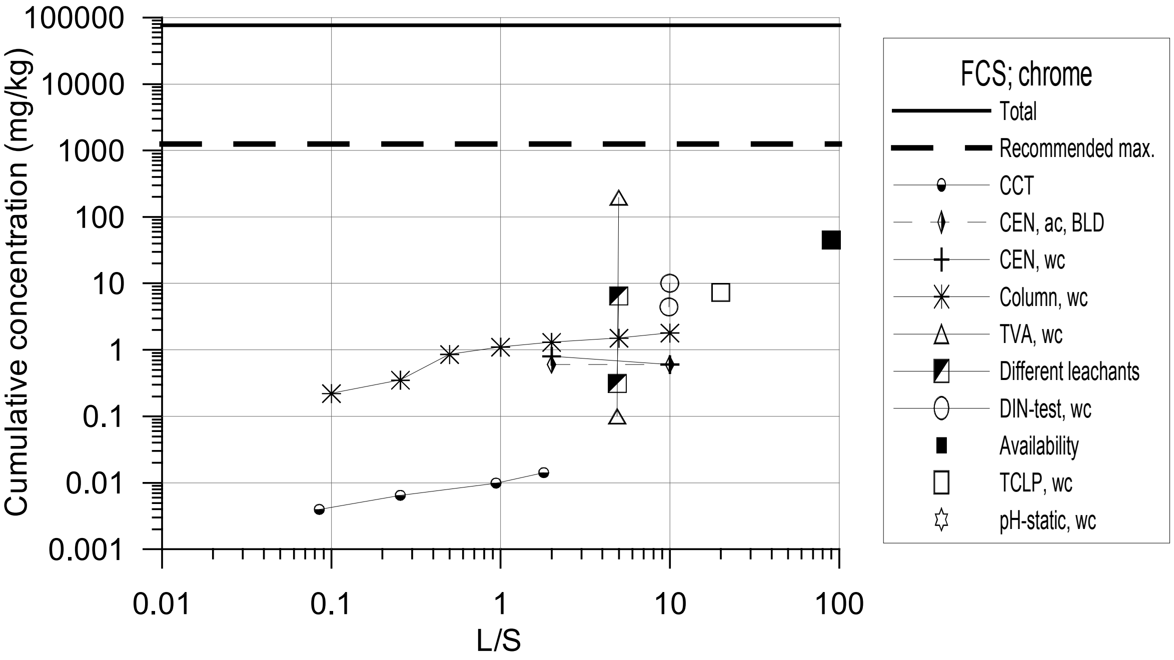

Figure 6. FCS. The leaching of chrome.

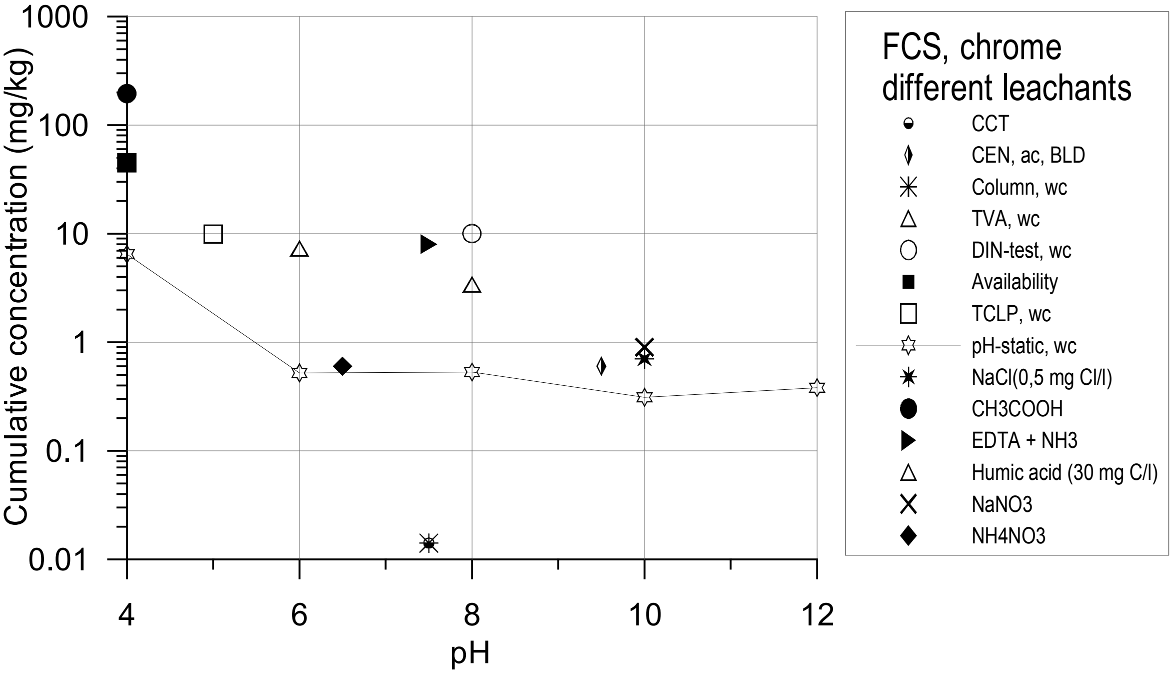

Figure 7. FCS. The leaching of chrome as a function of pH.

4.4 Future developments, limitations and errors

The climate chamber test is an expensive and time-consuming test. To make the test more efficient, more than two specimens should be handled at the same time.

The climate chamber test method has some limitations with leachate analysis. The first limitation is with leachant. The use of salt solution as a leachant increases the leaching of sodium, potassium, calcium, magnesium and sulpahte. The real leaching and its changes are difficult to distinguish from the initial constituence of these elements in salt solution. Because the parametrical and climate chamber tests have shown that salt solution does not increase leaching, the use of fresh water instead of salt solution as the leachant would give a clearer picture of the leaching process. The second limitation is the analysis technique. The real scatter of test results is quite small. Yet, the accuracy of analysis changed from ± 10% to ± 30%, which is quite big. The limit of detection with some elements is high, which hides the real leaching behaviour of that element. With more expensive analysis methods, the accuracy could be decreased and the limit of detection could be lowered.

The simulated road construction is very simple: it has only one construction layer. This simplification causes some errors in test results. In a real road construction the flowing paths of water through many construction layers are more complicated because of the covering asphalt layer. A new uncracked asphalt layer is practically impermeable. The ingress of water to a road construction happens via the slopes, capillary rise from ground water and through the crackings of an older asphalt layer. Thus, in the real road construction water infiltrates mainly horizontally, but in CCT water infiltrates vertically. The total quantity of water flowing through a road construction is also difficult to assess. In short, the flowing conditions in the climate chamber test are simple and they do not give the whole picture of the flowing in the sense of leaching.

5. Conclusions

The climate chamber test is a new, very promising test method to simulate the leaching of alternative materials. Even though it is expensive, it is the only test method, which simulates the varying climatic conditions. The test includes twenty accelerated drying - wetting and freezing - thawing cycles. Tested materials were ferrochrome and blast furnace slags. These climatic cycles did not increase the leaching of any element studied, when we verified them with other leaching test results. Furthermore, the use of salt solution does not affect the leaching of the elements studied. On the contrary, the leaching in the climate chamber test, like in many other simulation tests, is clearly less than in small-scale parametrical tests.

The solubility of harmful elements of FCS is so small that the use of FCS is acceptable in every part of a road construction, while slag is covered or bound. In spite of the great total amount of chrome, the leaching of chrome is moderate. The leaching of harmful elements of BFS is also very moderate and fulfills today's environmental requirements, while slag is covered or bound.

The flowing conditions in the climate chamber test differ from real road construction, where water ingress happens via slopes, though the cracks of asphalt layer and capillary rise from ground water. The greatest part of water infiltrates the road construction horizontally. In the climate chamber test the water infiltrates through the specimen vertically from top to bottom.

Besides the error in flowing conditions, there are some limitations with CCT method. First, the leached amounts of many metals are very low – in many cases below the limit of detection. The limit of detection and accuracy of results depend on the analysis technique, which could be lowered with more expensive analysis technique. Second, the use of salt solution as a leachant increases the leaching of sodium, potassium, calcium, magnesium and sulpahte. It is difficult to distinguish the real increasing of leaching from the initial constituence of these elements in a salt solution. Therefore, we recommend the use of pure water as a leachant in the future. Another future development could be the measurement of frost heave or some other mechanical property.

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The use of flotation sand in earth construction

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ABSTRACT**:** Flotation sand, comparable to sand by its material properties, is a by-product of calcite flotation. The capillary rise of flotation sand is lower than 90 cm, the material is non–frost-susceptible (SP < 0.5 mm^2/Kh), and its hydraulic conductivity is higher than 10^{-6} m/s. Its friction angle is approximately 44° and therefore a little greater than that of sand with a corresponding grain size. By its technical properties, flotation sand is a suitable material for the filter layer of road construction as well as for filling structures that require a frost resistant material with a high bearing capacity. Refined with mixture materials, such as bentonite, it is also a suitable material as a hydraulic barrier in landfill covers. In addition, flotation sand is greatly strengthened when bound with bark ash, for example, thus fulfilling the quality requirements set for bound materials of road structures. Flotation sand does not contain any materials that are harmful to the environment.

1. Introduction

Approximately 70 million tons of natural rock material is used annually in earth construction in Finland. The decline in good quality rock material resources, the need for protection, and the growing distances in transportation have all increased the need for applying substitute materials for sand and gravel. Simultaneously, various fields of industry generate a great number of mineral by-products that can be utilized in earth construction. Also, waste management legislation requires replacing natural materials with waste and by-products. Nevertheless, if these materials are to be utilized in earth construction, certain technical properties and environmental qualifications are required of them. In the initial stages of using recycled material, the material properties have to be examined more comprehensively compared to traditional materials, whose use is based on results achieved during long-term utilization. Defining long-term behavior often requires test constructions and monitoring of the structures before actual utilization.

This article deals with the material properties of the by-product of calcite enrichment at the Lappeenranta mine of Partek Nordkalk Oyj Abp, and its suitability as an earth construction material. A total of 100 000 tons of flotation sand is generated annually.

2. Materials and methods

2.1 Materials

The grain size distribution of flotation sand varies in the different sections of the disposal area. The coarse fraction is deposited close to the discharge pipe, and the finer fraction is carried along in water, further away from the pipe. The grain size distribution of the coarser fraction equals that of sand, and the finer component is equavalent to silt sand (Fig. 1). Both materials are even-grained. The average grain size d_{50} of the fine flotation sand is 0.08 mm and of the coarse flotation sand, 0.16 mm.

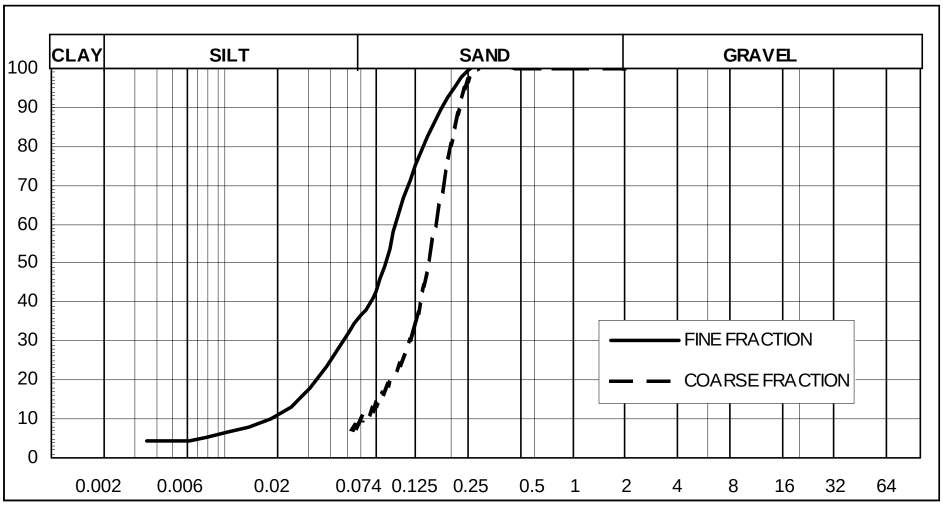

Figure 1. Grain size distribution of flotation sand in the disposal area. Partek Nordkalk Oyj Abp Lappeenranta mine.

Bark ash from Enso Oy’s Imatra Works was used to strengthen the flotation sand and calcium bentonite was used to decrease their hydraulic conductivity.

2.2 Methods

The material properties of flotation sand was determined by methods commonly used in geotechnical research Only principles of the most essential test methods used in this research are presented in table 1.

Table 1. Test methods used in flotation sand research.

Property, parameter	*Principle of test method*
Environmental validity	
**total elemental content*	*ICP-AES*
Hydraulic properties	
**hydraulic conductivity*	**flexible-wall permeameter*
**capillary rise*	**capillarymeter*
**water retention capacity*	**pressure plate apparatus*
Frost	
**segregation potential*	**frost heave test*
**freeze-thaw durability*	**change of length, compressive strength test*
**water durability*	**water immersion test*
Thermal properties	
**thermal conductivity*	**thermal needle probe*
Mechanical properties	
**shear strength*	**triaxial test*
**resilient modulus*	**dynamic triaxial test*
**tensile strength*	**bending beam test*
**bearing capacity*	**CBR-test*

2.3 Sample preparation

When using mixture and binding materials, cylindrical test samples of the flotation sand is prepared. Water was added to the mass to achieve optimum water content. The masses were then mixed together mechanically. The process of mixing was continued until the binding material, based on visual examination, was completely blended with the dry aggregate. Compaction of the samples tested (compressive strength test, freeze – thaw test, water immersion test) using oneaxial compression test equipment was performed using a gyrator compactor into a 4” mold. The target degree of density was 95%. The height of the compacted samples was 100 ±2 mm. Compaction of the samples tested using dynamic triaxial equipment and bending capacity equipment was performed with a hand rammer. After the test samples were prepared, they were stored in a closed plastic box on top of a steel grating at room temperature. There was 10 centimeters of water at the bottom of the plastic box.

Calcium bentonite and flotation sand were mechanically mixed together to form a material of uniform quality, after which the target amount of water was added. The degree of density of the samples was set either at 90% or 95%. The samples were compacted in a slightly higher water content than the optimum water content.

3. Results and discussions

3.1 Environmental validity

The mineralogical composition of flotation sand is wollastonite, quartz, calcite, dolomite and. The results of elemental analyses of flotation sand is presented in Table 1. The major elements are Ca, Mg and Fe. Because all trace elements are lower than the proposed threshold values set for materials used in earth construction (Assmuth 1997), the material can be used without limit (table 1). Only the beryllium content (1.3 mg/kg) of the coarse fraction slightly exceeds the lower limit value (1.0 mg/kg), but it is still clearly lower than the upper limit value (10 mg/kg). The beryllium content of the fine fraction is lower than the defining value (< 0.5 mg/kg). It must be noted that the beryllium content is lower than the background content in Finnish soil.

Table 2. Elemental contents of flotation sand. The table also presents the suggested values for concentrations of harmful materials in soil. The results are reported in milligrams per kilogram of dry matter (mg/kg).

	Flotation sand Fine fraction (mg/kg)	Flotation sand Coarse fraction (mg/kg)	Judgement criteria (Assmuth (1997)) Upper limit value (mg/kg)	Lower limit value (mg/kg)
Al	2430	5280		
As	<10	<10	13	60
B	<5	5	5	50
Ba	29.4	39.7	600	600
Be	<0.5	1.3	1	10
Ca	233000	205000		
Cd	<0.5	<0.5	0.3	10
Co	<1	1.8	50	200
Cr	3.2	7.2	80	500
Cu	6.6	8.7	32	400
Fe	1850	3910		
K	361	929		
Mg	4020	4000		
Mn	52.6	99.4		
Mo	<3	<3	5	200
Na	466	899		
Ni	<2	4.0	40	300
P	431	358		
Pb	<5	<5	38	300
S	359	830		
Sb	<15	<15	5	40
Sr	296	277		
Ti	184	354		
V	1.1	4.5	50	500
Zn	8.4	13.6	90	700

3.2 The Material Properties of flotation sand

The physical properties of flotation sand is presented in table 3. Its values of friction angles correspond to the values of sand. The cohesion of the fine fraction flotation sand is greater than that of the coarse fraction flotation sand. According to the CBR value (CBR = 40%), the resilient modulus of the materials is appr. 185 MPa, calculated with an empirical formula[1] (table 3).

Both fractions are non-frost-susceptible (SP<0.5 mm^2/Kh), and their hydraulic conductivities are ($k>10^{-6}$ m/s). Their capillary rise is lower than the values (0.9 m) set for filter layers in the conditions for quality control of the Finnish National Road Administration. The thermal conductivity of flotation sand is equal to that of sand in the same degree of density and water content (table 3).

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[1] $Mr=17.6 \; xCBR^{0.64}$ (MPa)

Table 3. Material properties of flotation sand determined by laboratory tests.

Property	Coarse fraction	Fine fraction
Specific gravity ρ (t/m^3)	2.89	2.88
PH	8.6	8.6
Maximun dry density γ_{dmax} kN/m^3	17.6	17.7
Optimum water content w_{opt}	13	14
Capillary rise h_c cm	78	86
Hydraulic conductivity k (m/s)	$10^{-5.0}$	$10^{-5.6}$
Friction angle ϕ	44.7°	43.7°
Cohesion c (kPa)	3	15
CBR-value	42	51
Segregation potential SP_0 (mm^2/Kh)	0	0.4
Maximum frost heave h (mm)	0.5	0.1
Thermal conductivity λ (W/Km)		
-unfrozen (+22 °C)	1.17	1.13
-frozen (-15 °C)	1.50	1.41

3.3 Material properties of bound flotation sand

Compressive strength and modulus of elasticity

After 28 days of curing, the compressive strength of flotation sand bound with bark ash varies between 1.3 and 5.5 MPa, depending on the grain size of the flotation sand and the amount of bark ash (Fig. 2). As the amount of bark ash increases, the compressive strength increases in a linear manner. After the first 28 days the increase is minor. The modulus of elasticity varies between 76 and 221 MPa. The changes in the modulus of elasticity are similar to the changes in compressive strength.

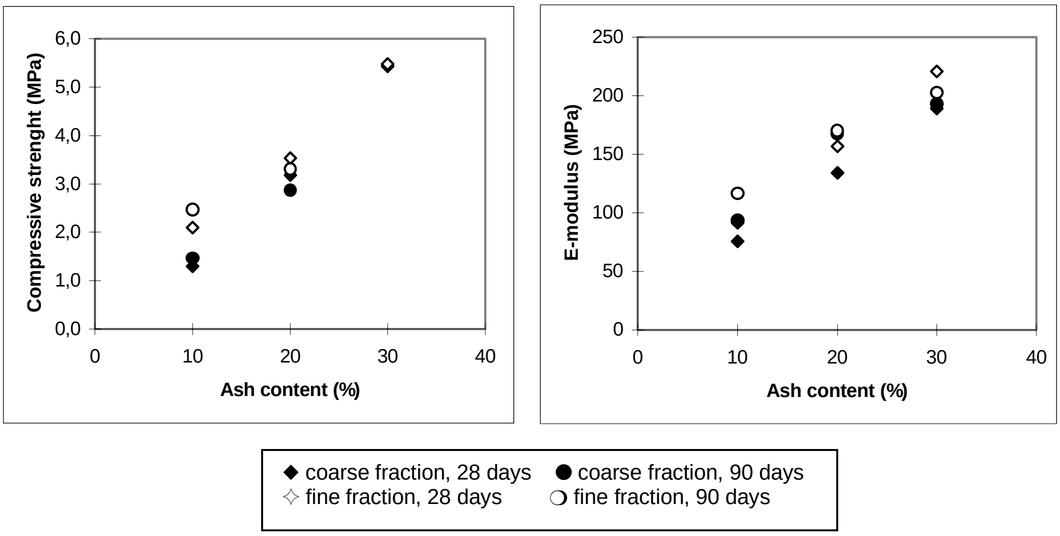

Figure 2. Compressive strength and modulus of elasticity of flotation sand bound with bark ash as a function of time and amount of bark ash.

Resilient modulus

The resilient modulus of flotation sand bound with bark ash increases as a function of the sum of principal stresses, the grain size of the flotation sand, and the amount of bark ash. For example, with the sum of principal stresses of θ = 50 kPa, the resilient modulus varies between 548 and 787 MPa (Fig. 3 and Table 4). The values of the resilient modulus of sand are equal to the values of high quality crushed aggregate.

Table 4. Resilient modulus of flotation sand bound with bark ash as a function of the sum of the principal stresses $\theta = 50$ kPa, $\theta = 100$ kPa and $\theta = 200$ kPa.

Flotation sand + bark ash	*R^2*	*Resilient modulus M_r (MPa)*		
		$\theta = 50$ kPa	*$\theta = 100$ kPa*	*$\theta = 150$ kPa*
Coarse fraction + 10% bark ash	*0.86*	*584*	*660*	*872*
Fine fraction + 10% bark ash	*0.91*	*685*	*524*	*623*
Coarse fraction + 30% bark ash	*0.85*	*651*	*685*	*734*
Fine fraction + 30% bark ash	*0.94*	*787*	*540*	*728*

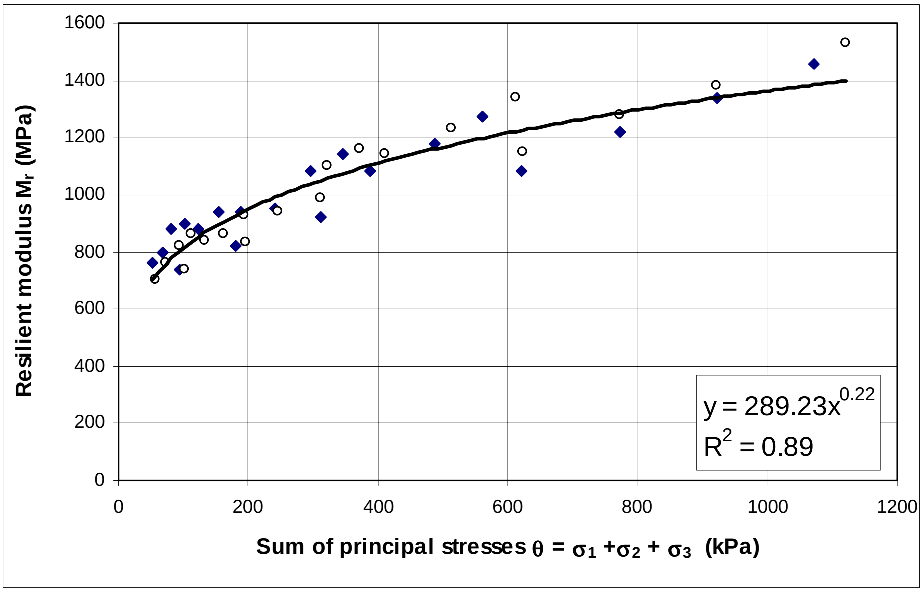

Figure 3. Resilient modulus of flotation sand bound with bark ash as a function of the sum of the principal stresses and the power curve fitted to measurement observations. Curing time 90 days, amount of bark ash 30%, degree of density D = 95% ($\gamma_{dmax.} = 17.6$ kN/m^3, $w_{opt.} = 14\%$).

Freeze-thaw durability and water immersion

The compressive strength of flotation sand bound with bark ash does not decrease significantly after freeze-thaw cycles or after immersion in water (Fig. 4). In the samples that were visually examined, there were no signs of ruptures or brittle fractures after freeze-thaw tests and water immersion tests. Also, changes in length were minor in these tests. The test samples absorbed only <10% water during the tests.

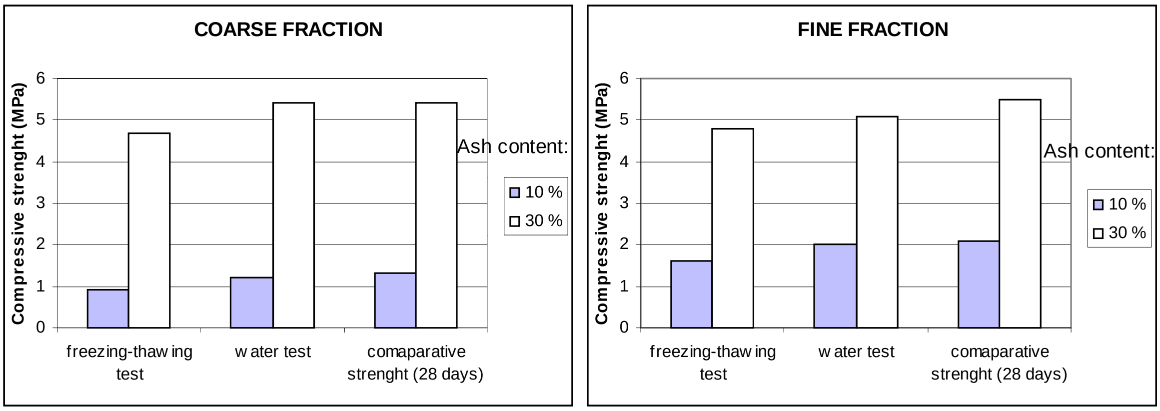

Figure 4. Compressive strength of the test samples after freeze-thaw tests and a water immersion test. The figure presents the compressive strength of the samples without freeze-thaw cycles. Curing time (28 days).

3.4 Material properties of flotation sand and bentonite mixture

Frost susceptibility and hydraulic conductivity

The frost heave test was repeated as four freeze-thaw cycles. The segregation potential was defined after the first cycle. After the frost heave tests, the hydraulic conductivity of the samples was measured using a flexible-wall permeameter.

The flotation sand was found to be non-frost-susceptible, excluding the material fine fraction flotation sand + 4% bentonite, which was low frost-susceptible (table 5). After the four freeze-thaw cycles that were also frost heave tests, the hydraulic conductivity of each samples was < $10^{-9.0}$ m/s.

Table 5. Frost susceptibility and hydraulic conductivity of the mixture of flotation sand and bentonite after frost heave tests.

Material	Number cycles	Degree of density [%]	Water content [%]	Segregation potential [mm^2/Kh]	Classification of frostsusceptibility	Hydraulic conductivity [m/s]
Fine fraction + 6% bentonite	4	94.9	16.2	0	Non-frost-susceptible	$10^{-9.0}$
Fine fraction + 6% bentonite	4	89.8	16.2	0	Non-frost-susceptible	$10^{-9.0}$
Fine fraction + 4% bentonite	4	94.7	16.1	1.0	Low-frost-susceptible	$10^{-9.1}$
Coarse fraction + 6% bentonite	4	94.7	16.2	0	Non-frost-susceptible	$10^{-9.4}$
Coarse fraction + 6% bentonite	4	89.7	16.2	0	Non-frost-susceptible	$10^{-9.9}$
Coarse fraction + 4% bentonite	4	94.7	16.0	0	Non-frost-susceptible	$10^{-9.0}$

3.5 Utilization of flotation sand in landfill structures

The suitability of flotation sand as a filling material for landfill cover was ascertained in a test structure carried out at the factory landfill site of Partek Nordkalk Oy. The test structure was built particularly to study the feasibility of using flotation sand as the hydraulic barrier layer of landfill when its additive materials were bentonite and other commercial additives. Clay was used as a reference material in the hydraulic barrier. Flotation sand were also used on the surface of the waste layer to smooth inequalities. The follow-up measurements of the test structures includes the amount and quality of the water infiltrating through the cover, the settlement, temperature and volumetric water content. The details of the results are beyond the scope of this paper.

4. Summary and conclusion

The concentrations of harmful elements in flotation sand are very low and below limit values used in the evaluation of environmental suitability. Therefore, the material can be used without limit in earth construction.

The grain size distribution of flotation sand is even-grained and equals that of silty sand and sand. The capillary rise is lower than 90 cm, the material is non-frost-susceptible (SP<0.5 mm^2/Kh), and its hydraulic conductivity is greater than 10^{-6} m/s. Its friction angle is approximately 44° and therefore a little greater than that of sand with a corresponding grain size. According to the CBR value, the load-bearing capacity of flotation sand is as good as the material of a good base course. The coarse fraction of flotation sand fulfils the requirements set for a material used in a filter layer in the guideline for quality control of the Finnish National Road Administration.

Flotation sand bound with bark ash fulfill the quality requirements for the material for the base course layer in road structures, among others.

The hydraulic conductivity of flotation sand can be effectively reduced with bentonite. With a bentonite content of approximately 6%, the hydraulic conductivity is $>10^{-9}$ m/s, which fulfills the hydraulic barrier requirements set for landfill cover structures, for example. The mixture of bentonite and flotation sand is non-frost-susceptble and at the most, low frost-susceptible. Freeze - thaw cycles do not increase the hydraulic conductivity of the flotation sand-bentonite mixture.

According to the research results, the potential uses of flotation sand are the filter layers of road and street constructions, environmental structures, and the pre-filling and surface layers of the landfill covers. Refined with admixture materials like bentonite, flotation sand can also be used in the barrier layer of landfill covers. As a bound material, with binding materials like bark ash, for example, flotation sand are suitable for other pavement structures of road and street constructions. To resolve the long-term behavior of the material, test structures should be used particularly to find out the environmental and mechanical durability of the bound material.

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Molybdenum transport in coal fly ash soil constructions

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ABSTRACT: There are remarkable possibilities to economically use a major part of coal fly ashes in soil construction applications. This, however, requires that the environmental effects of fly ashes are known and can be controlled. This paper discusses a research on the transport of molybdenum from ash structures to the environment in the long term. The research has involved both laboratory investigations on fly ash samples and tests on samples from full-scale constructions. The results have shown for example that; the amount of leachable molybdenum relative to the total content of molybdenum varies remarkably between the coal ashes from different sources; clay absorbs molybdenum more effectively than sandy moraine; with declining pH values the subsoil layer beneath the ash layer prevents further transport of molybdenum; the studies conducted at the 20 years old construction support the results of laboratory investigations. On the basis of the investigations a transport model was constructed for clay and moraine soils. The model can be used to calculate the transport of molybdenum in the soil and ground water beneath the coal ash layer during the next 100 years. The calculations indicate that the transport of molybdenum is insignificant and not beyond half meter under the fly ash structure.

1. Introduction

The Finnish research project discussed in this paper was about the transport of molybdenum from ash structures to the environment in the long term. The research was conducted on coal fly ash from three power plants (Fortum Power, Helsinki Energy and Pohjolan Voima) that incinerate coal from different sources. Coal fly ash was assembled during the production period in 1998, and more than 15 different samples were taken for the laboratory studies.

In addition to the laboratory studies two different full-scale constructions with fly ash from Helsinki Energy were studied during the research project. Soil samples were taken from a 20 years old test construction in Maunula. Soil samples and water samples from lysimetres and ground water pipes were taken from a 2 years old site in Knuters, Sipoo.

The concentration, availability and leaching of molybdenum were determined from the 15 fly ash samples. On the basis of the results it was possible to determine the differently behaving fractions of the ashes. Also the buffer and retention capacity of certain soil types (clay and sandy moraine) were determined with laboratory tests.

The results were used to construct a dynamic transport model for molybdenum. The model was tested with help of data from the full-scale constructions. On the basis of the model the first molybdenum nomograms were made to provide a tool for the environmental assessment of fly ashes.

2. Laboratory investigations

2.1 Concentration and availability of molybdenum

The molybdenum occurs in following different fractions in the fly ashes:
a permanently adsorbed part;
a fast released part;
a slowly released part.

In order to specify the relation and variation of the different fractions the laboratory investigations were constructed to determine the total content and availability (CEN prEN 12457)of molybdenum in the fly ash samples, and the long-term leaching (NEN 7343) of molybdenum from the strengthened but not stabilised fly ashes.

The results of the CEN and long-term leachning tests are compiled in Table 1 below.

Table 1. Results of laboratory investigations on Mo content of coal fly ashes (FA) from three power plants in Finland. CEN = total availability by CEN prEN 12457, NEN = leaching by NEN 7343.

FA 1	mg (Mo)/kg		FA 2	mg (Mo)/kg		FA 3	mg (Mo)/kg	
	CEN	NEN		CEN	NEN		CEN	NEN
4–99	4,1	4,12	4–99 I	7,1	7,51	5–99	3	0,83
5–99 I	4,3	3,44	4–99 II	7	4,9	10–99	5,7	1,08
5–99 II	3,9	4,12	4–99 III	4,7	4,93	11–99 I	5,3	1,18
10–99 I	2,8	-	10–99	5,1	-	11–99 II	6,6	-
10–99 II	3,8	4,34	11–99 I	4,7	5,44			
10–99 III	4,4	6,56	11–99 II	3,5	-			
11–99	4,2	-	11–99 III	3,4	-			
			12–99	3,1	3,06			

The results have indicated that the available (leaching) fraction of molybdenum in the different ashes varies remarkably, between 30 and 70% of the total content. The correlation between the availability (CEN) and the long-term leaching (NEN) of molybdenum is given in Figure 1. These results show that there is not a clear correlation of these tests. Part of the ashes seems to have values of same level in both of the tests (FA1 and FA2) but part of the ashes shows long-term leaching that is only a fraction of the total availability (FA3). One of the reasons might be in the different strengthening and setting behaviour of the ashes.

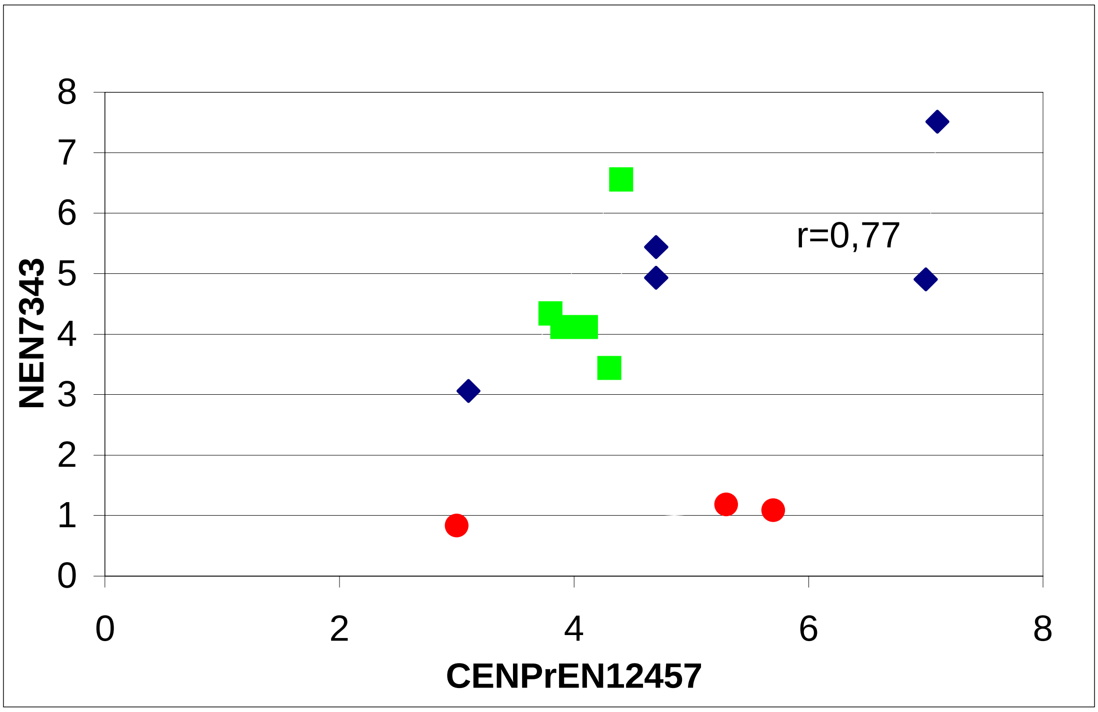

Figure 1. Correlation of results from CEN- and NEN-tests (compare Table 1).

2.2 Determination of the retention and the buffer capacity of soil

The retention capacity of the soil for molybdenum was investigated with two different soil types, with clay and sandy moraine. In a concentration of 5, 10 and 20 mg /kg molybdenum was added in the soil samples. The retention of molybdenum was studied at three different pH values (pH 6, 8 and 10). Figure 2 gives the results.

The results in Figure 2 show that the retention capacity of clay was high at pH 6 and for all Mo concentrations. At pH 8 the retention was a little more than 20%. Sandy moraine did not have as good a retention capacity. In case the Mo concentration is small (≤ 5 mg/kg) all of the molybdenum is retained but with higher concentrations the retaining fraction is smaller. Neither of the soil types had retention capacity at pH ≥ 10. The laboratory tests certified by the tests on field samples have shown that the retention capacity for molybdenum will remarkably increase with a declining pH value.

The seepage water from the ash construction was used to determine the buffer capacity of clay and sand moraine. In Figure 3 this can be seen by the pH value as a function of L/S (liquid/solid).

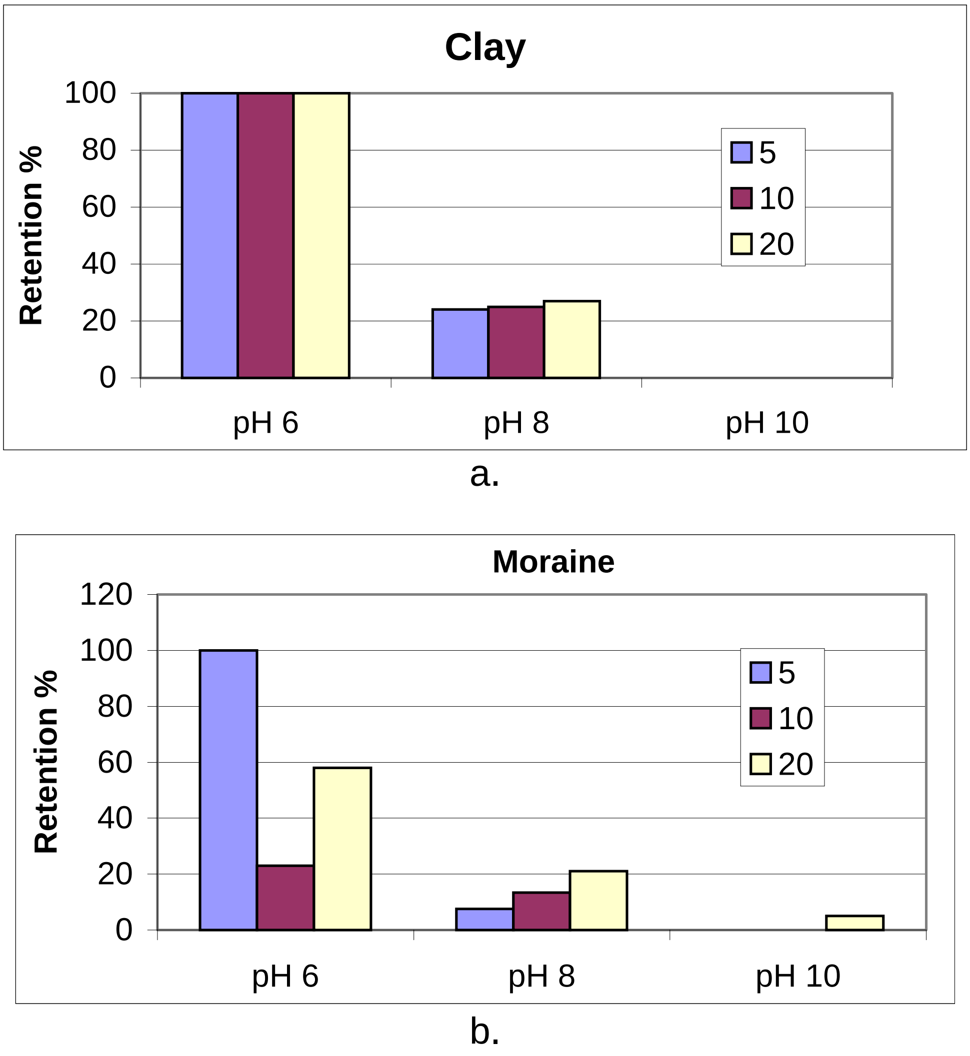

Figure 2. Retention of Mo by clay (a) and sand moraine (b).

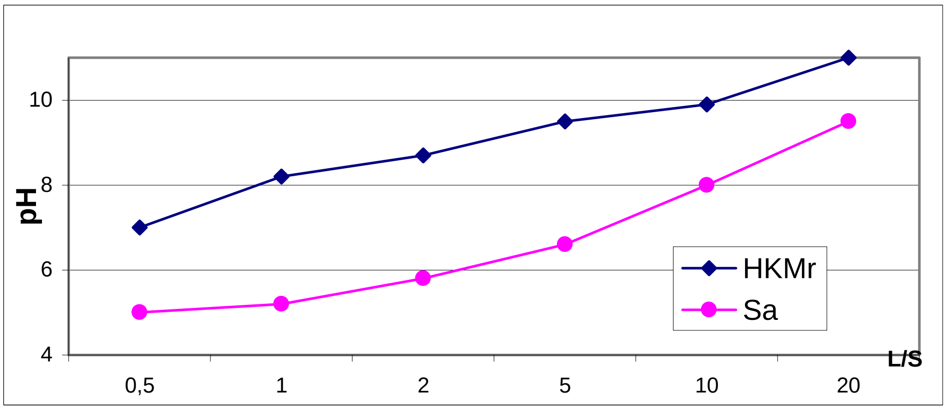

Figure 3. The buffer capacity of clay and sand moraine for molybdenum of water extracts from fly ash layer. Correlation of pH and L/S (a mass of L=liquid percolating through the mass of S=solid).

3. The dynamic transport model for molybdenum

3.1. Description and construction of the model

A dynamic transport model is used to calculate the amount of released molybdenum from an ash structure and the transport of the released molybdenum in the soil beneath the ash layer. Additionally it is possible to assess the increase of molybdenum content in the ground water zone. The parameters for the transport model are the data from the column (NEN-) test, i.e. the cumulative leaching of molybdenum as a function of L/S. The mathematical formula of the model was defined by precision of the leaching calculated by the model with the results of column tests. The transport model combines hydrological and chemical sub-models and uses the methodology of differential calculus to calculate the transport of molybdenum and its adsorption or desorption in a layer structure (van Genuchten and Gray 1978, Moldrup et al. 1994a, 1994 b).

3.2 Testing of the model

The transport model has been tested with help of a 20 years old, gravel covered ash road. The thickness of the ash layer is 0,5 metres and the soil beneath is clay. The model was tested with help of the column test results of the 15 new ash samples because no leaching tests (NEN) were made on the ash for the full-scale construction 20 years ago.

Soil samples were taken from several depths (each 10 cm) of the full-scale structure. The total content and availability (CEN) of molybdenum were determined from the samples. A graph was drawn with the measured and calculated Mo content relative to the depth. These results have indicated that the calculated values match with the values determined in the laboratory. These also show that the model functions and that the chosen parameters are the right ones.

3.3 Nomograms based on the model

With help of pre-drawn nomograms the dynamic transport model is applicable for different ash structures and soil conditions. Figure 4 gives an example of a nomogram to determine the transport of molybdenum when the subsoil is clay and the yearly rain fall 200 mm. The nomogram gives the maximum molybdenum concentration beneath the ash layer in the long term with a given leaching (column test) of the ash material and thickness of the ash layer.

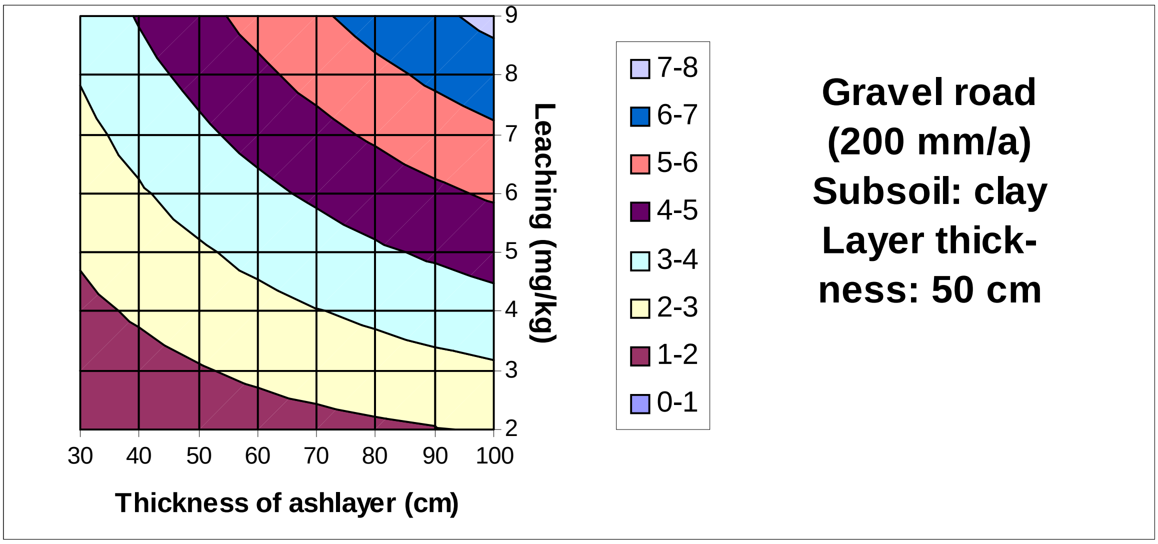

Figure 4. An example of a nomogram for a case specified as follows: a gravel road structure where there is 50 cm clay under the fly ash layer. The concentration of molybdenum in the clay layer is given as a function of the cumulative leaching of Mo and the thickness of the fly ash layer. Yearly rainfall is assessed to be around 200 mm.

4. Conclusions

The research project discussed in this paper has been concentrating on the transport of molybdenum in the environment of ash structures. Following aspects can be concluded on the basis of the results, for example

1. The total content and availability (leaching fraction) of molybdenum as well as their relation vary remarkably between the fly ashes from different sources. Therefore it is not possible to determine the leaching of molybdenum on the basis of the total content. Therefore, the quality control of fly ashes should include the determination of the leaching fraction e.g. with a CEN-test.
2. The pH value quickly decreases in the soil layers beneath a fly ash layer. Therefore the leaching fraction of molybdenum accumulates in the soil immediately underneath the fly ash layer which has been shown with field tests and the mathematical transport model.
3. The dynamic transport model constructed in this project has been shown to function properly with the chosen parameters. The model can be used to calculate the long-term transport of molybdenum in the soil and ground water. The values of the model were shown to correlate well with the values determined from samples taken at a 20 years old construction site. Similar dynamic transport models can be constructed to assess the transport of other substances.
4. The dynamic transport model has also been used to calculate the molybdenum concentration in the ground water in the long term. These results indicate that there is no environmental risk in regard to the molybdenum from the given ash constructions. Similar results have been obtained from the long-term monitoring at full-scale test constructions.

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Use of blastfurnace slag, a by-product of the steel industry, for road construction purposes

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ABSTRACT: The development of blast furnace slag sand stabilisation began in the middle of the 1980 ´s. The objective was to develop a method to prevent the damage of the load-bearing layers top part (rock materials pulverisation). With cooperation of Rautaruukki Oy and SKJ Company a method was developed which fulfills the given edge conditions. At the same time an environment friendly method was achieved which makes good use of industrial by-product, blast furnace slag. The new method clearly increase the lifetime of the structure. The use of blast furnace slag sand stabilisation expanded in 1991 when more powerful rotavators for stabilisation work were available. The compression strength of the stabilised material, soil cement, at the age of 90 days is 3,0 MPa. The bearing values at the age on one year have been from 700–800 MN/m^2. Another good property is its ability to reset if the stabilised structure is damaged (cracked). The method has been used mainly in the Northern Finland area, but nowadays the economic range of use is the whole country.

1. Development path

The idea of using blastfurnace slag in road construction is not a new one. It was originally tested in the Lestijoki, Kalajoki and Pyhäjoki valleys in Northern Ostrobothnia for purely practical reasons:

- There was a shortage of roadmaking materials. Sand had been obtained mainly from the sea shore and aggregate for the sub-base and load-bearing layer from crushed rock.
- Considerable problems of bearing damage and crazing had arisen, mainly because of in situ pulverization of the crushed rock aggregate (originating from banded gneiss with a Los Angeles value in the range 15–20).
- The Raahe Steel Works of Rautaruukki Co. were close at hand.

Figure 1. Pulverization in a bearing layer.

Figure 2. Air-cooled blastfurnace slag as a sub-base and bearing layer.

The first regular use was made of this material, in the form of air-cooled blastfurnace slag, by the Central Ostrobothnia district of the Finnish Road Administration in 1974, and this was soon followed by experiments with both crushed slag and powdered granulated slag (for stabilization). Numerous short stretches of road were constructed with each of these and their costs compared and durability monitored.

Air-cooled blastfurnace slag was used instead of crushed rock aggregate to produce a combined sub-base and bearing layer, giving good bearing capacity results and proving economical by comparison with the latter material within a radius of approx. 100 km of the Rautaruukki works. Insulation tests showed that the material creates quite a good insulating layer, with a thermal conductivity of 0.8–1.0 as compared with around 1.5 for conventional materials.

2. Criteria for developing stabilization with granulated blastfurnace slag

It was in the Road Administration's interests, however, to find a means of making more economical use of blastfurnace slag, in accordance with the following criteria:

- Its use should be economically justifiable anywhere in Finland, regardless of transport distance.
- Its use should be possible in principle anywhere throughout the 77,000 km of the Administration's road network.
- Its use should be environmentally friendly (in accordance with the principles of sustainable development).
- The working methods should be simple.
- The work should be easy to outsource.

The development work commenced in the early 1980's as a joint project between the construction department of the Central Ostrobothnia road district, as it was at that time, and Rautaruukki Co., the functions of which were later taken over by SKJ Ltd. The key to solving the problem lay in the use of crushed blastfurnace slag #0–4 as a temporary surface while the road was under construction. This promised to be inexpensive and highly successful, as it led to good binding of the upper part of the bearing layer but still allowed the bound material to be reworked.

Figure 3. Use of crushed blastfurnace slag as a temporary surface during road construction work.

Subsequent development efforts set out from this idea. The #0–4 mm crushed blastfurnace slag used initially was later replaced by #0–4 mm granulated blastfurnace slag which gave improved performance.

Small test stretches of road were constructed each year using various milling machines, e.g. Ruukkiaura, although these were still somewhat ineffective, and it was only towards the end of the decade, when the Northern Finland-based construction firm Jaara Oy acquired a heavy milling machine with a view to stabilization use that granulated blastfurnace slag became a viable alternative for that purpose.

3. Projects carried out

The first large-scale stabilization work to make use of granulated blastfurnace slag was performed on main road no. 85 at Kärsämäki in 1991, covering an area of 150,000 m². Since then some stabilization work has been carried out by this method every year, and experiences have been promising.

Areas stabilized with granulated blastfurnace slag in 1991–1999

1991	150.000 m^2
1992	200.000 m^2
1993	800.000 m^2
1994	600.000 m^2
1995	500.000 m^2
1996	400.000 m^2
1997	581.000 m^2
1998	310.000 m^2
1999	350.000 m^2
2000	500.000 m^2.

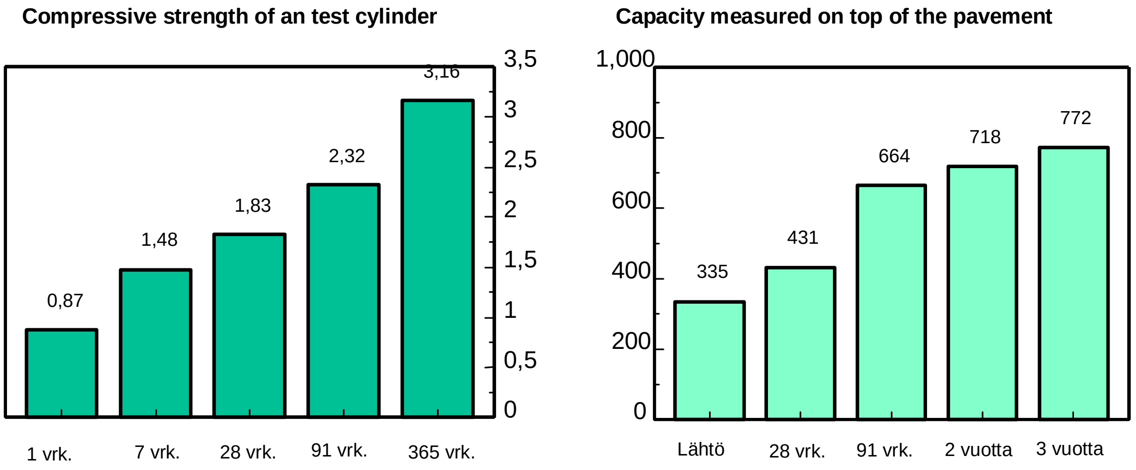

Figure 4. Mean compressive strengths and bearing capacities achieved using granulated blastfurnace slag for stabilization.

- Following this relatively long period of use, we can now say that we have achieved the advantages that we were looking for, and quite a number of others, besides:
- The method is environmentally friendly and follows the principles of sustainable development.
- It represents a re-use of the material already contained in the road.
- It makes use of an industrial by-product, blastfurnace slag.
- The resulting structure is durable, with a long service life, and has a good bearing capacity.
- The method is simple and causes little interruption of traffic while the work is taking place.
- It is a cheap source of binder.
- The method is cheap in terms of total costs per m² (mean FIM 8–13, depending on the site and the width of the road).
- The work can be done by subcontractors.
- The production rate is high (1.5 km per shift at a road width of 10 m).
- Any cracks that appear are restabilized automatically.

Each site nevertheless requires pre-testing to determine the correct formula for optimal stabilization.

Standard formula used at present:

Granulated blastfurnace slag 4.5%

Portland cement 0,5–1,5% as a catalyst

The main area in which the method is being applied at present is naturally the province of Oulu and its immediate surroundings, where is used by both the Road Administration and the urban and rural councils.

4. Development pospects

Work is naturally still going on through interaction with road constructors to improve the product and related working methods.

The main trends in development are towards:

- Stabilization with granulated blastfurnace slag alone (without catalyst).
- Optimization of quantities of granulated blastfurnace slag.

The product is currently being marketed under the name of "Eco-Road".

Figure 5. Eco-Road.

The product is being supplied continually to the Road Administration and other customers.

5. New prospects for the use of blastfurnace slag

Research has been going on for many years into the use of granulated blastfurnace slag on gravel roads for repair and dust prevention purposes. The latest project commenced in September 1999. It is probable that a new product will be announced for this purpose during the year 2000.

Figure 6. Dust binding on the wearing course of a clay-gravel road.

Finnish guidance for the use of secondary products in earth and road construction

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ABSTRACT: In the project “Secondary products in earth construction – assessment of applicability” guidance was developed for the assessment of the environmental and technical applicability of secondary products for use in earth and road construction. The project was a part of the Finnish Environmental Geotechnology Programme. The preparation of the guidance was a collaboration involving several research institutes.

The guidance presents the legislative requirements for the utilisation of secondary products in earthworks, recommendations for the investigation of environmental and technical applicability, recommendations for environmental and technical criteria of the utilisation in earthworks and recommendations for product quality control procedures.

A tiered system is presented for the assessment of environmental compliance. The assessment levels are 1) Concentrations of harmful components, 2) Leaching of harmful components from unpaved and paved constructions, 3) Risk assessment.

1. Introduction

About 70 million tonnes of natural mineral aggregate are used each year in Finland for earth and road construction. Depletion of the best materials, the need for resource conservation and lengthened transport distances have all increased the need to introduce substitute materials for natural aggregates. At the same time industry, construction and other similar activities produce large quantities of potentially usable secondary products. Current waste legislation also supports the use of wastes as substitutes for natural materials. Usage of the secondary products of industry and other activities requires that they be proven to be environmentally friendly and technically suitable.

The usage of secondary materials has been hindered by uncertainty about their environmental impacts and technical performance. There is very little practical experience of the long-term performance of most of the materials. There has also been confusion about the procedures that should be used to assess the technical and environmental applicability of the products. The methods of investigation have been developed or changed, and the data on older projects is not comparable with the present investigation data. Up until the 1980s the assessment of environmental acceptability was not considered as necessary as it is nowadays.

To investigate the environmental, technical and legal preconditions of the use of secondary products, the project “Secondary products in earth construction – assessment of applicability” was started as a part of the Finnish Environmental Geotechnology Programme. The main objective of the project was to develop guidance for the assessment of the environmental and technical applicability of industrial by-products and other secondary products for use in earthworks and road construction (Mroueh et al. 2000). Several research institutes participated in the work. In addition, all the interested parties had an opportunity to contribute to the contents of the guidance through participation in the steering groups or project workshops and during circulation of the guidance for comment.

2. The scope of the guidance

The guidance applies to the utilisation of industrial by-products and secondary products in earthworks and road construction. Most of the potential materials are mineral products comparable to natural aggregates. Some organic-based materials may, however, also be used, for example in balancing structures. The pollutant content of these materials must be low or they must be bound to the material so that their migration into the environment is minimised.

Table 1 presents industrial by-products and other secondary materials that have been used in earth construction in Finland. These include fly and bottom ash of coal combustion, blast-furnace slag and some other steel and metal industry slags. The use of crushed concrete began a few years ago and has since grown considerably. Some organic or predominantly organic products, e.g. shredded tyres, are already being used in various constructions. Asphalt pavements are being recycled into material for new pavements and other structures. Moreover, the prerequisites for the usage of several other materials have been investigated in research and test construction projects.

The guidance covers conventional earth constructions, such as road and street constructions, various field structures and their foundations. It is recommended that, in the first place, secondary materials be used in large or medium size cases, because control of the utilisation in small constructions is far more difficult.

The following applications are beyond the scope of the guidance:

- Landscaping, agricultural and forestry use, which are regulated by fertiliser legislation.
- The disposal of waste into the sea, which has a permit procedure of its own.
- The utilisation of secondary products in landfill constructions, for which the requirements clearly differ from those for road and field constructions.

3. The basic studies

The environmental, legal and technical preconditions for the use of secondary materials were extensively investigated during the preparation of the guidance. For example the following aspects were studied during the project:

Environmental and health risks of the use of industrial by-products and the methodologies of risk assessment (Wahlstrom et al 1999). The report deals with the effects of most common harmful components present in secondary products on human health and the environment, the migration of harmful components and the possibilities of exposure during various stages of construction. The risks caused by this exposure are also assessed. The risks considered are primarily related to human health because the data needed for ecological risk assessment is still under development. The proposed risk assessment concept was also tested in a case study on the use of coal fly ash in earth construction.

Table 1. Industrial by-products used in earth construction in Finland and their estimated annual consumption, 1998–1999.

Activity	Production, t/a	Amount used in earthworks		Usage in earth construction/ (other usage)
		t/a	%	
Energy production				
Coal fly ash	350 000	190 000	40	Road and field construction, earthfill / (Production of cement and concrete 30%, asphalt filler 5%)
Coal bottom ash	78 000	53 300	70	Road and field construction
Peat fly ash	180 000	78 800	60	Mainly earthfill
Peat bottom ash and slag	33 000	11 000	33	Mainly earthfill
Metallurgic industry				
Blast furnace slag	550 000			(Production of cement, use as fertiliser)
- unground sand and slag		200 000	36	Road constructions
- ground slag		120 000	22	Binder in soil stabilisation
Slag from LD steel production	170 000	18 500	10	Use as fertiliser
Slag from ferrochrome production	290 000	290 000	100	
Construction				
Crushed concrete	200 000	100 000	17	Road and field construction
Tyres	30 000	27 700	92	Road and landfill construction
Road construction				
Pavement materials	150 000	150 000		Recycling to pavements
Structural courses	160 000			
Forest industry				
Fibre and paste suspensions	128 000		55	Landfill construction
Ash	210 000			Landfill construction/(forest fertiliser), total usage 55%
Chemical industry				
Ferro sulphate gypsum	70 000			Binder in soil stabilisation

Life-cycle environmental impacts of the use of secondary materials and natural aggregates, and the methodologies of life-cycle environmental impact assessment of road construction (Eskola et al. 1999, Laine-Ylijoki et al. 1999). A life-cycle impact assessment procedure for the comparison and evaluation of alternative road and earth constructions was proposed. Additionally, a database containing the environmental burdens of the most significant construction materials and unit operations as well as the information required for the calculation of the data was constructed. In order to evaluate the applicability of the methodology, the use of coal ash, crushed concrete waste and granulated blast-furnace slag was compared with the use of natural materials in corresponding applications. An Excel-based computer application was compiled on the basis of the data.

Environmental criteria of the utilisation of industrial by-products in earth constructions (Sorvari 2000). Environmental criteria for the utilisation of secondary products in earthworks were drawn up during the project. For the basis of the study the environmental criteria and approaches used in various countries were studied. A tiered system is presented for the assessment of environmental compliance. The system is based on soil guideline values and on leaching values which are calculated on the basis of Dutch leaching models.

Methods for laboratory-scale functional testing of the secondary products used in earthworks (Tammirinne et al. 1999, 2000) . Guidance and descriptions of laboratory methods recommended for investigation of the technical performance of secondary products in road constructions were compiled. Reference values for the assessment of results were also presented.

The binding and transport of harmful components in soil (Heikkinen & Salminen 2000). The factors that impact on the fate of harmful components in soil were studied on the basis of literature and a field investigation. The focus of the study was on the most common components leaching from secondary products, their migration and binding in Finnish soil. In the field study the migration of inorganic compounds from an older fly ash construction was investigated. On the basis of the study recommendations were given about the soil and bedrock conditions to be considered when planning the utilisation of by-products.

The Finnish environmental permit practice and suggestions for the development of more adaptable legal measures (Kauppila 2000). Those factors in the present legislation and administrative practice which hinder the use of secondary materials in earthworks were studied. The aim was to establish a knowledge base for deregulation of the present permit procedure and harmonisation of permit practices.

Quality control system for the production and use of the secondary materials in earthworks. The aim of the project is to draw up a quality control standard for the production of secondary materials used in earthworks and to draft material standards for three reference materials. These materials are crushed concrete, blast-furnace slag and bottom ash from pulverised coal combustion.

Landfill acceptability of industrial waste (Wahlstrom et al 2000). Recommendations about the landfill acceptability of mineral by-products, such as parameters to be investigated and investigation methods suitable for these investigations, are presented. Some examples of criteria applicable for assessment of the landfill acceptability of typical industrial by-products are also given.

4. Permit procedure

An environmental permit is required if an industrial by-product or secondary material is regarded as waste, which is usually the case. According to the Finnish Environmental Act the permit is issued by the local environmental authority if the amount of waste being used is less than 5 000 t. For larger amounts the permitting authority is the regional environmental centre. It usually takes more than four months to obtain the permit. This is one of the biggest barriers to the use of secondary products, because the use of natural aggregates is much less complicated.

On the basis of the study of the legislative barriers, the Ministry of the Environment has started to prepare a decree of the Council of State. The decree covers the use of selected waste materials in earth construction. The aim is to give general regulations concerning the conditions on which the use of the materials is permitted and thus to release their use from the permit obligation.

5. Investigations for the assessment of environmental compliance

When industrial by-products or secondary products are used in earthworks, the migration of harmful compounds from the material is considered to be the most significant environmental hazard. Besides leaching, it is also important to consider other properties of the material and to check the environmental impacts of the entire utilisation chain. Before assessing environmental compliance, the testing agency has to ensure that all the potentially hazardous compounds and properties of the material have been measured or investigated.

Besides the conservation of natural materials, the utilisation of by-products may have other positive effects, such as reduction of energy use or emissions. Up to now, the legislation has not required consideration of these impacts during the permit procedure for waste utilisation in earthworks. According to the new environmental legislation more weight is, however, put on integrated environmental assessment.

The main phases of investigations for the assessment of environmental compliance of industrial by-products or secondary products are presented in Figure 1.

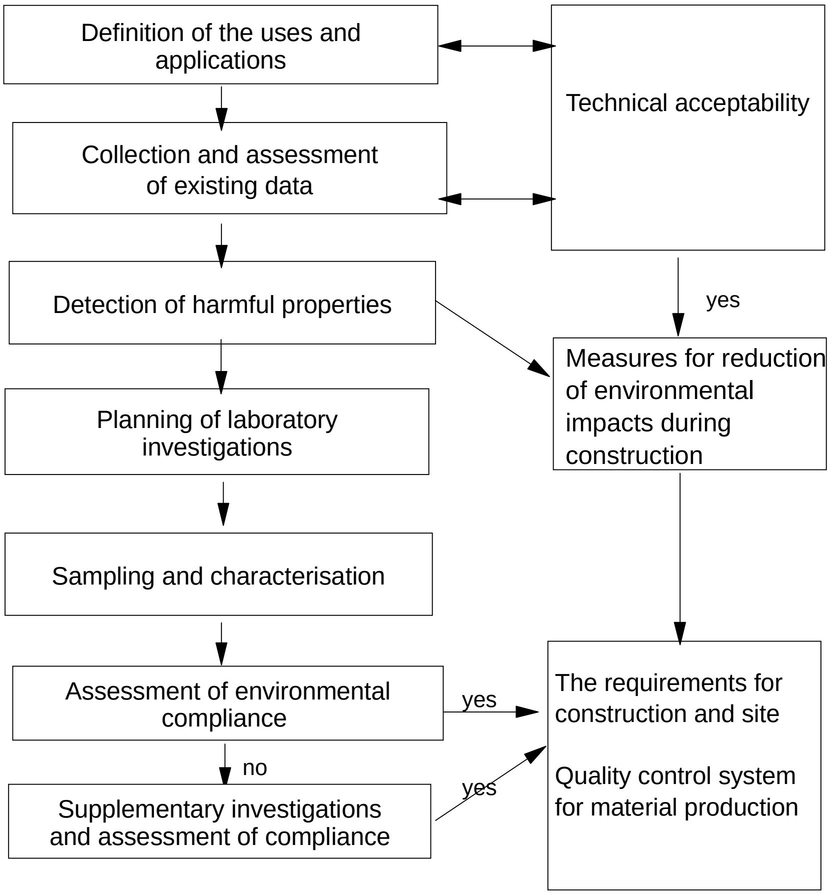

Figure 1. Environmental assessment of secondary products: the main phases of investigation.

The basic characterisation of industrial by-products is usually a demanding task. The testing must be planned case by case. At least the following compounds and parameters shall be selected for further investigation:

- Compounds with a concentration that is expected to be at least on the level of Finnish soil target values
- Compounds on which there is insufficient information about their concentration or harmfulness
- Compounds with a concentration that may exceed the Finnish occupational exposure limits.

When the investigations are planned, one must ensure that all the significant parameters are studied, that the methods used are reliable and suitable for the investigation and that the expertise of the performer of the study is sufficient.

Sampling is one of the most critical stages of experimental investigations, because the sample has to reliably represent the material or batch of material under investigation. The sampling plan must be based on the objectives of the study and on the properties of the material to be investigated. For example, for environmental characterisation it is recommended that at least 20 samples be taken systematically, one sample per day over a period of four weeks.

The report also presents the methods recommended for basic characterisation, which include determination of the concentration of inorganic and organic compounds in the material, determination of leaching behaviour using the column leaching test (NEN 7343 or Nordtest ENVIR 002), the diffusion leaching test (NEN 7345) and the pH-stat leaching test, and methods for analysis of test eluates.

6. Assessment of environmental compliance

A tiered system is presented for the assessment of environmental compliance. The assessment levels are as follows:

1. Concentrations of the harmful components.

If the concentrations of all the inorganic compounds are below the Finnish soil target values and the concentrations of the hazardous organic compounds are below the detection level, the material is suitable for use in earthworks without restrictions. In the case of these values being exceeded, the use of material in ground water areas suitable for water supply is not recommended without a risk assessment.

2. Leaching of harmful components from constructions.

The leaching of inorganic compounds from the material is compared to the leaching values which were drafted as a part of the project by the Finnish Environment Institute. The recommended leaching tests are the column leaching test, NEN 7343, and the diffusion leaching test, NEN 7345.

Long-term performance is assessed by using a test simulating varying pH conditions or on the basis of expert assessment.

The leaching values (Table 2) are presented for unpaved constructions and for constructions paved with slightly water-permeable material, such as asphalt. The material must be placed above the upper ground water level. Sites on which the ground is from slightly to moderately permeable are considered as most suitable for the use of these products.

3. Risk assessment.

In the case of non-compliance with points 1 or 2 above, the material may be used on the basis of material- or site-specific risk assessment.

7. Technical compliance

In most cases it is recommended that the technical compliance be investigated step by step. If the material is totally ”new” the basic parameters to investigate usually include grading, compactibility and hardening. In most cases it is possible to make a preliminary screening of potential applications based on the above-mentioned data, the mode of production and chemical content of the material.

Further studies are then scheduled on the basis of the planned application. The report presents recommendations for the laboratory investigation of industrial by-products which are planned to be used in road construction.

8. Production control of the materials

In most cases it is not necessary to repeat the extensive basic characterisation of materials. In connection with the characterisation, a production control system for the assurance of conformity of the materials with environmental and technical specifications is established. Only in the case of significant changes of the quality of the material, such as changes in the production process or raw materials, it may be necessary to renew some or all the characterisation tests.

The production control system is material-specific. The technical characteristics that are significant for the application and the most critical environmental characteristics are selected for periodic control. Homogeneous materials with well-known basic characteristics require less monitoring than more complicated and less investigated materials.

Table 2. Suggested Finnish leaching values for the mineral materials used in earth construction (Sorvari 2000).

	Granular material	Granular material	Monolithic material
Substance	Unpaved	Paved	
	Emax, mg/kg	Emax, mg/kg	Emax, mg/m^2
As	0.14	0.85	58
Ba	10	28	2 800
Cd	0.011	0.015	2.1
Co	1.1	2.5	280
Cr	2.0	5.1	550
Cu	1.1	2.0	250
Hg	0.014	0.032	1.6
Mo	0.31	0.50	70
Ni	1.2	2.1	270
Pb	1.0	1.8	210
Sb	0.12	0.40	36
Se	0.060	0.098	14
Sn	0.85	3.1	280
V	2.2	10	700
Zn	1.5	2.7	330
F	11	25	2 800
CN, free	0.060	0.098	14
SO_4	1 500	n.a	n.a
Cl	250	n.a	n.a

Summary

Based on an extensive study on various factors affecting the acceptability of secondary products for earth construction, guidance was developed for assessment of the environmental and technical applicability of these materials. The guidance was prepared as a collaboration involving several research institutes.

The guidance presents the legislative requirements for the utilisation of secondary products in earth construction, recommendations for the investigation of environmental and technical applicability, recommendations for environmental and technical criteria of the utilisation in earthworks and road construction, and recommendations for product quality control procedures.

There are many material- and site-specific factors that affect the environmental and technical applicability of the materials. At the same time, practical experience of the use of the materials is mostly quite limited. Therefore the recommended general requirements are conservative. The objective is to ensure the technical performance, to safeguard human health and to protect the environment. Exceptions can be made if it is possible to prove the applicability of a material at a determined site or at sites of a determined type, based on material or site-specific risk assessment or on technical investigations and constructional requirements.

Adequate certainty about the applicability of secondary products will improve the prerequisites of utilisation, because it is possible to avoid negative experience due to the improper use of the materials.

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Project "Slags in geotechnical engineering"

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ABSTRACT: The use of slags has been based for decades on experiences and no dimensioning instructions have been available until the 1990's. Attention was not paid to the systematic development of slags before the late 1980's at which point the use of air-cooled blast-furnace slag was so extensive that there was an evident need for drawing up instructions in order to avoid structural problems possibly arising from its incorrect use. The first instructions were completed in 1989, accompanied by the introduction of new applications particularly for the use of granulated blast-furnace slag both in structural road layers and in stabilizing the base course. The new applications and the stricter technical requirements placed on the products were one reason for launching the five-year "Slags in geotechnical engineering" project. According to the aim set for the project, design, dimensioning and construction instructions should be drawn up for all the slags produced at the Rautaruukki Group's works in Finland with regard to their use for earthwork and road construction purposes. To achieve this aim, the project was divided into three sub-fields, i.e. the use of slags 1) in structural road layers, 2) as a binding agent in stabilizing structural layers and 3) as a binding agent in mix and deep stabilisation.

1. Introduction

A remarkable amount of different kind of slags is produced in different phases of steel-making process. In Finland, total slag production from Rautaruukki Raahe steel works and Fundia Wire Koverhar steel works is 1 000 000 tons. Even in a very modern integrated steel works, like Rautaruukki Raahe steel works, the amount of slag per one produced ton of steel is more than 300 kg. This amount of slag is a total amount, which consists of blast-furnace slag, desulphuring slag, converter slag and slag from secondary metallurgy (Fig. 1).

First step in slag utilization is separating of metallic part i.e. scrap from slag. The most valuable part of slag utilization is returning of this separated scrap back to iron- and steel-making processes. However, ever increasing attention is paid to non-metallic slag and its utilization. Main reasons for this kind of development are cost savings in storaging and avoiding of environmental penalty fees. Very essential part of main product i.e. steel is the fact that steel producer must show how it is taking environment into consideration. It has been recognised that by systematic R&D work and effective marketing by-products utilization may also be a good business.

Over recent years, more and more emphasis in road building, has been placed on cost saving. As a result of this, the recycling of used road materials and the use of cheaper industrial by-products has been developed. Environmental factors have also played their part in this development.

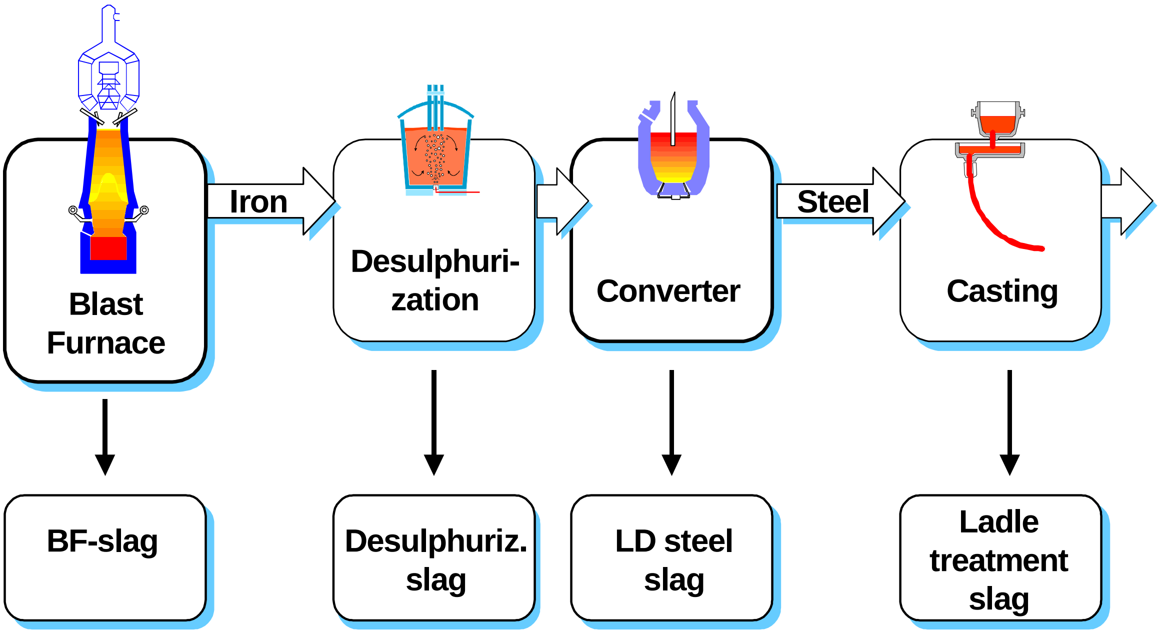

Figure 1. Slag types from integrated steel-making processes.

2. R&D project implementation

2.1 Preliminary preparations and project organising

The principal responsibility in the whole project management and implementation was carried out by SKJ-companies Ltd., which is a subsidiary of Rautaruukki Oyj, the biggest steel producer in Northern European countries. Before starting the actual planning of project one seminar was held in order to get ideas and new aspects for the project. Experts from different interest groups were invited and representatives from research institutes, universities and road constructors were present in the seminar.

After comprehensive analysis and several smaller work group meetings the actual project organising and detailed planning was started. Contacts with the research institutes, universities and road constructors played important role and thanks to effective netting SKJ managed to create a project, which would be able to work technically efficiently.

Financial support was received from Technology Development Centre of Finland (Tekes). Rautaruukki Oyj and Finnish Road Administration played also important role, former by offering R&D services and latter by constructing the experimental road sections. University of Oulu took care of most of the laboratory work. Geotechnical laboratory carried out a huge amount of different kind of laboratory tests. Some research work was also made in the Department of Geology and Department of Chemistry. Research Centre of Finland (VTT) had important role as a coordinator of several associated projects, which were financied by Tekes and by-product companies like SKJ.

2.2 Actual project work

The actual project work was started at the beginning of year 1995 and project was carried through according to diagram shown in Figure 2. Total implementation time for the project was five years and one addtional year is needed to finish all the instruction work. The most important instructions were made during the project.

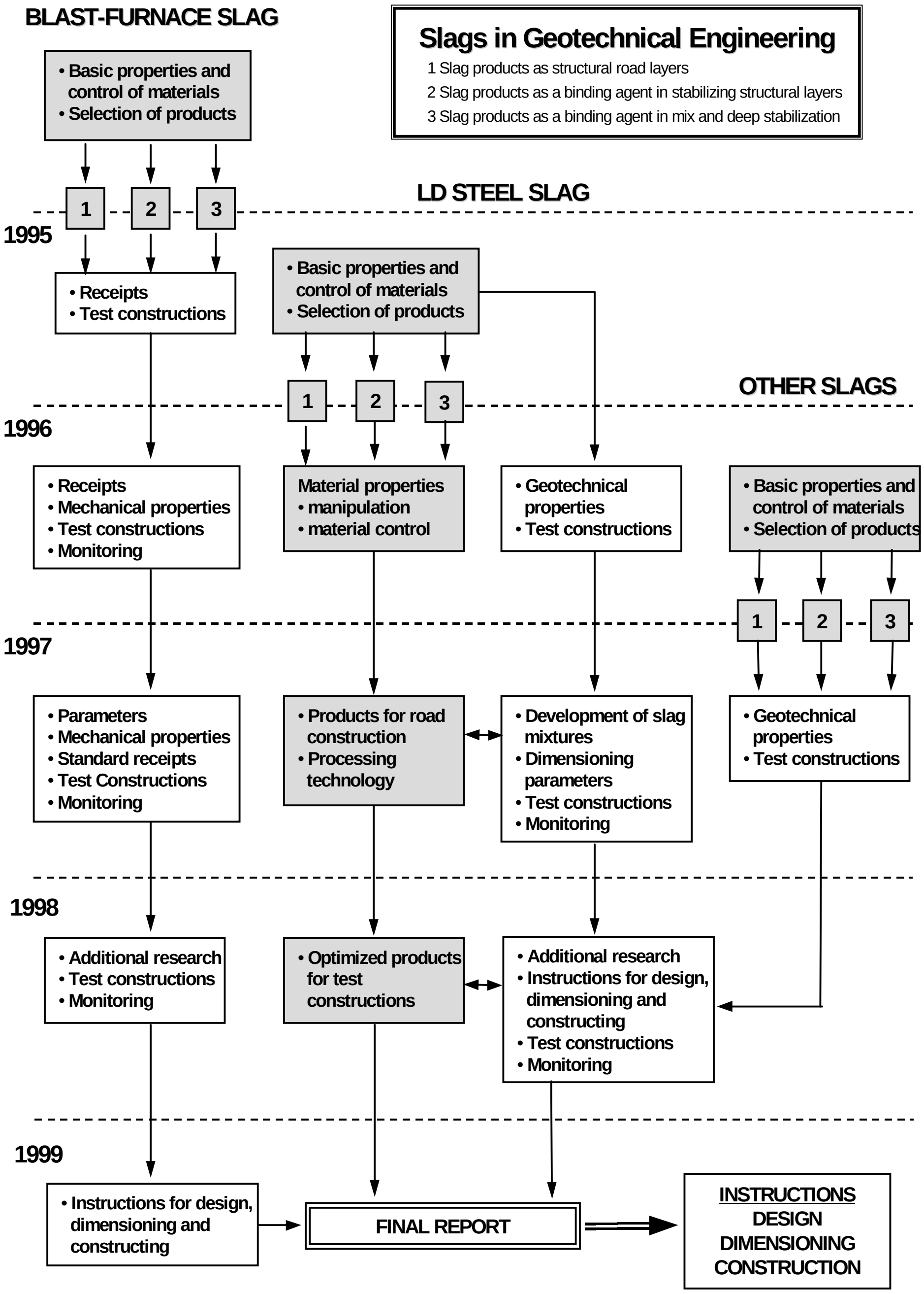

Figure 2. Research sectors in actual project work according to slag types under research.

The project was divided into three parts. Those were: 1) slag products as structural road layers, 2) slag products as a binding agent in stabilizing structural layers and 3) slag products as a binding agent in mix and deep stabilization. A number of smaller researches on the use of slags as structural materials in road construction was also implemented, and a number of slag products with greatly varying grain-size distributions were examined and developed.

In all these areas of research, there was in progress, an effort to increase knowledge of the basic properties of these materials. For the LD steel slag, desulphurizing slag, and ladle treatment slag, this means determining the technical properties, and for the blast-furnace slag and LD steel slag, the binding properties.

Area 1 research concentrated upon developing LD steel slag and blast-furnace slag products. In addition the suitability of desulphurization and ladle treatment slags was studied. Main goal for area 1 research work was to increase understanding concerning material behaviour of each slag type.

In area 2 studies water cooled blast-furnace slag, refined in various degrees, for use as a binder in the stabilizing of road courses, was developed. The products were granulated blast-furnace slag, preground granulated blast-furnace slag and ground granulated blast-furnace slag. In addition, included in this area of the research was LD slag, which was used in its original form or as an activator refined in various degrees. Cement was also used as an activator.

The main accent in area 3 was on the binding properties of ground granulated, cement activated BF slag, primarily in the stabilization of clay materials.

There are two possible ways of implementing the research and development work in order to improve the quality of the final product. One way is to change the properties of the product (Figure 3). This would happen for example by grinding coarse slag gravel into a finer product. Other way is to develop a new way of using the product. For example granulated blast furnace slag has conventionally used in Finland as massive layer in road construction. In the early 90’s its utilization was developed in such a way that nowadays exactly the same product is used for a more demanding purposes, that is as an binding agent in road stabilization.

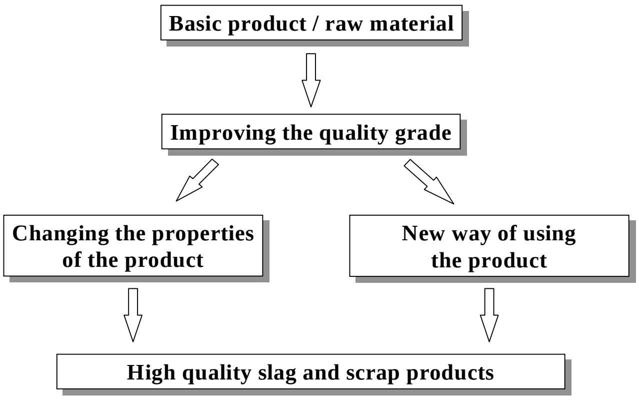

Figure 3. Two ways of implementing R&D work.

For the blastfurnace slag the research concentrated on binder techniques of stabilization, and uses in massive layers (unbound layers).

In relation to the study of stabilizing binder materials, a comprehensive investigation was already done on factors affecting the strength of stabilized materials (Mäkikyrö 1995). The development of binder material mixes, and determination of technical properties with the aim of producing procedures and instructions, was done on the basis of this previous study. These studies was focused on stabilization of recovered road materials and till. In parallel with these, studies was made in connection with the stabilizing of crushed rock. Materials to be used as binder were cement activated granulated blast-furnace slag, preground granulated blast-furnace slag and ground granulated blast-furnace slag.

Mix- and deep stabilizing studies was done on the stabilizing of clays using cement activated ground granulated blast-furnace slag.

For LD steel slag the research concentrated on two main sections: 1) the use of LD steel slag as a replacement for natural materials and air cooled blast-furnace slag in massive constructions and 2) the use of LD steel slag in slag binders for stabilizing of road courses. The use of LD steel slag in slag mixtures was studied only in some minor extent.

The emphasis in research was to put on producing LD slag products of a more valuable nature. The overall aim of the research was to determine the design parameters for construction courses using slags, and those using slag binders. The determination was made in relation to bearing capacity and frost resistance properties.

The use of LD steel slag as a replacement for natural materials and air cooled blast-furnace slag in massive constructions means in practise determining the properties of LD slag aggregates and comparing those properties to natural aggregates and blast-furnace slag. Possible changes in technical properties in a course of time was also taken into consideration.

The slag products, which were used in the binder material research were, granulated blast-furnace slag, preground granulated blast-furnace slag, ground granulated blast-furnace slag (400 m^2/kg, Blaine), LD steel slag (0–3 mm), preground LD slag, ground LD slag (150 m^2/kg, Blaine) and cement. The aim of the binder material research was the replacing of the cement, used as activator, by LD slag wherever possible. In addition the binding properties of LD slag itself was studied. The first stage of the research was to develop more reactive slag binders. In the second stage the regulation of the ratio of binder materials in relation to the natural materials used for binding was investigated.

One of the most important studies regarding LD steel slag was that of determining the expansion properties, and in particular, means of controlling expansion. The primary aim was to find a structural solution to stability.

Only some small laboratory studies has been made concerning desulphurization slag and ladle treatment slag. The aim was to determine the basic properties of these slags and get idea of their technical behaviour.

The amounts of laboratory tests and materials during the whole project were huge. Several thousands of single tests was made and about 15 tons of material was handled in laboratory only. Testing methods were so called ’basic geotechnical tests’ i.e. the amount of results is remarkable and the methods were quite simple.

A central part of all areas of the research was the constructing of trial road constructions, in cooperation with the Finnish National Road Administration. The design of the trial constructions was based on the results of the laboratory tests. A very important part of the monitoring of the trial road courses was that of measuring both bearing capacity and any possible changes occurring due to frost.

In the summer of 1995 seven trial stretches (each 100 m) of on-site stabilized road, using cement activated granulated blast-furnace slag stabilizer was built. Stabilizing was carried out so, that the materials of the old road pavement has been utilized as aggregate of the new layer, which was stabilized (Figure 4). The existing natural rock material and the old bituminous pavement materials was used for improving the road. New material was used only for laying the new wearing course. Typical thickness of stabilized layer was 150-200 mm and wearing course was bituminous asphalt concrete, thickness 50–100 mm.

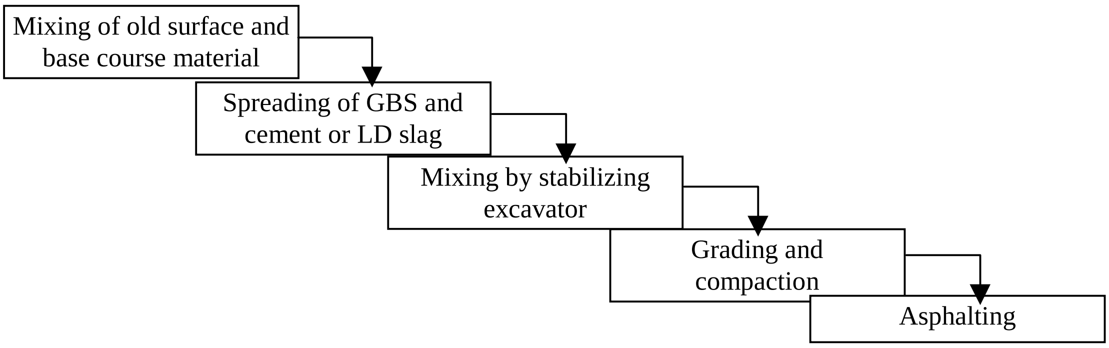

Figure 4. Different stages in so called on site stabilization technique.

At the end of 1995 a trial in connection with pillar type, deep stabilization was carried out, using cement activated ground granulated blastfurnace slag. This test construction was made as a part of Road Administartion's research project TPPT. In 1996, the first instrumented trial constructions using LD slag was built, in connection with massive constructions. In summer 1997 totally 10 trial sections were built. Five sections were made with the on-site stabilization techniques and five was made as massive layers. A schematic picture of test sections with massive slag structure is presented in Figure 5.

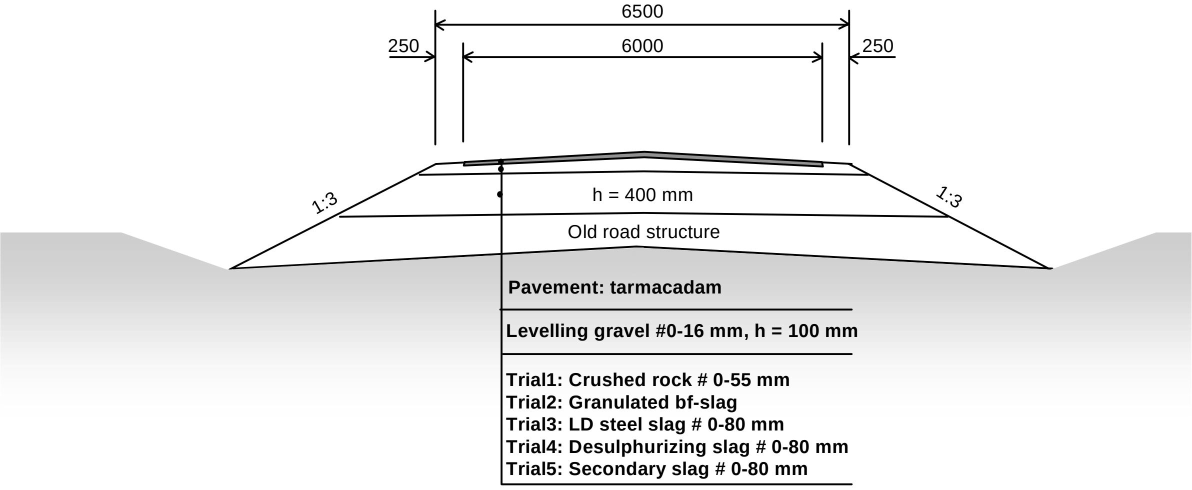

Figure 5. A schematic cross-section of test constructions with massive slag structures.

Instrumented constructions included following measurements: frost penetration, moisture content in different layers, thermal regime from 10 different depths (-10 cm to -350 cm), thickness of snow in road slope and thermal conductivity. Measurements has been made 6 times a year and load bearing measurement with falling weight deflectometer three times a year. Monitoring of test sections will be continued several years from now on.

2.3 Results

During the whole project thousands of tests was made in laboratory. Major amount of these tests were so called basic laboratory tests, the aim of which was to produce as much measured data as possible in order to get a reliable idea of material behaviour of different slag types, especially those for LD steel slag. Research work was done for various product fractions from fine powder up to very coarse crushed aggregates.

The main result for the entire project was instructions for the use of slag products in road construction. Some of the instruction were drawn up during the project implementation (Tielaitoksen selvityksiä 38/1998, Finnra Reports 18/1999 and Siira et.al. 1999) and others (Slag products in earth structures, Slag products in construction on weak subsoils and Stabilization with granulated blast-furnace slag) are still under preparation work and will be finished by the end of year 2000.

Figure 6 shows one example of development work for slag-based binders. The effect of the amount of slag components in slag-based binder was tested by mixing selected slag components and using them as binder for stabilizing of crushed rock material. LD3 is ground LD steel slag (150 m^2/kg, Blaine) and GBS is normal granulated blast-furnace slag produced in Rautaruukki Raahe steel works. In this kind of binder LD slag is used as an activator instead of cement. Results indicate that the increasing amount of activator results increasing compression strength. However, the degree of strength should be higher in order to fulfill the demands set for stabilizad road base.

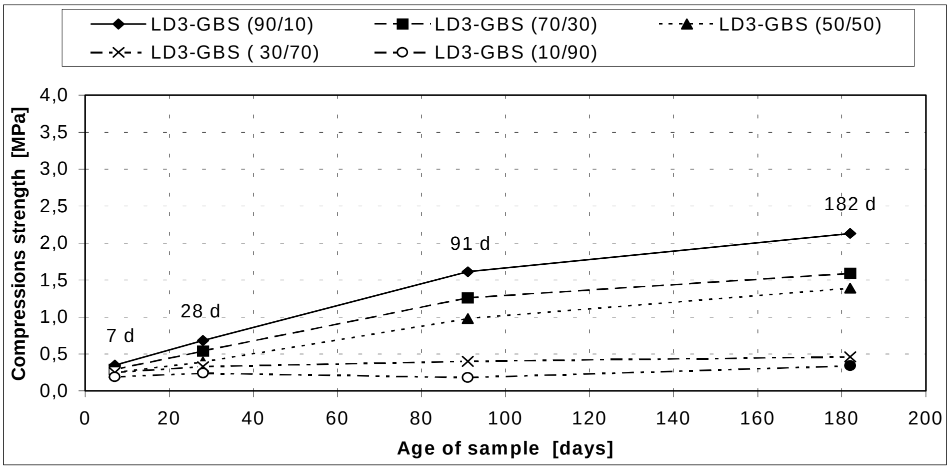

Figure 6. The effect of the amount of slag components in slag-based binder. Stabilized material was crushed rock.

Measurements of bearing capacities of stabilized roads was essential part of monitoring test road sections. Figure 7 shows the development of bearing capacity for one test section made by stabilizing old road base with granulated blast-furnace slag, which was activated by cement. A remarkable increasing for E_2 -modulus was achieved during the first year of monitoring after which the value has remained on the same level.

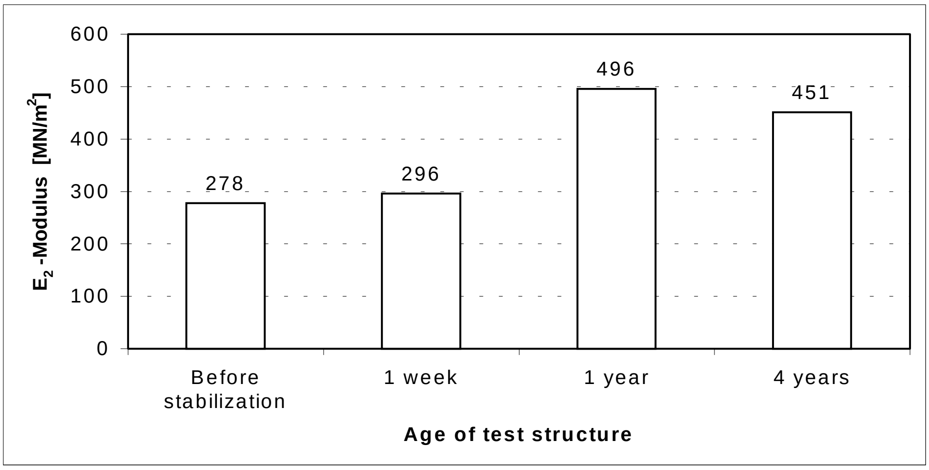

Figure 7. The improvement of bearing capacity of one test structure made in 1995. Values are mean values from ten different measuring points.

3. Summary and conclusions

The main goal for the project was to prepare instructions for the use of slag products in road construction. To achieve this result a lot of research work was done both in laboratory and in actual conditions i.e. on test constructions. Project was implemented according to time schedule, which was set at the beginning and only some changes was made for the plans during the project. The main result i.e. instructions was also achieved and by this way one big step was taken ahead in upgraded slag utilization in Finland.

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LD steel slag – from raw material into product

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ABSTRACT: Blast-furnace slag has already established its position as an earth work and road construction material in Finland. LD steel slag has been used as an asphalt aggregate material and as soil conditioner in agriculture. Yet approximately one third of all the LD slag produced remains in stock each year. It was thus considered necessary to develop uses for LD slag in particular, which has the largest volume. LD slag surveys were conducted as part of the five-year project “Slags in geotechnical engineering”. The research was carried out in phases by deciding on the main development guidelines on the basis of written reports and chemical and mineralogical analyses. This was followed by preliminary laboratory tests to implement the actual experimental program. Test structures were made after extensive laboratory tests in order to examine in actual conditions the use of LD slag as a solid material and as a binding agent. The results obtained from the laboratory tests indicated that LD slag has a large potential for use in earthwork and road construction projects.

1. Introduction

In Finland, totally 1 000 000 tons of different kind of slags arises in two integrated steel mills as a by-product of iron- and steel-making. From this amount about 200 000 tons is LD steel slag, which is a by-product of steel-making. Major amount of this material, 70% of total sales, is sold for agriculture as soil conditioner. Some part is utilised in road construction and also in earth works in steel mill area.

At first stage of steel slag utilization metallic part i.e. scrap is separated from slag. Returning of scrap back to steel-making process is the most important way of utilising LD steel slag. The use of LD slag derived products in road construction and agriculture are the most important applications for the use of non-metallic part of LD steel slag. The use of LD steel slag products in the structural courses in road construction has so far been mostly restricted to trials, whereas its use as aggregate in asphalt is standard practice despite the small annual amounts in this application. The main reason for this is the resources of good natural stone aggregates, which are available almost everywhere in Finland. On the other hand, the use of LD steel slag in agriculture as soil conditioner has considered to be more refined way of utilisation. As a result of effective marketing and good experiences market situation for slag products in agriculture is at the moment very satisfying. Despite successful sales in agriculture every year some amount of LD slag is put into storage piles. The amount of material put into storage has varied from 5% even to one third of the whole production.

To achieve 100% degree of utilisation, a lot of systematic R&D work has been done and possibilities for upgraded utilisation already exists. Possibilities for the utilisation vary from massive coarse material in embankments into activator powder in so called on site stabilisation techniques. The key question is to convince customers of the technical and environmental properties of LD steel slag products as well as to minimise production costs.

2. Development work from raw materials into LD slag products

2.1 General features of road construction

Major demands are placed on the bearing capacity of road materials, as road structures are required to withstand the loads imposed on them for decades without deterioration under conditions which often vary greatly in terms of both temperature and humidity. In addition, there are very few means available in the case of roads for influencing the conditions which the structures are required to withstand. It is often difficult to obtain sufficiently high-quality materials, and environmental factors have very cental role regarding the use of materials.

In Finland an exceptionally heavy strain is placed on road structures, due to the ground features and the climate. In addition to this, traffic loads are high, as 70% of goods are carried by road. The melting of the seasonal frost in spring, along with the high traffic loads makes great demands on design and construction, and also on the road materials used.

Over recent years, more and more emphasis in road building, has been placed on cost saving. As a result of this, the recycling of used road materials and the use of cheaper industrial by-products has been developed. Environmental factors have also played their part in this development.

2.2 Finnish design practise

The most of the Finnish roads are of unbound (flexible) construction but the change to bound type, semi-rigid construction has increased over recent years. This is the result of both the increase in load bearing requirements, and the reduction in availability of good natural road materials, due to the environmental restrictions being placed on them.

Roads are classified in Finland according to the volume of traffic which they carry. Traffic volume is expressed by a equivalent standard axle loads (ESALs). The roads are designed such that each road class is given a so called target bearing capacity. In addition to this, in frost susceptible areas the frost classification is checked.

The Odemark equation is used in calculations of the bearing capacities of pavement structures. The modulus of elasticity (E-modulus) of the materials used are given in the tables. The E-modulus varies according to the type of the material, eg. sand, gravel or crushed rock, and grain distribution curve, and in some cases also upon the moisture content. For example the E-modulus of crushed gravel is between 150...300 MN/m^2, sand 30...100 MN/m^2 and crushed blast-furnace slag 600 MN/m^2.

Another alternative for designing bearing capacities is the analytical procedure. The tension/deformation analysis used in slag instructions sets out from the notion of restricting the compression deformation of the layer beneath the slag. This criterion was developed by the Asphalt Institute, and its permitted base compression deformations are the smallest of all the durability criteria currently in use. (Finnra Reports 18/1999)

Analytical dimensioning uses a dynamic E-modulus for the slag layer base, which is usually determined by means of a CBR test or a dynamic triaxial test.

Structural displacement occurs as a result of subsoil freezing and thawing, which manifests itself in the form of cracks and unevennesses on the road surface. Thawing of the frozen soil in spring impairs the load bearing capacity of the subgrade. The major principle in frost dimensioning is to examine freezing from both a technical and an economic perspective. The costs arising from restricting freezing should be in correct proportion to the likelihood of damage, the resulting defects and the costs of repairing the damage. Frost dimensioning is used as a means for restricting frost heave differences in order to reduce surface unevenness and cracks. The reduced bearing capacity after the thawing of the frost in spring must also be taken into consideration when calculating bearing capacity. Frost dimensioning sets out from the category of the road concerned and the prevailing soil and groundwater conditions. (TVL, Kansio B)

2.3 The use of slag products in road construction

Slag products can be used in a variety of road structures, mainly depending on their hydraulic and thermal properties (Figure. 1).

When used as a massive material, an individual slag product constitutes the primary material in a road layer. This type of use takes maximum advantage of the good bearing and thermo-technical properties of slag. The use of slag products also enables the construction of thinner structural layers than with natural rock.

The use of slag in mixes is primarily aimed at improving bearing capacity by employing mixtures composed of different types of slag or combinations of slag and natural rock. Another aim is to ensure that the favourable properties of slag can be exploited to the full and that any restricting factors associated with the slag can be eliminated. The slags used in compounds have a coarser grain-size distribution than those used as binding agents.

Slags can be used as binding agents in both the stabilization of structural layers and strengthening of the subgrade. The former makes maximally efficient use of the existing road materials, while the latter can be achieved in the form of either mix stabilization, deep stabilization or a combination of the two.

Steel slags and air-cooled ferrochromium slag lend themselves for use as pavement aggregates better than do most natural rock materials.

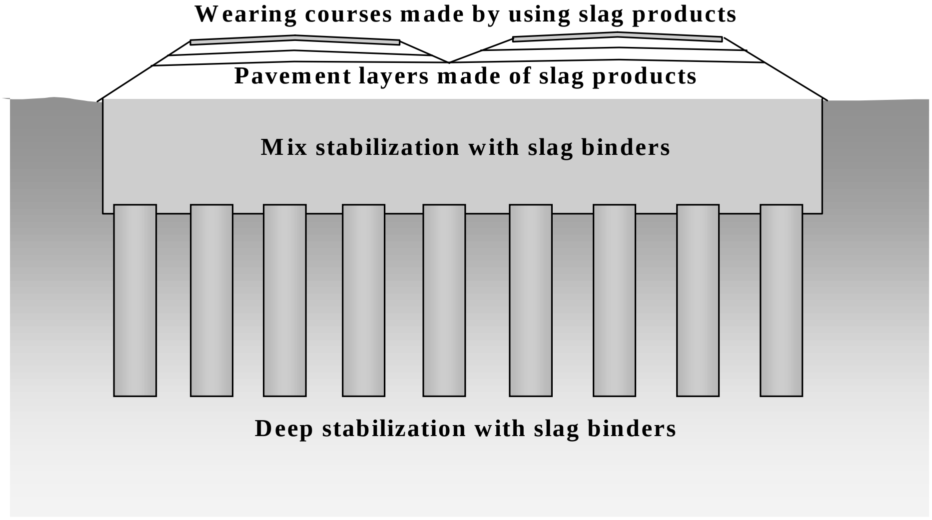

Figure 1. Use of slag products in road structures.

2.4 Slags in geotechnical engineering

Slag products are developed and sold in Finland by SKJ-companies Ltd., which together with the Technology Development Centre were engaged in financing a 5-year project called "Slags in geotechnical engineering". The project was implemented jointly with the Geotechnical Laboratory at the University of Oulu and the Finnish Road Administration, and was aimed at yielding design, dimensioning and construction instructions for the use of slag products for road construction purposes. The project was divided into three parts, which were as follows: 1) slag products as structural road layers, 2) slag products as a binding agent in stabilizing structural layers and 3) slag products as a binding agent in mix and deep stabilization. A number of smaller research and development projects on the use of slags as structural materials in road construction are also being implemented, and a number of slag products with greatly varying grain-size distributions are currently being examined and developed in Finland.

2.5 Research program for LD steel slag

Research program for LD steel slag was carried out in above mentioned parts 1) and 2). Research was divided into chronological sections according to subject matters (Table 1). Before starting overall research program some preliminary studies were done to determine the basis on which the research would be carried out. Three kinds of LD steel slag, of differing grain size, were chosen for these preliminary studies. First sample was approximately 1 year old slag, crushed at the end of 1994 and screened spring 1995, for use as asphalt aggregate. Second sample was 2–3 years old, crushed in autumn 1994 and from which the asphalt and agricultural fractions were removed. Earlier this type of material was recycled to the steel-making process. Third sample was the undercut from the first sample, with the agricultural fraction removed. Grain size of agricultural fraction is 0–3 mm.

Table 1. Starting dates for each phase of the research program for LD steel slag.

Year	Month	Phase of the research program
1995	May	Litterature survey (Mäkikyrö, 1996)
1995	June	Mineralogical and chemical research (Hiltunen, 1996)
1995	October	Preliminary studies
1996	January	Research for massive use (Holma, 1997)
1996	February	Research for binder use
1996	May	Research for mixture use
1996	June	Material behaviour research
1996	September	Experimental constructions
1997	July	Experimental constructions

Fraction range in studies has been wide varying from LD slag powder into very coarse lump slag products, the grain size of which can reach even the value 150 mm (Figure 2).

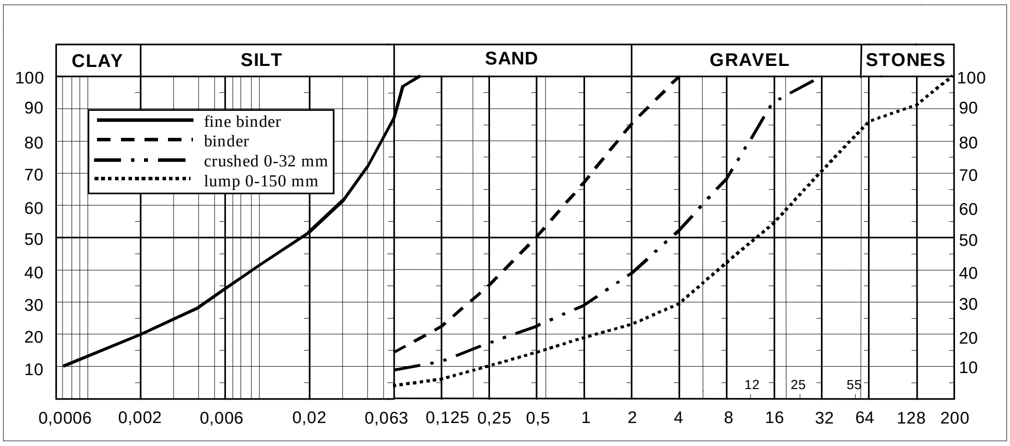

Figure 2. Examples of the grain-size distributions of LD slag products subject to research and development work.

From the litterature survey and preliminary studies it was found that LD steel slag is more reactive than blast-furnace slag. After 2 months the compressive strength of the LD slag was 1.8 MPa, a figure which could not be achieved with unactivated blast-furnace slag. One significant result, from the point of view of use in Finnish road construction, was that the thermal conductivity of LD and blast-furnace slags were found to be very similar.

From the litterature survey and preliminary studies, it appeared that LD slag is similar to air-cooled blast-furnace slag, for use as a road construction material. One negative factor is the much greater weight when considering transport. When using LD slag, the possibility of expansion occurring, must of course be taken into account.

After finishing litterature survey and preliminary laboratory studies the overall research program was started for LD slag products. Research work for massive use was carried out by means of diploma thesis (Holma, 1997). The idea was to make wide range of basic laboratory tests in order to determine all the needed parameters, which are needed in designing of road structure.

The emphasis in research concerning binder and mixture use was to be put on producing LD slag products of a more valuable nature. The overall aim of the research was to determine the design parameters for building courses using slag mixtures, and those using slag binders. In the mixing and binding agent tests, the aims were:

- To develop the technical properties of mixed and stabilized materials, so that they are at least as good as those of individual slags.
- The eliminating of factors, which may prevent use of the LD slag.
- The enhancing of slag properties which complement each other.
- To develop more refined and valuable products.
- To reduce road building costs.

As a result of market situation and evaluation of future needs the studies concerning the use of LD slag in mixtures were cut down and tests were made only for mixtures made of granulated blast-furnace slag and LD slag. Results indicated that by using mixed materials some benefits can be reached. Those are better reactivity and bearing properties. Despite the decreased amount of expansion of LD slag, it still caused problems.

The slag products, which were used in the binder material research were granulated blast-furnace slag, preground granulated blast-furnace slag, ground granulated blast-furnace slag (400 m^2/kg, Blaine), LD steel slag (0–3 mm), preground LD slag, ground LD slag (150 m^2/kg, Blaine) and cement. The aim of the binder material research was the replacing of the cement, used as activator, by LD slag wherever possible. In addition the binding properties of LD slag itself was studied. The first stage of the research was to develop more reactive slag binders. In the second stage the regulation of the ratio of binder materials in relation to the natural materials used for binding was investigated.

Figure 3 shows that blast-furnace slag activated with LD slag (GBS/LD) is very competing binder with blast-furnace slag activated with cement (GBS/CEM) and cement (CEM) alone.

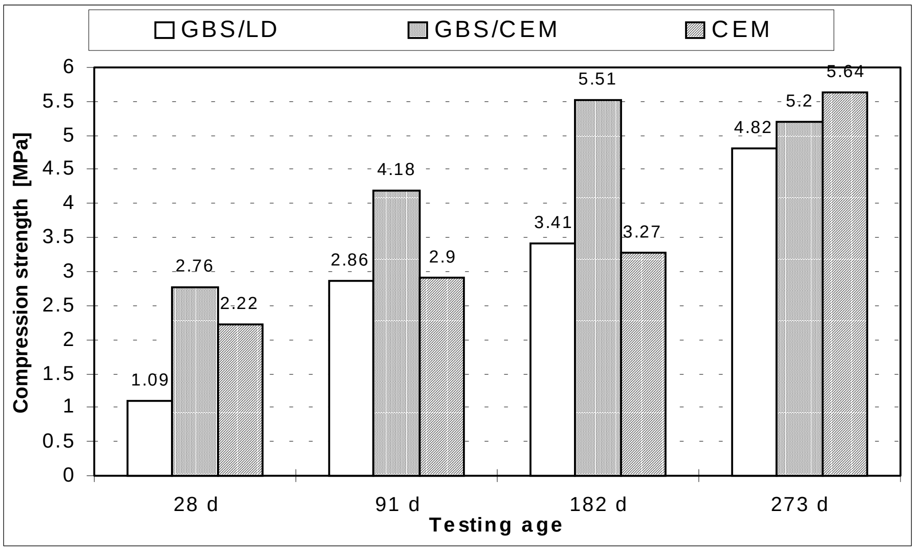

Figure 3. Compression strength for the samples stabilized with different kind of binders, GBS = granulated blast-furnace slag, LD = LD steel slag and CEM = ordinary portland cement.

A very essential part of research work has been experimental constructions in order to get measured information from actual conditions. Totally 19 test sections has been made during project "Slags in geotechnical engineering". LD steel slag has been tested in four of those sections. Test sections were constructed in 1995–1997 and follow-up program for them is still continuing.

According to Falling Weight Deflectometer (FWD) measurements a structure, which is stabilized with granulated blast-furnace slag activated with LD slag (GBS/LD), is totally comparable with the "traditional" applications i.e. blast-furnace slag activated with cement (GBS/CEM) and cement (CEM) alone (Figure 4). In a course of time the slowly hardening slag-based binders reach the strength of cement, the binding reactions of which are faster than those for slags. Similar encouraging results has been achieved also from massive structural test sections made of coarser LD slag aggregates.

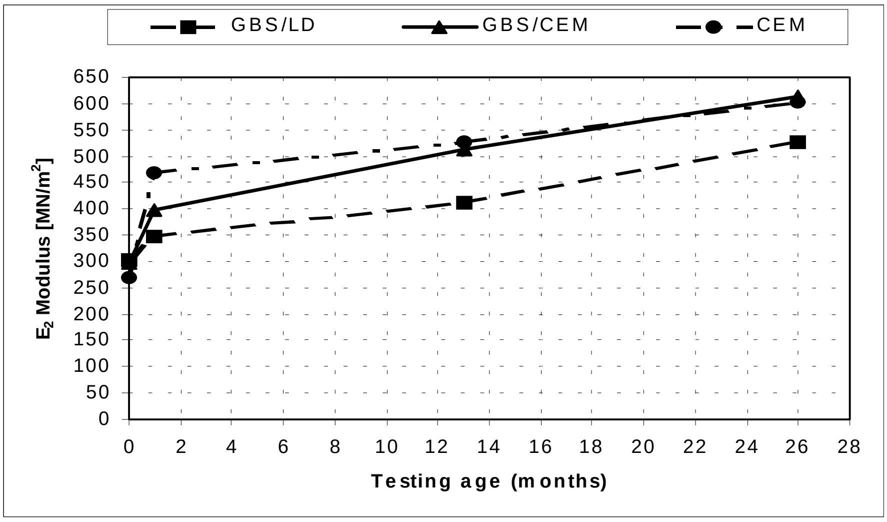

Figure 4. E_2 -moduli values for test sections stabilized with different kind of binders, GBS = granulated blast-furnace slag, LD = LD steel slag and CEM = ordinary portland cement.

One of the most important studies regarding LD steel slag is that of determining the expansion properties, and in particular, means of controlling expansion. The primary aim has been to find a structural solution to stability. In this case, the previously mentioned slag mixtures and slag-natural material mixtures, among others, come into the question.

3. Conclusions

LD steel slag can be used for practically all road construction purposes. Its use as a binding agent in a fine, crushed form and in ground form has been examined, the point of departure being its utilization of LD steel slag together with granulated blast-furnace slag to replace cement in slag-based binding agents. LD steel slag acts as a means of activating and maintaining the blast-furnace slag hydration reaction. One of the main guidelines in research into the use of slag in mixtures has been that the drawbacks caused by the possible expansion of LD steel slag can be eliminated by ensuring that the compound also contains products that do not swell, such as blast-furnace slag, natural rock or both. The primary aim in developing the use of LD steel slag as a massive material has been that maximally effective use should be made of its bearing and thermal insulation properties. Special attention in all research into the development of uses for LD steel slag has been paid to the effect of time, i.e. to the changes which take place in its technical properties with time.

Continuous research and development work is needed to fulfill future demands set for upgraded LD slag utilisation. Iron- and steel-making produces huge amounts of good raw materials (Figure 5). To create markets and to carry on development work one should know what are the needs of customers, what is the market situation now and in the future and what are the competing products, which in turn results price competition. By systematic and controlled product development it is possible to achieve new markets, which very often requires co-operation with the environmental authorities. In order to convince authorities and new customers one needs further upgrading in order to convert these raw materials from iron and steel production into products for road construction.

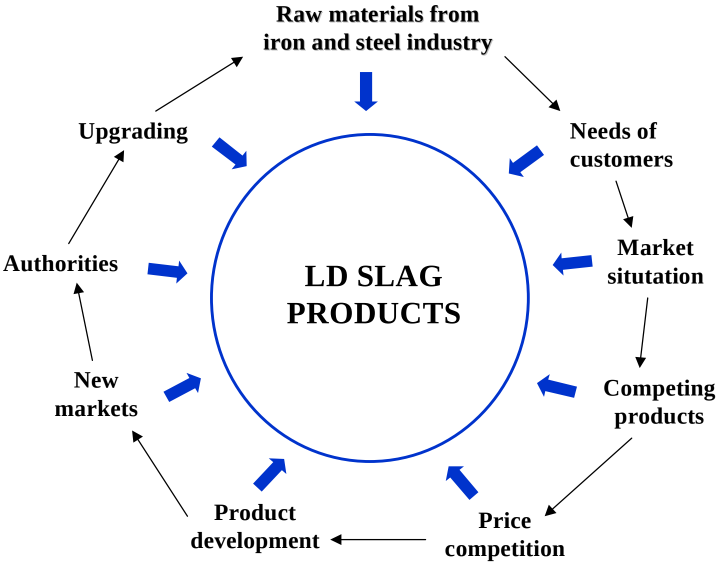

Figure 5. Continuous research and development work to fulfill future demands set for upgraded LD steel slag utilization.

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Use of fibre clay in landfill cover structures

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ABSTRACT: According to the Finnish and EU waste and landfill regulations a two meters thick cover structure is to be built on a landfill when it is closed. The use of this amount of suitable natural soil materials is not possible without enormous costs and changes in the environment.

The aim of this development project was to create a method for landfill closing with industrial by-product materials. The project was based on the fact that the fibre sludge of paper industry was found to have a low enough water permeability for the impermeable barrier layer of landfill cover structure.

The environmental characteristics of fibre clay and fly ash were studied by using standardised test methods. The soluble concentrations of hazardous compounds studied in fibre clay were below limit values. The geotechnical properties of fibre clay material are similar to non-cohesive soil. The fibre clay material stands unbalanced settlement better than the natural soils in the same applications. Because of the easy handling and good material characteristics the structures can be modified later.

The experience shows that the landfill structures can be built almost solely by using waste materials.

1. Introduction

Based on the principles of sustainable development, Finnish and EU waste and landfill regulations direct us to reduce waste and to utilize waste materials when ever possible. The Finnish government decision on landfills (861/97) and the Council Directive on the Landfill of waste give the general principles for landfill closing and the structural requirements. (European Union 1999, Suomen säädöskokoelma 1997)

In earlier studies the paper sludge or fibre sludge or fibre clay whatever one calls it was found to be suitable for earth construction purposes because its durability and water impermeability. In our project the material studies were continued and construction materials and methods developed further.

The landfill cover structure was chosen to be the pioneer application, because the geotechnical requirements are suitable. It is also quite natural and safe to start the utilization of a waste material in a waste management application where the environmental risks are taken into consideration anyway, and the area already has a potential pollution source on it.

2. Landfill cover structure

The requirements of the landfill cover structure are based on the regulations, according to which the clean surface waters and external run-off waters are to be kept separate from the waste and landfill leachate. The landfill is to be managed so that the amount of landfill leachate leaving the site and its impacts on the environment are minimised. Landfill gas is to be collected and treated or combusted as required. The layers of the cover structure are presented in table 1.

Table 1. The required cover structure in closed landfills (Suomen säädöskokoelma 861/97).

Layer	**Classification of landfill**	
	Ordinary waste	**Hazardous waste**
Surface/vegetation ≥1,0 m	required	required
Drainage layer ≥0,5 m	required	required
Impermeable barrier ≥0,5 m	required	required
Artificial barrier	not required	required
Gas collection layer	required	if necessary

3. Fibre clay

3.1 Origin

Fibre clay is the paper sludge material, which is collected from the primary settlement of the waste water treatment in paper mills. The material is called fibre clay because it consists mainly of two portions: fibres of different length and clay (mostly kaolin). Based on the paper manufacturing process the fibre clays can be divided in two categories: wood-containing paper sludge and chemical pulp paper sludge. Also de-inking residue of paper processing is considered fibre clay, since it has similar properties as primary paper sludge. (Viatek Oy 1998)

3.2 Technical properties

The technical properties of fibre clay have been studied for several years, especially in USA. Research have been done also in Finland for some years now.

The quality of industrial by-products, e.g. fibre clay and fly ash, varies a lot depending on the process etc. During these studies, for example a difference of 37…61% in water content, a difference of 0,7…1,7 x 10^{-8} m/s in water permeability and a difference of 13…29 kPa in shear stress was observed in fibre clay. Also the studied fly ash has a great variation in quality. (Viatek Oy/SGT 1998)

Storage has less effect on the properties of de-inking residue fibre clay than those of the wood containing and chemical pulp containing fibre clays. As to fibre clays, their water content drops, organic matter content drops and water permeability decreases during storage. (Moo-Young 1995) When stored in a silo, the properties of the ash do not in practice alter, but when stored in piles the strength drops and water content increases (Viatek Oy/SGT 1998).

The water permeability is the most important factor when considering the use of fibre clay in the impermeable barrier structure. The measured water permeability of three different fibre clays in laboratory were 0,1…2 x 10^{-8} m/s. When fly ash is added to fibre clay for better strength, the water permeability increases. On the other hand, bentonite, for example, can be used to reduce the permeability. In the field conditions the water permeability was found to vary from less than 10^{-8} to 8 x 10^{-8} m/s in different test sites. The measurement was done right after construction. Because of the consolidation of the structure the actual “final” water permeability values are not achieved until after a year or so. In addition to the consolidation, also the decomposition of the organic matter causes compaction and reduction in water permeability in the structure. (Viatek Oy 1998)

The second best property of fibre clay in landfill structure is its capability to stand differential settlement and deformation. Fibre clay is a plastic material, which can be made stiffer with additives. The effective strength parameters of fibre clay are roughly equivalent to silt parameters. (Viatek Oy 1998)

3.3 Environmental properties

Analyses of total element contents were carried out on samples taken from used by-products at test structure sites. In total content analyses extracts are removed from samples using nitrohydrochloric acid at 90^{o}C and analysed by ICP-AES or MS methods. Results were compared with proposed highest levels of toxic substances permitted in construction materials used in earthworks and with other currently valid guidelines.

Soluble concentrations were tested using Dutch method NEN-7341. Phosphorus, nitrogen, COD_{Mn} and TOC were tested with NEN-7343 method.

No harmful concentrations were found in fibre clay, but fly ash and desulphurization residue, which are mainly used as additives, have some slightly high soluble heavy metal concentrations. (Envitop Oy 1998a)

An odour survey of construction materials (volatile sulphur compounds) was also done in Koivissilta landfill and the results showed that concentrations of odour causing compounds of the studied fibre clay do not cause harm to health (VTT 1998).

4. Test structure

4.1 Structure and materials

In the Koivissilta landfill three test fields were constructed in 1998 for *in situ* studies. The materials used for the impermeable barrier layers on the fields differ from each other, figure 1. One field was made of 3:1 mixture of waste fibre (paper mill sludge) and fly ash. The two other fields were constructed of plain fibre clay material, another of these materials was crushed and mixed before spreading. The monitoring has been focused on the impermeable barrier layer. (Viatek Oy 1999)

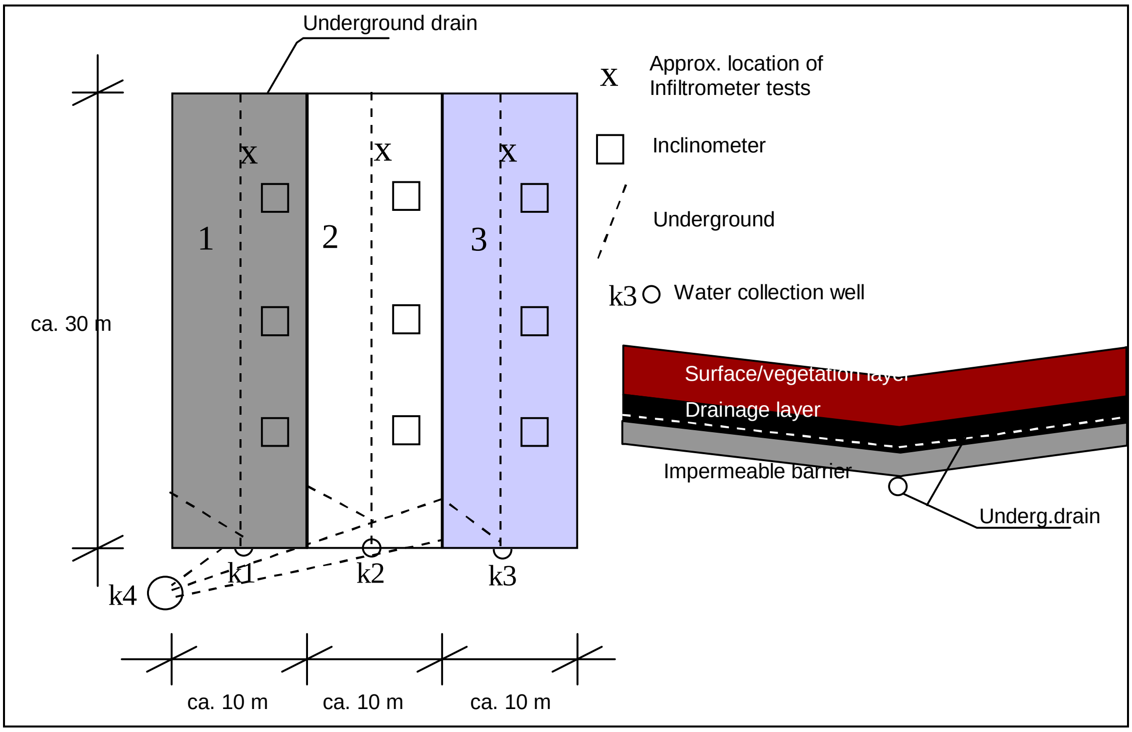

Figure 1. Principles of Koivissilta test structures.

4.2 Monitoring methods

The test structure studies include the monitoring of water permeability, strength, stability of the slopes, biodegradation, leachate volume and characteristics. The first couple of monitoring rounds have been carried out.

The geotechnical properties have been monitored for two years. The last tests and samples were taken in October-November 1999. The methods include the measurement of water content (drying in 105°C), dry density and permeability in situ and in laboratory with flexible wall permeameter (triaxially stressed).

The stability of the structure on the slope was studied with installed pipes, which are made of thin aluminium and which bend in accordance to the movements of the structure layers. The movements of the pipes are monitored with separate electronic equipment and the results are processed with computers.

Conditions of decomposition were evaluated by measurement of pH and redox potential.

4.3 Results

The slope stability has been monitored three times in 1998 and once in1999. The results showed that no substantial movements had occurred. The movement is approximately 20–60 mm/year towards downhill.

Some water content and dry density results are shown in table 2. Water content has dropped almost one third and dry density risen about 100 kg/m^3 during one year monitoring.

Table 2. Water content and dry density of test structure material.

Impermeable barrier material	27.11.1998		18.–20.10.1999	
	W (%)	ρ (kg/m^3)	W (%)	ρ (kg/m^3)
Field 1	125…138	570…580	99,5	630
Field 2	57…63	790…880	52,8	910
Field 3	136…145	490…500	99,9	630

The in situ water permeability results are shown in the table 3. Both in situ and laboratory results indicate reduction in permeability.

Table 3. Permeability results, field and laboratory.

Impermeable barrier material	Permeability (m/s)			
	May 1998	27.11.1998	18.–20.10.1999	lab
Field 1	$k < 10^{-8}$	$k = 7{,}9 * 10^{-9}$	$4{,}3 * 10^{-9}$	$7{,}8 * 10^{-10}$
Field 2	$k = 2…3 * 10^{-8}$	$k = 1{,}0 * 10^{-6}$	$4{,}4 * 10^{-8}$	$6{,}1 * 10^{-8}$
Field 3	$k < 10^{-8}$	$k = 1{,}0 * 10^{-8}$	$4{,}4 * 10^{-9}$	$6{,}3 * 10^{-10}$

In the decomposition investigation, a state of oxygenation was observed at over a metre down from the living layer. In this state, decomposition of organic matter to carbon dioxide and water is rapid. The impermeable barrier layer is in a non-oxygenated state where microbiological decomposition takes place anaerobically, figure 2. (Envitop Oy 1998b)

Fibre clay can be assumed to degrade more slowly under these circumstances than in aerobic conditions. The barrier layer can be estimated to hold its protective characteristics long enough (at least 30–50 years) due to the fact that most of the consolidation of a landfill happens during the first 10–30 years after which the changes in shape are not remarkable and the fact that the fibre clay layer becomes even more compact when the organic matter stars to decompose.

There are no relevant results of the leachate characteristics yet.

5. Conclusions

The main result and conclusion during the development project was the find that fibre clay is a proper material for landfill impermeable barrier layer because of its low permeability and good capability to stand differential settlement and deformation. Another important conclusion is the fact that the landfill cover structure can be built using almost solely industrial by-product materials. This development project has also lead to commercialised solutions and further product development.

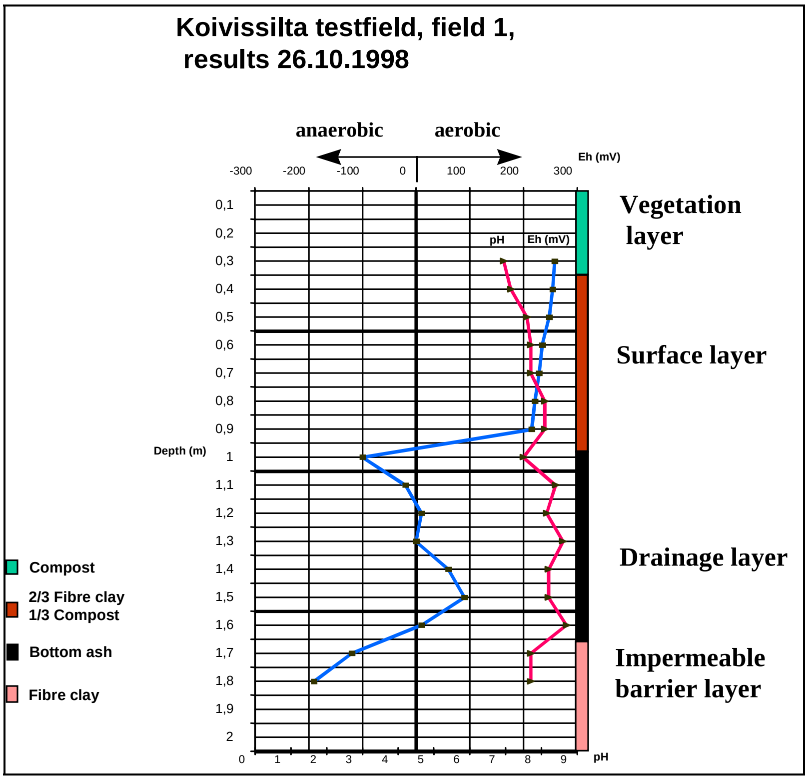

Figure 2. Redox-measurement results of Koivissilta test field.

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Field hydraulic conductivity of a paper mill sludge hydraulic barrier using two stage borehole tests

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ABSTRACT: This paper deals with the field hydraulic conductivity evaluation of a paper sludge landfill cover located in Corinth, New York that was completed in 1995. This landfill cover, a demonstration project, consists of compacted clay and paper sludge hydraulic barrier sections. Laboratory flexible-wall hydraulic conductivity tests were performed on in-situ samples obtained adjacent to in-situ two-stage borehole (TSB) test locations. The TSB test is a field infiltration test that has gained popularity over the last several years for the evaluation of hydraulic barriers. The objectives of this study were to evaluate the paper sludge long-term field hydraulic conductivity, and compare relative differences between laboratory and field hydraulic conductivity values. Results indicate that paper sludge is a suitable hydraulic barrier material alternative since laboratory and field hydraulic conductivity values were near or less than 1×10^{-9} m/s (the typical regulatory requirement), similar to compacted clays. Overall, the paper sludge field hydraulic conductivity values were about half an order of magnitude to one order of magnitude greater than those measured in the laboratory. In contrast, the compacted clay field hydraulic conductivity values were slightly lower than the measured laboratory values. The main difference between laboratory and field hydraulic conductivity values for each hydraulic barrier material type is attributed to effective stress sensitivity. Paper sludge is very sensitive to effective stress relative to compacted clay. Additional factors, advantages and disadvantages were discussed for laboratory and in-situ TSB tests.

1. Introduction

1.1 Paper mill sludge landfill covers

In recent years, paper mill sludge has emerged as an alternative landfill cover hydraulic barrier material instead of compacted clay. Paper mill sludge is the residual material from the paper making process produced by a wastewater treatment plant. Recycling paper sludge often creates a win-win situation for the landfill owner (often a municipality) who saves the cost of obtaining clay that may not be readily available, and the paper mill which saves the cost of sludge disposal.

Paper sludges are high water content materials that typically have high organic contents, high compressibilities and low shear strengths. Several researchers have investigated the geotechnical and geoenvironmental properties of paper sludge (e.g., Zimmie et al. 1995, Moo-Young and Zimmie 1996, Kraus et al. 1997, Benson and Wang 1999 and Quiroz 2000). These studies have shown that paper sludge hydraulic barriers can achieve hydraulic conductivity values of 1×10^{-9} m/s or less, comparable to compacted clays.

Moreover, the unique geotechnical field behavior of paper sludge is a result of its geotechnical properties, which are in a different range when compared to typical soils (e.g., sands, silts and clays). For example, after construction, paper sludge barriers undergo high settlement stains due to primary and secondary consolidation ranging from 18% to 35%, even under the low overburden pressures of a typical landfill cover. These settlement strains induce large reductions in void ratio causing decreases in hydraulic conductivity. This behavior is especially important in cases where marginal hydraulic conductivity values are measured, since the paper sludge hydraulic barriers improve with time. Thus the long-term evaluation of in-situ hydraulic conductivity is an important issue and should be considered in post-closure paper sludge landfill cover monitoring strategies.

1.2 Objectives

The purpose of this project was to evaluate the long-term field performance of a paper sludge landfill cover constructed in 1995, and compare the differences between laboratory and field hydraulic conductivity values. Currently, little information exists on the in-situ measurement of hydraulic conductivity for paper sludge landfill covers. The measurement of hydraulic conductivity using flexible-wall triaxial cell permeameters is probably the best method of laboratory testing (Zimmie 1981, Daniel et al. 1984). However, in general, one problem with laboratory tests is the amount of disturbance applied in the sampling process. This disturbance is significant in the retrieval of paper sludge samples due to high fiber contents and low shear strength ranges. In addition, the stress condition applied in a triaxial cell is different from actual, in-situ stresses (i.e., $\sigma_1 = \sigma_3$ versus K_0 stress condition). Therefore, the measured laboratory hydraulic conductivity values may be different from the in-situ values. An alternative is the in-situ measurement of hydraulic conductivity using the Two-Stage Borehole (TSB) test, also known as the Boutwell test (Daniel 1989, Trautwein and Boutwell 1994). The comparison between ex-situ and in-situ hydraulic conductivity testing will provide additional hydraulic conductivity behavior information essential to the application of paper sludge hydraulic barrier technology.

2. Town of Corinth landfill

The paper sludge landfill is located in Corinth, New York and has a footprint of about 5.2 ha. Since paper sludge was considered experimental and non-conventional within the State of New York, this landfill closure was approved as a demonstration project. Thus the landfill cover had a compacted clay and paper sludge barrier layer section to provide a direct comparison between each barrier layer type. Approximately 4.1 ha is covered with a 1.2 m thick paper sludge layer, while the remaining 1.1 ha is covered with compacted clay about 45 cm thick. An overburden sand layer about 75 cm to 100 cm was placed on the paper sludge hydraulic barrier as a barrier protection and top soil layer. The landfill closure was completed in 1995.

The paper sludge for the hydraulic barrier was obtained from the International Paper (IP) Co. located in Corinth. Fresh paper sludge produced by the wastewater treatment plant and old paper sludge harvested from the paper mill’s sludge landfill was used for the barrier layer. Moo-Young and Zimmie (1997) and Floess et al. (1998) have presented the construction aspects and geotechnical properties for the Town of Corinth Landfill and IP paper sludge.

2.1 IP paper sludge geotechnical properties

The initial geotechnical properties of the IP paper sludge were measured during the construction phase of the Town of Corinth Landfill cover (Moo-Young and Zimmie 1996). In general, water contents, organic contents, and specific gravities varied from 150% to 220%, 42% to 56%, and 1.80 to 1.97, respectively. These geotechnical properties are in a completely different range when compared to typical compacted clays. High water contents and high organic contents account for the large compression index (C_c) values, 1.27 to 1.96, measured for IP sludge. As a result, large settlement strains due to consolidation are expected after construction of the barrier layer.

3. Methodology and approach

A comparative testing program was developed to measure laboratory and field hydraulic conductivity values for the Town of Corinth Landfill cover. Four testing locations were selected on the landfill hydraulic barrier, three in the sludge section and one in the clay section. The tests were conducted during the summer and fall of 1999.

3.1 Sample retrieval

Hydraulic barrier specimens were obtained using 73 mm diameter thin-walled Shelby tubes. Compacted clay samples are typically retrieved using a slow, steady insertion effort such that a continuous, intact sample is obtained. However, this method is not very effective for paper sludge sampling due to the low shear strengths and high organic contents of the sludge (Moo-Young and Zimmie 1996, Benson and Wang 2000, and Quiroz 2000). A slow insertion and resistance to shearing by the organic fibers often compresses the sludge, greatly disturbing the soil matrix. Therefore, paper sludge samples should be retrieved using a clean, dynamic effort to obtain a more “undisturbed” sample and higher recovery rates. The most common method is to simply place a Shelby tube on the paper sludge then apply a dynamic effort, say with a sledge hammer, to quickly insert and cut through the fibrous sludge. A block of wood placed on top of the tube during hammering is often used to protect the Shelby tube. Shelby tubes samples were obtained adjacent to the two-stage borehole test locations. These samples were extruded and trimmed for laboratory hydraulic conductivity testing.

3.2 Laboratory hydraulic conductivity tests

Laboratory flexible-wall triaxial hydraulic conductivity tests were performed on in-situ specimens in accordance with ASTM D-5084. The procedures were modified when testing the paper sludge specimens to account for its unique behavior. Large volume changes can be expected due to the compressible nature of the sludge, and gas generation has been encountered in some cases during hydraulic conductivity tests (Benson and Wang 2000). The effective stress applied during testing was 34.5 kPa, a typical landfill cover stress, which was accomplished using a cell pressure of 310.5 kPa and a back pressure of 276 kPa. A gradient of about 21 was applied across the specimen during the permeation phase of the test.

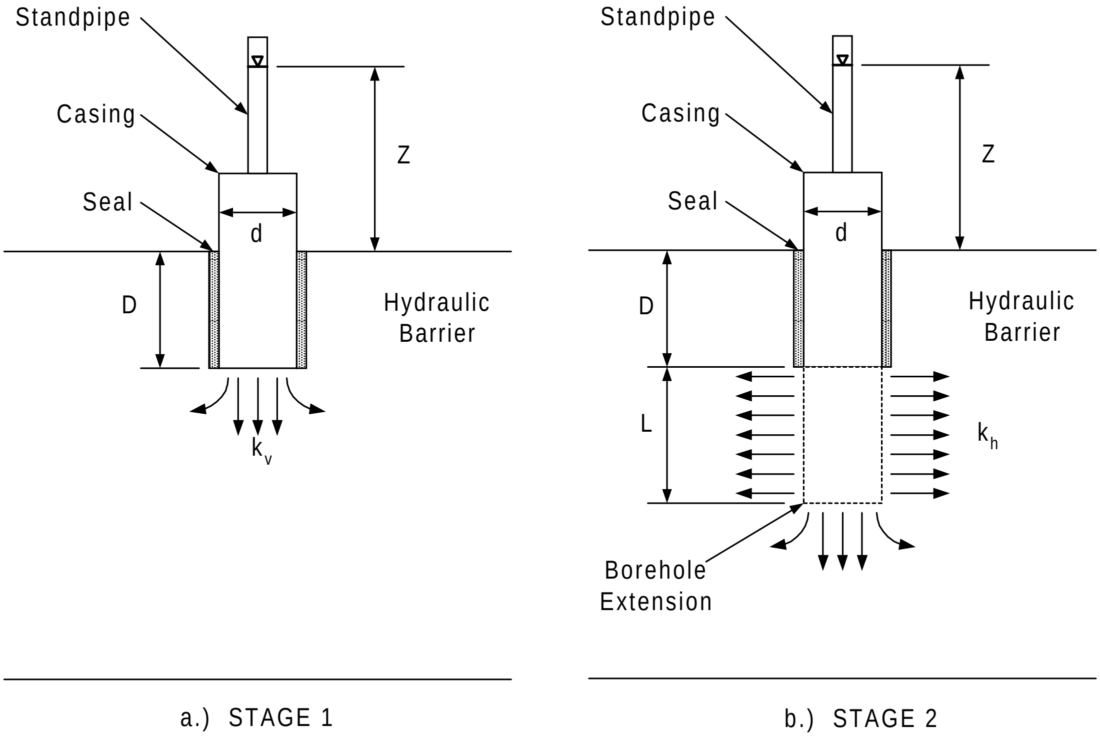
One important aspect of laboratory paper sludge hydraulic conductivity testing is effective stress specification. Since paper sludge is highly compressible, it is sensitive to testing pressures. Thus, as the applied effective stress increases, the hydraulic conductivity decreases. For example, by simply doubling the applied effective stress from 34.5 kPa to 69 kPa, a one order of magnitude decrease in hydraulic conductivity is not unusual for paper sludges. In practice, laboratory hydraulic conductivity tests are conducted at two effective stresses, 34.5 kPa and 69 kPa, for predictive purposes (Moo-Young and Zimmie 1995 and Quiroz 2000). The 34.5 kPa test results represent current hydraulic conductivity values or those immediately after construction, while the 69 kPa results are used to provide long-term hydraulic conductivity values (i.e., a decreasing hydraulic conductivity trend) after subsequent consolidation.

3.3 Field hydraulic conductivity tests (two-stage borehole tests)

The in-situ hydraulic conductivity was measured using the two-stage borehole (TSB) test following the procedures outlined in ASTM D-6391. This field test is often used to evaluate compacted clay hydraulic barriers within the United States due to its lower cost and shorter testing times in comparison to other field methods such as the sealed double ring infiltrometer test (SDRI) (Trautwein and Boutwell 1994). Holes about 1.3 m × 1.3 m were excavated down to the paper sludge barrier layer for TSB testing.

The TSB test method uses a sealed, cased borehole and monitors the water level in a standpipe. Using the falling head method, the rate of flow into the soil is measured. The first of the two stages is conducted with the casing flush with the bottom of the borehole. In this phase, the vertical hydraulic conductivity, k_v, is dominant (Figure 1 a.). Flow into the soil is monitored until it is constant, then the first stage hydraulic conductivity, k_1, is determined. The subsequent second stage involves extending the borehole below the bottom of the casing and monitoring the falling water level (Figure 1 b.). During this phase, the horizontal hydraulic conductivity, k_v, is dominant. Again, once the inflow is constant, the second stage hydraulic conductivity, k_2, can be determined. Finally, knowing k_1, k_2, and various test parameters, the values of k_v and k_h can be uncoupled.

From a practical standpoint, if the test is performed to determine if k_v is less than some specified value, sometimes only the first stage may be conducted. If the “apparent hydraulic conductivity” (arithmetic time-weighted average hydraulic conductivity) for the first stage is constant and below the specified value, then the test may be terminated (ASTM D-6391).



a.) STAGE 1 b.) STAGE 2

Figure 1. Two-stage borehole test for hydraulic barriers: a.) first stage of infiltration, b.) second stage of infiltration (after Trautwein and Boutwell 1994).

When conducting TSB tests on paper sludge, Benson and Wang (2000) recommended keeping Z less than D. This prevents hydraulic fracturing due to near zero effective stress at the bottom of the borehole, which can cause a rapid head loss in the standpipe, yielding incorrect hydraulic conductivity values. This was generally not a problem for the tests conducted in this study since the barriers had an overburden sand layer about 75 cm to 100 cm, resulting in relatively high effective stresses. The estimated effective stress at the bottom of the casing was about 18.9 kPa and test times lasted about 1 month to acquire constant k_1 and k_2 values.

4. Results and discussion

The results of the laboratory hydraulic conductivity tests conducted on in-situ samples of the Town of Corinth Landfill cover are presented in Table 1. In general, under an effective stress of 34.5 kPa the hydraulic conductivity values were less than the typical regulatory limit of 1×10^{-9} m/s. The paper sludge proved to be an effective hydraulic barrier material similar to the compacted clay.

Table 2 shows the results of the in-situ, two-stage borehole tests conducted on the clay and paper sludge sections of the Town of Corinth Landfill. The k_v value is the main parameter of interest for landfill covers and liners. For an average effective stress of 18.9 kPa, the paper sludge k_v values (including the "apparent hydraulic conductivity" value for sample sludge-3) were about half an order of magnitude or less greater than 1×10^{-9} m/s; while the compacted clay exhibited a k_v much lower than 1×10^{-9} m/s. Since the paper sludge is a highly compressible material that can experience a large degree of secondary consolidation (Quiroz 2000) it is expected that continued barrier layer settlement will further decrease the vertical hydraulic conductivity to meet regulatory requirements.

Table 1. Laboratory flexible-wall hydraulic conductivity test results for the Town of Corinth Landfill cover.

Sample	Effective Stress (kPa)	k_{lab} (m/s)
clay-1	34.5	2.0×10^{-10}
sludge-1	34.5	5.2×10^{-10}
sludge-2	34.5	7.9×10^{-10}
sludge-3	34.5	5.2×10^{-10}

Table 2. Two-stage borehole, field hydraulic conductivity test results for the Town of Corinth Landfill cover.

Sample	Effective Stress (kPa)	k_h (m/s)	k_v (m/s)
clay-1	18.9	1.0×10^{-8}	9.1×10^{-11}
sludge-1	18.9	2.3×10^{-9}	2.3×10^{-9}
sludge-2	18.9	1.3×10^{-8}	2.2×10^{-9}
sludge-3 [a]	18.9	---	---

[a] Only stage one was completed ("apparent hydraulic conductivity" = 5.2×10^{-9} m/s).

For the paper sludge, the laboratory and field results indicated that field k_v values (including the "apparent hydraulic conductivity" value for sample sludge-3) were about half an order of magnitude to one order of magnitude greater than those measured in the laboratory. This is primarily due to differences in effective stress, 34.5 kPa in the laboratory versus about 18.9 kPa in the field. Since paper sludge is highly compressible, it is sensitive to confining pressures, i.e., as the effective stress increases the hydraulic conductivity decreases due to reductions in void ratio and/or constriction of microscopic flow channels. Therefore, for the paper sludge hydraulic barrier, greater hydraulic conductivity values were measured by the in-situ two-stage borehole tests. In contrast, for the compacted clay samples, the difference in hydraulic conductivity between laboratory and field values was less than half an order of magnitude, which is not surprising since typical compacted clay barriers are not very compressible. LaPlante and Zimmie (1992) and Othman and Benson (1992) showed less than a half an order of magnitude decrease in hydraulic conductivity for compacted clays subjected to effective stress levels increasing from about 15 kPa to 200 kPa. Testing considerations which also affect hydraulic conductivity results are sample size or test volume affected, soil saturation levels, and quality of soil tested (how many defects present, micropores versus macropores, etc.). An additional hydraulic conductivity testing aspect specific to paper sludge is sample disturbance since it is a low strength and highly compressible material. The in-situ TSB test for paper sludges may be a more suitable method for evaluating field performance since it minimizes sample disturbance. However, as discussed previously, laboratory tests may provide additional data since you can vary effective stress levels to acquire an indication of sensitivity to confining pressures and potential long-term predictions after subsequent consolidation.

5. Summary and conclusions

Hydraulic conductivity analyses was performed on the Town of Corinth Landfill cover located in the State of New York. This unique 5.2 ha landfill cover demonstration project had a 4.1 ha paper sludge hydraulic barrier layer section and a 1.1 ha compacted clay barrier layer section. A total of four locations (one on clay and three on paper sludge) were tested via laboratory flexible-wall triaxial hydraulic conductivity tests and in-situ two-stage borehole tests. The objective of this study was to evaluate the long-term performance of the landfill cover, especially the paper sludge barrier layer section, and compare the differences in laboratory and field hydraulic conductivity values.

The laboratory hydraulic conductivity tests performed using an effective stress of 34.5 kPa showed that the paper sludge and compacted clay samples had hydraulic conductivity values less than the typical regulatory limit, 1×10^{-9} m/s. This is not surprising for compacted clay barriers, however, it does show that paper sludge is a suitable hydraulic barrier material alternative. The in-situ two stage borehole tests conducted at an average effective stress of about 18.9 kPa showed that the compacted clay k_v value was much less than 1×10^{-9} m/s, however, the paper sludge k_v values were half an order magnitude or less greater than 1×10^{-9} m/s. Also, the differences between laboratory and field hydraulic conductivity values were about half an order of magnitude to one order of magnitude. The differences between the compacted clay and paper sludge k_v values, as well as the laboratory and field hydraulic conductivity values, was a result of the high compressibility of paper sludge. Since paper sludge is very sensitive to effective stress (i.e., as the effective stress increases the hydraulic conductivity decreases) relative to clay, higher hydraulic conductivity values are expected from the tests conducted at lower effective stresses. Nonetheless, it should be noted that for all practical purposes the paper sludge hydraulic barrier is an effective hydraulic barrier. Moreover, due to high water contents and high organic contents, the paper sludge barrier layer is expected to undergo a considerable amount of consolidation which will continue to reduce void ratios and decrease hydraulic conductivity.

It was also noted that sample disturbance can play an important role in sludge hydraulic conductivity values due to its low shear strengths and high organic fiber contents which can impede the retrieval of quality “undisturbed” samples. Typically, a dynamic sampling method is best for sludge to minimize sample disturbance. As an alternative, in-situ hydraulic conductivity tests such as the two-stage borehole test can give a more accurate estimation of field performance. However, the flexibility of laboratory tests which can be used for predictive purposes by testing under two confining stress levels (see Section 4) is an advantage. Overall, hydraulic conductivity monitoring strategies should be closely examined for paper sludge hydraulic barriers since there are several differences, advantages and disadvantages between laboratory and in-situ hydraulic conductivity tests.

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Definition of environmental criteria for the industrial by-products used in earth construction

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ABSTRACT: At present in Finland, Dutch methodologies and criteria are frequently employed in the environmental assessment of the by-products used in earth construction. As the result of the study concerning the development of national criteria, a hierarchical procedure is presented. Composition and solubility standards were developed as well. The derivation of solubility criteria (MPEs), was mainly based on Dutch leaching models and the Finnish target values of soil. Conservative risk assumptions were used as a starting point in the definition of parameter values. Different MPE alternatives were created by changing the values of the parameters defining the acceptable load into soil. A risk-benefit analysis was executed by using a decision analysis (SMART method) in order to identify the best MPE alternative. In the definition of the final MPE values, land use, the uncertainties of analytical methods and the non-uniformity of target values (soil) were considered. The proposed solubility standards differ slightly from the corresponding Dutch values. According to the results of leaching tests, water-cooled blast-furnace slag and crushed concrete can be considered recyclable whereas most of the fly ashes from coal combustion could be used only in a prefabricated form.

1. Introduction

In Finland, significant amounts of natural mineral aggregates e.g. rock, gravel and sand is spent in earth construction every year. In industrial activities, several wastes having suitable technical properties to be used as a substitute for primary materials are produced. The materials used traditionally in earth construction include blast-furnace slag, crushed concrete from demolition works and fly ash from energy production. Environmental competence is the key factor in the assessment of the reusability of different by-products.

In Finland, the use and disposal of by-products is mainly regulated by the Waste Act. All industrial by-products are considered wastes and normally, an environmental permit has to be applied in order to reprocess, reuse or recycle them in a large scale. Depending on the amount of the by-product, the permit is granted by a regional environmental center or municipality. The permit process is often considered time-consuming and laborious. For experimental construction projects, there is a simpler notification procedure. At present, there is no official code-of-practice concerning acceptability definition. The permit to use a waste material in earth construction has been granted on case-by-case basis. The decision criteria have varied.

Previously, different leaching tests and criteria based mainly on the 100-fold quality standards of domestic water have been employed. During the last few years, Dutch test methodologies and criteria have been adopted. The Dutch criteria are based on Dutch legislation, environmental conditions and guideline values and are as such not directly applicable to Finnish conditions. The definition of unified national environmental guidelines has been considered an important development need.

2. The development of the code-of-practice

2.1 Principles

The primary condition of the reusability of a by-product is that it may not be hazardous i.e. it has to be disposable in a landfill designed for non-hazardous wastes.

The basis of the development of environmental criteria was the existing or prospective Finnish legislation. Following the legislation, the priority was given to the prevention of ground water contamination. This protection is accomplished by limiting the use of by-products outside the classified ground water areas. The second principle was the prevention of the soil contamination. This is accomplished by substance-specific limit values, which define the acceptable, negligible emission to soil.

2.2 Structure

A hierarchical procedure for the definition of environmental competence of by-products is proposed (Sorvari, 2000). Environmental competence can be assessed in different levels depending on the characteristics of the waste material. The criteria defined for separate assessment levels are applicable only to the areas receiving background load i.e. non-sensitive areas like urban areas in general.

At the highest assessment level, the composition of the material is compared with the composition standards, which correspond the target values representing a clean soil. If these values are exceeded, as is normally the case, the solubility of harmful substances must be examined with leaching tests. As test methods, primarily the NEN 7343 column test and NEN 7345 diffusion test should be used. The solubility in various, relevant pH conditions should be studied as well. The results are compared with the solubility standards i.e. Maximum Permissible Emission (MPE) values. If these are exceeded, the material can be studied further by using a case-specific risk assessment (RA) procedure, in which environmental conditions (e.g. transportation and exposure routes, recipients) and the long term stability of the material are taken into account. The risk assessment can be material-specific or site-specific. If it can be stated that there is no harm to human health or the environment, the material can be used at the site characterized in the RA. The methodologies, methods and contents of the risk assessment are not defined in this context. For executing RAs, separate guidance have been prepared (Sorvari & Assmuth, 1998; Wahlström et al., 1999).

For organic substances, no MPE values are given because there is no consensus concerning suitable leaching test methods. In the case of organic substances, environmental competence can be defined only by a comparison with the target values of soil and a detailed risk assessment procedure.

The composition of the material is compared also with the limit values of soil. If these values are exceeded, the definition of the environmental competence should not be based exclusively on solubility, but the stability of the material (possible changes in properties), other transportation routes and possible direct exposure routes (e.g. inhalation of dust during construction etc.) have to be taken into account.

3. The definition of the solubility standards (MPE values)

3.1 Materials and methods

To define the MPE values for metals, Dutch leaching models (Aalbers et al., 1996) were used. These are based on extrapolation and interpolation of laboratory scale measurements and the definition of a maximum permissible load to soil. The definition of the acceptable load is based on the target values of soil. In the calculations, parameter values describing conditions in Finland e.g. soil characteristics, weather conditions and the properties of by-products were employed. The information about the values was gathered from several sources and calculations were done by using a Monte Carlo technique. Separate MPE values were calculated for different applications (granular vs. prefabricated material, uncovered vs. covered structure). The time scale was fixed to 100 years and the thickness of the by-product layer to 0.7 m. Different MPE value alternatives were created by modifying the parameter values, which describe the "permissible load" i.e. the acceptable increase of the concentrations in the soil underneath a by-product structure (• , % compared with the target values of soil) and the height of the soil layer below a by-product structure (h_s, m), Conservative values i.e. • = 1% and h_s = 0.2 m were used as a starting point.

Finnish soil is both horizontally and vertically very heterogeneous. The main soil type is sandy till, which represents 75% of all tills (Koljonen, 1992). Altogether 54% of the total land area is covered by till in thick layers. The MPE values were derived only for the soil type till.

A sensitivity analysis was done in order to test the sensitivity of the calculated MPE values to parameter variations. For some metals, the target values of soil have been defined according to the clay and organic matter content, which is one of the reasons why the sensitivity analysis had to be done separately for each individual substance.

For sulfate and chloride, for which no soil target values exist, the MPE values were derived from the national quality standards issued for domestic water. The national target value of chloride is 25 mg l^{-1}. The corresponding quality criteria of sulphate is 150 mg l^{-1}.

The sample size in the Monte Carlo calculations was defined according to the acceptable uncertainty of the medians of the MPE values. Here, the range of +/-2 percentiles was selected leading to a sample size of 2500.

3.2 Decision analysis

The best alternative of the MPE values of metals was defined by using a SMART method (Simple Multi-attribute Rating Technique) and the methodology employed in the previous study concerning the selection of a water supply system (Tenhunen & Seppälä, 1996). The SMART method is described in detail by Von Winterfelt and Edwards (1986). Along with the environmental risk, social and economical benefits e.g. the saving of natural resources and landfill space, construction costs as well as social disadvantages were taken into account (Fig. 1).

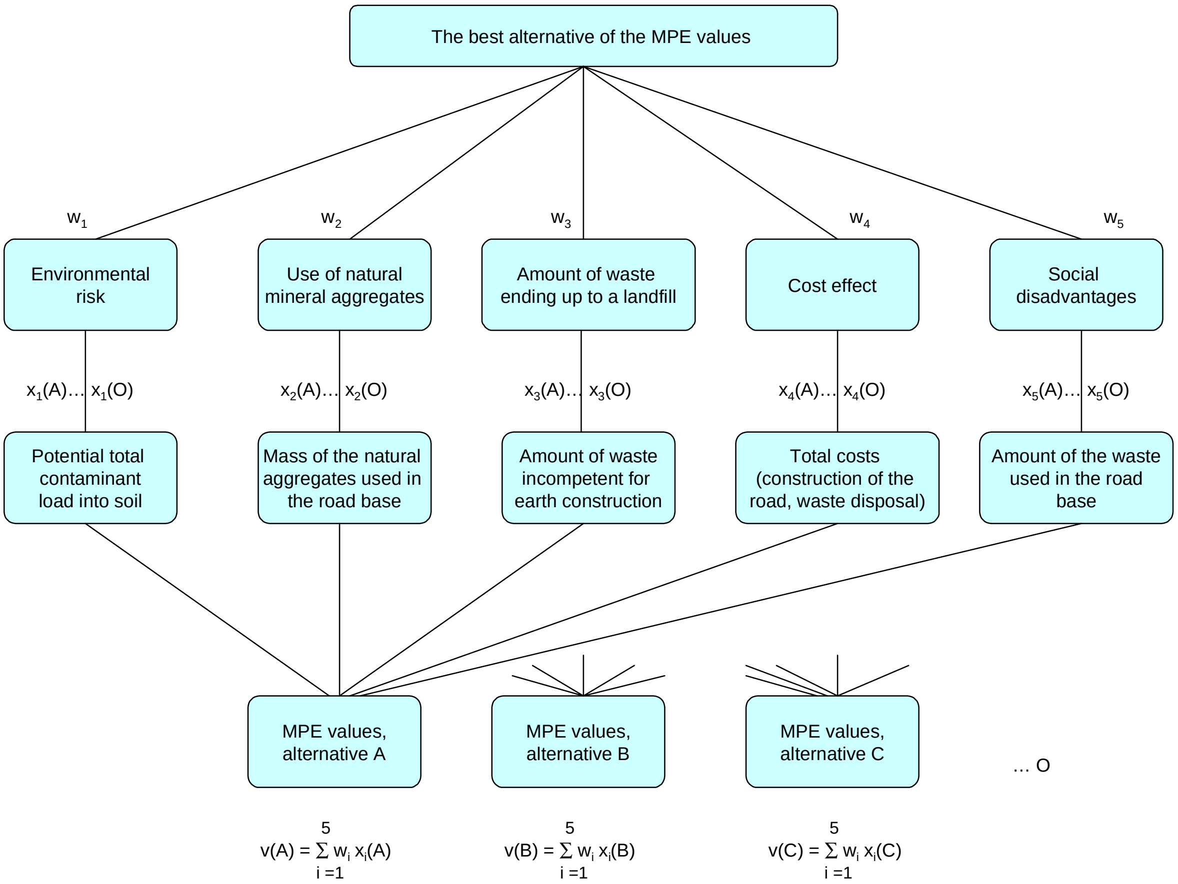

Figure 1. The decision criteria used in the decision analytical study of the different solubility standards i.e. MPE (Maximum Permissible Emission) value alternatives (A…O). w_i = weighting coefficient of an individual decision criteria i (i = 1…5), $x_i(A)… x_i(O)$ = indexed numerical value of a decision criteria i (i = 1…5) corresponding an individual MPEs alternative (A…O), v(A)…v(O) = total value of the individual MPEs alternative (A…O).

In the indexing (to a range from 0 to 100) of the decision criteria values, a linear regression was assumed for all criteria. The sum of the indexed values (x_i) multiplied by the criteria-specific weighting factor (w_i), represent the total value of the individual MPEs alternative. This value describes the superiority of an individual alternative compared with the other alternatives.

The analysis was executed for a 12 m wide road structure containing either natural mineral aggregates (sand, gravel), fly ash from coal combustion or crushed concrete in the base course. The data concerning the consumption of the materials was taken from the previous life cycle assessment report (Eskola et al., 1999). Several experts representing material producers and waste management and construction companies were interviewed in the collection of the data concerning the costs of construction and landfill disposal.

In the definition of the values for the decision criterion “amount of waste ending up to a landfill”, it was assumed that all the material, which is not environmentally competent (i.e. at least one of the MPE values is exceeded) is disposed in a landfill. The value of the decision criterion “social disadvantages” was assumed to correspond the amount of the recycled by-product.

The derivation of the separate MPE alternatives was based on the variations of the parameters • and h_s (see above) and the prognosis of the recycling competence (% of the total mass of the by-product produced) of the fly ash and crushed concrete in the different structure types (paved, unpaved, granular material, prefabricated material). The prognosis was based on the results of previous leaching tests collected from several information sources around the country.

Only environmental authorities i.e. representatives of the Ministry of the Environment took part in the weighting of the decision criteria. Since the study aimed at the definition of national environmental criteria, in which task the Ministry is the responsible instance, the involvement of other stakeholders e.g. the representatives of industry, the users of by-products etc. was considered unnecessary.

3.3 Results

According to the sensitivity analysis, the key parameters in the definition of MPE values are those which define the acceptable load into the soil underneath a by-product structure i.e. parameters • , h and h_s. For covered (paved) structures, also the time scale (J) was critical. In the case of a prefabricated material, the density of the soil was decisive as well. When all the parameters which define the acceptable load (J, • , h, h_s) were standardized, the density of the soil and by-product, substance-specific constants describing the rate of leaching (•), and the infiltration rate (N_i, mm a^{-1}) were identified to be the key parameters. In the case of a prefabricated material, correction factors which take weather conditions into account (f_{ext} and f_{tem}) were also important. The results of the sensitivity analysis depend significantly on the selection of parameter values (e.g. extreme values, statistical variables and the shape of the distribution).

In the decision analysis, the criterion "environmental risk" received a weighting coefficient 0.75 and the criterion "use of natural mineral aggregates" coefficient 0.25, correspondingly. The coefficient of 0 was given to the other criteria. In the final definition of the MPE values, especially aspects like the type of the land use and the uncertainties of the analytical methods (soil and waste analyses, leaching tests) were considered. The non-uniformity of the national target values was taken into account as well. The resulting MPE values correspond the marginal load defined as “a load that can cause a 5% increase of concentrations (clean soil) in the 1 m thick soil layer underneath a by-product structure”. Due to the non-uniformity of the national target values, the Dutch target values were used in the calculation of the MPE values of Ba, Co, Ni, Sb, and Sn. The final MPE values are presented below (Table 1).

Table 1. Proposal of the solubility standards for the by-products used in earth construction.

Substance	*Granular material* Uncovered, mg kg^{-1}	*Granular material* covered, mg kg^{-1}	*Prefabricated material* mg m^{-2}
As	*0.14*	*0.85*	*58*
Ba	10	28	2800
Cd	0.011	0.015	2.1
Co	1.1	2.5	280
Cr	2.0	5.1	550
Cu	1.1	2.0	250
Hg	0.014	0.032	1.6
Mo	0.31	0.50	70
Ni	1.2	2.1	270
Pb	1.0	1.8	210
Sb	0.12	0.40	36
Se	0.060	0.098	14
Sn	0.85	3.1	280
V	2.2	10	700
Zn	1.5	2.7	330
F	11	25	2800
CN, free	0.060	0.098	14
SO_4	1500	-	-
Cl	250	-	-

4. Conclusions

Based on the study, new national environmental criteria for the use of by-products in earth construction were proposed. The final solubility standards differ from the corresponding Dutch values and are mainly less strict than the solubility standards issued in some other countries (Table 2). The distinction is due to differences between 1) the analytical methods (especially between leaching tests) 2) the bases, foundations, methods and principles of the assessment and definition of risks/load and 3) the risk management and waste management policies.

The disparities between the proposed Finnish criteria compared with the corresponding Dutch values are mainly due to the differences in the target values of soil, and in the parameters describing the acceptable load and environmental conditions. Especially the standards issued for covered (paved) structures differ from the corresponding Dutch ones. This is due to the different infiltration rates used in calculations. In this study, the value of 34 mm a^{-1} was employed for the infiltration through covered structures. This represents 10% of the infiltration rate through unpaved structures. In the Netherlands the corresponding value was 6 mm a^{-1}.

Table 2. Some solubility standards for the use of by-products in earth construction, issued in different countries (mg kg^{-1}). All values have been transformed to equivalent units by using the L/S-ratio of the corresponding leaching test. a) uncovered b) covered structures. References: ÖNORM S 2072 1990; LAGA 1995; Aalbers 1996; Department of Natural Resources 1999; Rasmussen 1999.

Substance	Finland		the Netherlands		Germany, dw		fs	Austria	Denmark	USA, Wisconsin	
	a)	b)	a)	b)	a)	b)	b)	a)	b)	a)	b)
As	0.14	0.85	0.88	7.0	0.10	0.50	0.60	1.0	0.016	0.20	10
Ba	10	28	5.5	58	-	-	-	10	0.60	16	40
Cd	0.011	0.015	0.032	0.066	0.02	0.10	0.10	0.05	0.0040	0.020	0.10
Co	1.1	2.5	0.42	2.5	-	-	1.5	1.0	-	-	-
Cr	2.0	5.1	1.3	12	0.30	-	3.0	1.0	0.020	0.40	2.0
Cu	1.1	2.0	0.72	3.5	0.50	2.0	-	10	0.090	5.2	26
Hg	0.014	0.032	0.02	0.076	0.0020	0.020	-	0.020	0.00020	0.008	0.040
Mo	0.31	0.50	0.28	0.91	-	-	1.5	-	-	-	-
Ni	1.2	2.1	1.1	3.7	0.50	1.0	2.0	1.0	0.020	0.80	2.0
Pb	1.0	1.8	1.9	8.7	0.40	1.0	-	1.0	0.010	0.06	0.30
Sb	0.12	0.40	0.045	0.43	-	-	-	-	-	-	-
Se	0.06	0.098	0.044	0.10	-	-	-	0.50	-	0.4	0.10
Sn	0.85	3.1	0.27	2.4	-	-	-	10	-	-	-
V	2.2	10	1.6	32	-	-	6.0	2.0	-	-	-
Zn	1.5	2.7	3.8	15	1.0	4.0	10	30	0.20	100	200
F	11	25	13	100	-	-	-	30	-	32	80
CN, free	0.06	0.098	0.013	0.076	-	-	-	0.20	-	1.6[1]	4.0[1]
SO_4	1500	-	750	22000	1500	6000	-	varies [2]	500	5000	10000
Cl	250	-	600	8800	200	1500	-	varies [2]	300	5000	10000

dw = demolition waste, fs = foundry sand; [1] total cyanide; [2]depends on the electric conductivity

Concerning some traditionally utilized by-products, the use of a non-prefabricated fly ash from coal combustion will be limited. Especially the conentrations of soluble selenium and molybdenum usually exceed the proposed MPE values except in the case of a prefabricated i.e. stabilized material. Further studies are needed in order to find out the significance of the Se and Mo load. According to the results of the previous leaching tests, water-cooled blast-furnace slag and crushed concrete can be considered environmentally competent.

The Dutch method, which was used for the derivation of MPE values, has the disadvantage of being very sensitive to the parameter values for which no "right" values - based on scientific facts - can be defined (refers to the parameters, which specify the acceptable load into soil). The definition of the MPE values of prefabricated structures is based on simple equations and the results are very sensitive to the definition of some correction factors describing the environmental conditions. Further more, mixture effects, speciation and the effects of different pH values is not taken into account. The definition of the permeability in the case of paved road structures is problematic because of the possible crack formation and infiltration through ramps.

The quantitative data concerning the chemical properties of Finnish by-products was somewhat inadequate. The national target values of soil need to be unified. Also, the knowledge of the adaptation of soil organisms, mixture effects, the accuracy of leaching models and the long-term behavior of soluble substances is insufficient.

The proposed environmental criteria is used as a basis in the preparation of the Council of State Decree, by which some by-products are exempted from a permit process. Along with this preparation work, the development of quality assurance procedures is ongoing.

Acknowledgements

The financial support of the National Technology Agency (TEKES) and the Finnish Ministry of the Environment is gratefully acknowledges.

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Testing of by-products in earth construction

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ABSTRACT: This article gives a very brief description of some demonstration projects carried out using different by-products, demolition waste (crushed concrete, brick rubble, crushed stone wool), coal fly ash, old asphalt pavements, blast-furnace slag, granulated peat fly ash, plastic waste, hematite, stabilised paper mill fibre sludge, etc. Test structures were built either as trial structures or as functional parts of real construction projects. The structures were built in accordance with general rules set by the pilot construction project team of Tekes's Ecogeotechnology R&D program, and were instrumented to measure and follow up the behaviour of the structure and materials. General remarks have been made on the usefulness of the field tests as a research tool in the chain from waste to construction material.

1. Introduction

From the outset of the Ecogeotechnology R&D program it was realised that various positive actions would be needed to encourage different parties in the earth building community to use industrial by-products in earth and road construction. To encourage the materials industry, as well as potential users, the National Technology Agency of Finland (Tekes), has given financial support for pilot construction in the form of demonstration projects.

After laboratory tests have been carried out to clarify the technical properties and leaching performance of the by-products, the R&D program has guided and helped companies to perform field demonstrations. Some of the test structures were built as functional parts of real construction projects. The structures were built in accordance with general rules set by the pilot construction working group. The structures were instrumented to measure and follow up the behaviour of both the structure themselves and the materials used in them. In order to encourage other companies and builders to use by-products, every pilot construction case will be reported publicly.

2. Testing programme

Crushed concrete, brick rubble, crushed rock wool, coal fly ash, old asphalt pavements, blast-furnace slag, granulated peat fly ash, plastic waste, hematite and stabilised paper mill fibre sludge were used in the test structures.

The index and technical properties of the materials relevant to the usage of the site in question were studied prior to the pilot construction. Research methods for soils and other conventional materials were used in the laboratory studies.

In the case of each pilot construction project, the local environmental authorities were informed. It was generally not necessary to apply for an environmental permit owing to the experimental nature of the construction. In order to assess the environmental acceptability of the materials, at least total content determinations and some leaching tests were carried out. These results were sent to the environmental authorities in connection with the permit application. As a rule, the initial situation with regard to the pilot construction site, its soil and groundwater was studied in order to observe any environmental effects that the use of a recycled material might have.

The structures of the pilot construction sites were generally designed by the consultant of the project in question in collaboration with the material supplier and client. The consultant was generally responsible for planning the follow-up measurements of the structures and for the practical implementation of the measurements in accordance with general rules set by the pilot construction programme.

A section of each pilot construction site was generally built using conventional materials and structures to serve as a reference.

Measurements and observations were made during the building work on all of the construction sites. The aim was to clarify the behaviour of the materials during the construction work and to ensure that the test structures were built as designed. The completed structures were instrumented so that the behaviour of the structures in normal service conditions (traffic loads, effects of weather, etc.) could be measured. In addition, environmental effects were clarified by means of on-site measurements and laboratory studies on samples.

A detailed report has been made on each pilot construction site. Each report contains information on the site and the material used as well as observations made during construction and the results of follow-up measurements. The reports also include conclusions on the behaviour of the structures, although in many cases these are based on the results of observations for only one year. Each site-specific report has been prepared by VTT on the basis of the measurements, observations and a report submitted by the consultant responsible for the site's design and follow-up.

Altogether 21 pilot constructions were made (Table 1). The first sites were built in 1997 and the last in summer 1999. Some of the pilot construction sites are very briefly described in this paper.

*Table 1. Pilot construction sites (***Bolded** *cases are included in this paper).*

Code		By-product	Test structure
MUK-	**1**	Crushed concrete BETOROC	Street
MUK-	**3**	Crushed concrete BETOROC	Road widening, bearing course
MUK-	**5**	Brick rubble	Light traffic lane and court yard
MUK-	**6**	Granulated peat ash	Street, insulation layer
MUK-	**8**	Granulated peat ash	Light traffic lane, insulation layer
MUK-	9	Steel slag	Test embankment
MUK-	**10**	Reclaimed asphalt	Street, wearing course
MUK-	11	Coal fly ash	Road, bearing course
MUK-	**12**	By-product from pigment industry / FINNSTABI	Local road, improvement of wearing course
MUK-	**13**	Hematite	Road, asphalt wearing course
MUK-	**14**	Plastic waste	Road, asphalt wearing course
MUK-	**16**	Coal fly ash + flue gas desulphurisation residues	Local road, improvement of bearing course
MUK-	17	Crushed stone wool	Light traffic lane, frost protective layer
MUK-	**18**	Granulated blast furnace slag	House building, fills
MUK-	**19**	Paper mill fibre sludge	Landfill, capping
MUK-	**20**	Coal fly ash + paper mill fibre sludge	Local road, wearing course
MUK-	**21**	Coal fly ash + blast furnace slag + FINNSTABI	Local road, wearing course
MUK-	**22**	Coal fly ash / grate ash + FINNSTABI / cement	Local road, improvement of wearing course
MUK-	24	Coal fly ash	Harbour yard, light fill
MUK-	25	Sludge (CC-stabile) + peat burning ash	Local road, improvement of wearing course
MUK-	26	Bark burning ash + steel slag	Local road, improvement of wearing course

2. Test results

Crushed concrete BETOROC

On the first site the pilot construction material was Lohja Envirotec's BETOROC crushed demolition concrete (unscreened and screened 0–50 mm). This was the first time that crushed demolition concrete had been used on a street construction site in Finland. The crushed concrete was used as a substitute for crushed stone in the bearing course.

The pilot construction materials on the second site were crushed concrete from reject hollow-core concrete slabs of a concrete element factory and from concrete railway sleepers. The particle size distribution of the crushed material was 0–50 mm. The crushed concrete was used in the structures as such. The crushed concrete was used as a substitute for crushed stone or aggregate in the bearing course of the road-widening pilot construction site.

Crushed concrete proved to be a very good road or street building material. The bearing capacity of the crushed material improved after construction because the concrete still retained some ability to reharden.

Instructions on the use of crushed concrete in road and street constructions have been prepared.

Brick rubble

The pilot construction material was brick rubble produced by Lohja Envirotec from the demolition waste of brick buildings. The particle size distributions of the screened and unscreened crushed material were 0–50 mm and 0–70 mm, respectively. The brick rubble used on the pilot construction sites substituted for gravel in the sub-base of a light traffic lane and court yard.

In bearing capacity measurements of the light traffic lane in the spring (after one winter) there were clear signs of frost damage in both the structural courses and the subgrade. Factors lowering the bearing capacity could include the moisture content of the brick rubble being raised above the level prevailing at the time of construction, some degree of particle size reduction occurring in the brick rubble, or loosening of the structure possibly due to consolidation of the subgrade. Brick rubble is more suitable for use in the filter course than in the sub-base.

The widespread use of brick rubble should be avoided in heavily loaded structural components and courses in which it would be subjected to moisture and freezing.

Granulated peat ash

Granulated ash from Tampere peat-fired power plant and from the process of Kuopio peat-fired power plant was used as a test material on a street construction site and a light traffic lane construction site, respectively. The ash from Kuopio contained industrial lime (5–6%) as a binder. The material was granulated using a continuously operating drum granulator (prototype). The purpose of the granulation and the binder was to improve the earth construction properties of the ash. Preliminary tests suggest that granulated peat ash has potential as a earth construction material.

The granulated ash was used on the street construction site as an insulation and filter course (thickness 50 cm). In the case of the light traffic lane the granulated peat ash substituted for sand in the filter course (thickness 30 cm). It became apparent already during the course of construction that the granulated peat ash was of poor quality and inferior to the granules used in the preliminary tests.

The pilot construction indicated that granulated peat ash produced by the prototype granulation method had extremely limited possible applications in earth construction.

Reclaimed asphalt

Two types of reclaimed asphalt were used as pilot construction materials:

- Freshly milled (not stockpiled) asphalt from as old pavement. The material was stored for only a very short period of time. The asphalt pavement from which the material was milled had been laid 6–7 years earlier.
- Crushed asphalt from the contractor's storage depot. Crushed asphalt is a material collected over a longer period of time from an assortment of sites. The variations in its quality can be great.

In the recycled asphalt pavements (AB18 wearing course and ABK18 bearing course) some of the virgin raw materials were replaced by milled or crushed asphalt, the amount of which varied between 20% and 60%.

Observations of the test sites suggest that the use of recycled asphalt in street construction is a usable solution.

The revised quality requirements for recycled asphalt included in the new Finnish Asphalt Specifications 2000 make them more appropriate as far as the functional properties of the pavement and practical work are concerned. This should promote the more widespread use of recycled asphalt in the future.

Coal fly ash

Fly ash (FA) and bottom ash (BA) from Fortum Oy's Meri-Pori coal-fired power plant were used as pilot construction materials. The fly ash was used in a cement-stabilised (6%) sub-base on a main road and at junctions. At the road junctions a cement-stabilised mixture of fly ash and bottom ash (FA 40% / BA 60%) was also used in the bearing course. The filter course of the junctions was made using bottom ash.

This pilot construction site is dealt with in greater detail in another paper of this conference: Juvankoski, M., Laaksonen, R. and Tammirinne, M. Testing of long-term geotechnical parameters of by-products in laboratory.

By-product from the pigment industry FINNSTABI

The improvement in frost resistance and spring bearing capacity of an old gravel road by means of a material called FINNSTABI was studied on this pilot construction site. FINNSTABI is processed from a by-product of Kemira Pigments Oy's Pori works. Prior to the pilot construction, serious serviceability problems had arisen on the site during the spring thaw period. In order to eliminate these problems, two different types of stabilised solutions were tested: a robust slab-like solution and, as an alternative to it, a looser and more flexible solution. A new 10 cm thick wearing course was laid on top of the stabilised courses.

Assessed on the basis of bearing capacities measured from the road surface, the stabilised solutions gave a 10...30% better improvement in the bearing capacity than the conventional repair method. Even though the targets set for the quality of the test structures were not achieved in all respects, the solutions nevertheless improved the service level and bearing capacity of the road during the spring thaw period.

Hematite

The limestone powder and pulp fibre used in the SMA asphalt pavement were entirely replaced by hematite filler in the pilot construction site. The hematite filler is an almost pure iron oxide filler (iron oxide 95% Fe_2O_3) generated as a by-product of sulphuric acid production at Kemira Chemicals Oy's apatite mine.

The results obtained from the test pavement indicate that hematite filler is suitable for use in asphalt. However, there was no evidence that the use of hematite filler resulted in any clear technical improvements in asphalt quality. The results indicated that hematite does not accelerate the ageing of bitumen. The iron colour of the hematite filler poses a slight problem in practice. The iron colour tends to cause a rust-like reddish discoloration of white road marking material.

Plastic waste

Soft asphalt concrete PAB-B16 with binder B600/900POL + plastic waste was used in the test pavement. Plastic waste (6% or 8%) and tall oil pitch (12%) was added to the binder, so altogether about 20% of the bitumen was replaced by recycled materials. The plastic used was 100% polyethylene waste plastic collected from agriculture. The plastic was pre-ground and most of its impurities removed.

The use of plastic in the PAB-B pavement has a favourable effect on the low-temperature and deformation resistance of the pavement. The pavement's water resistance was good. The studies suggest that the use of soft plastic asphalt on minor roads with low traffic volumes is a possible but still technically incomplete solution.

The plastic binder as manufactured for use in this field test does not meet the present quality requirements set for the binders of asphalt pavements. Before plastic can be used more widely as an asphalt pavement binder, the emissions generated in the laying of plastic asphalt will also have to be reduced.

Coal fly ash + flue gas desulphurisation residues

Fly ash produced in Helsingin Energia Oy's coal-fired power plant and desulphurisation residues from the cleaning of flue gases were used as pilot construction materials. The fly ash and flue gas desulphurisation residues were used in the sub-base and bearing course of the road. Fly ash taken directly from a silo was used alone in the sub-base and filter course. A mixture of fly ash and desulphurisation residues (FA/ DR: 75% / 25%) as well as cement-stabilised (5% cement), stockpiled fly ash were used in the sub-base and bearing course.

The compressive strengths of samples taken from the structure after the first winter (10...11 months after construction) agreed relatively well with the strengths of 28-day-old samples subjected to preliminary testing in the laboratory. The frost penetration depths during the first winter of observation were at most about 3/4 of the frost depth in the reference structure. The water contents of the materials had risen during the first winter 15...20%-points above the levels when the structures were sealed. The structures were well drained so the principal cause of the rise in water content was the hygroscopicity of the materials.

In the first year the performance of the test structures has been approximately in accordance with the targets set for them. However, the moisture content rise in the fly ash structure may detrimentally weaken the bearing capacity of the structure in the future.

Crushed stone wool

Crushed stone wool produced as by-product of the manufacture of insulation materials at Partek Paroc Oy Ab's factories was used as a pilot construction material.

This pilot construction site is dealt with in greater detail in another paper of this conference: Höynälä, H., Mäkelä, H., Krankka, J. Design of soil structures using crushed stone wool insulation.

Paper mill fibre sludge

Homogenised fibre sludge from UPM Kymmene Oy's Jämsänkoski paper mill and a mixture of fibre sludge and cement (6%) were used as the sealant material in an experimental groundwater protection structure for a waste treatment centre's waste treatment area. The water content of the sludge was 134% and the loss by combustion 59.4%. The technical properties of the fibre sludge were clarified in preliminary studies. The aim was to study the possibilities of using fibre sludge as the waterproofing layer of a groundwater protection structure with a water permeability requirement of less than $1*10^{-9}$ m/s.

Construction took place in summer 1999 and in infiltrometric measurements made in the following autumn an average water permeability of $3.3*10^{-9}$ m/s (range $2.4*10^{-9}$... $3.9*10^{-9}$ m/s) was obtained. The average water permeability obtained in the laboratory from corresponding samples was $4.2*10^{-9}$ m/s (range $4.0*10^{-9}$ ... $4.4*10^{-9}$ m/s).

The development of the structure’s water permeability and tightness continues to be monitored.

Coal, wood and peat fly ash + paper mill fibre sludge

The use of cement-stabilised fly ashes and mixtures of de-inking waste and fly ash as a means of improving the frost resistance and spring bearing capacity of old gravel roads was studied on pilot construction sites. The pilot construction materials used were:

- a mixture of fibre and fly ash from the combustion of wood and peat at the Kaipola mill of Fort James Suomi Oy and UPM Kymmene Oy (mixture ratio: 30 parts fly ash, 100 parts fibre)
- a mixture of fibre and Metsä Tissue Oy’s de-inking waste and fly ash from Mäntän Energia Oy’s peat-fired power plant (mixture ratio: 55 parts fly ash, 45 parts fibre)
- a mixture of fly ash and fibre waste from UPM Kymmene Oy’s Jämsänkoski mill (mixture ratio: 100 parts fly ash, 20 parts fibre)
- fly ash from the combustion of wood and peat at UPM Kymmene Oy’s Kaipola and Jämsänkoski mills

Cement (4–7%) was used as a binder in all of the mixtures.

Prior to the pilot construction, serious bearing capacity problems arose during the spring thaw period on the road selected as the test site. In order to remedy these problems, slab-like solutions of varying stiffnesses made from different material mixtures were tested on the pilot construction site. Fibre/fly ash structures were used on three of the site’s test sections and fly ash alone on two sections.

After the first year of follow-up measurements, the measured bearing capacities indicated that the effectiveness of the repair made using the fibre/fly ash structures was approximately the same as with the conventional repair method. On the other hand, the effectiveness of the stabilised fly ash was better than the conventional repair method. The recycled material structures have performed more or less in the desired manner during the first year of observation. Repair of the pavement structures has improved the road’s service level and bearing capacity during the spring thaw period.

Coal fly ash + blast furnace slag + FINNSTABI

The pilot construction materials used in the course stabilisation were coal fly ash from Fortum Oy’s Meri-Pori power plant together with blast furnace slag as the binder. Fly ash from Fortum Oy’s Meri-Pori power plant and UPM Kymmene Oy’s Rauma mill were used in the fly ash structures. Nordkalk Oy’s FINNSTABI mixture was used as a binder in both.

Prior to the pilot construction, serious problems arose during the spring thaw period on the road selected as the test site. In order to remedy these problems, slab-like solutions (thicknesses 20...35 cm, compressive strengths 0.4...3 MPa) of varying stiffnesses made from different materials and material mixtures were tested on the pilot construction site. Course stabilisation was used on two of the site’s test sections and stabilised fly ash on the other two sections. A new 10 cm thick wearing course was laid on top of the stabilised courses.

After the first year of follow-up measurements, the bearing capacities measured from the road surface indicated that the effectiveness of the repair made using the course stabilisation structures was almost the same as with the conventional repair method.

The effectiveness of stabilised fly ash was better than the conventional repair method.

The recycled material structures used on the pilot construction sites have mainly performed in the desired manner during the first year of observation, and have improved the road's service level and bearing capacity during the spring thaw period. However, some of the fly ash structures began to soften considerably during the spring thaw period and the condition of the road deteriorated to such an extent that the part of the structure had to be removed and replaced by crushed aggregate. The problems were probably caused by excessive water content of the fly ash during construction and the structure being more loosely constructed than had been planned.

Coal fly ash / grate ash + FINNSTABI and cement

The pilot construction materials used were:

- coal fly ash from Lahden Lämpövoima Oy's thermal power plant with Nordkalk Oy's FINNSTABI mixture as the binder
- fly ash from Enso-Gutzeit Timber Oy's Anjalankoski mill (fuels: bark and wood) with cement as the binder
- unstabilised fly as from UPM Kymmene Oy's Voikkaa mill (fuels: bark and sludge)
- stockpiled grate ash from Myllykoski Paper Oy's mill (fuels: coal and wood) with cement as the binder

Besides poor bearing capacity, the main problems with the road selected as the pilot construction site were edge problems associated with the widening of the road towards lateral ditches and gradual mixing of the structural courses with the subgrade. In order to remedy these problems, slab-like solutions of varying stiffnesses (thicknesses 20...25 cm, compressive strengths 1.5 ... 3 MPa) made using the above-mentioned materials and material mixtures were tested on the site. A new 10 cm thick wearing course was laid on top of the stabilised courses.

After the first year of follow-up measurements, the measured bearing capacities indicated that the effectiveness of the repair made using the fly ash structures was almost as good as that achieved by the conventional repair method. The grate ash structure had a weaker bearing capacity than both the other fly ash structures and the reference structures. Visual observation suggests that the most of the road's bearing capacity and edge problems have been solved and that the general condition of the road has remained significantly better than before.

3. Concluding general remarks

3.1 Prerequisites for the use of recycled materials

The prerequisites for the use of recycled materials in earth construction include the following:

- the material's use will not exceed the permitted level of environmental damage both during service and thereafter
- the material's use will not pose any health and safety risks for employees
- the material's technical properties are known to the degree of accuracy and reliability required for the design of the structure in question
- the material's technical properties are such that a structure made from the material will satisfy the functional performance requirements set for it over its entire design service life
- the designed structure can be built from the material using available machines and methods
- the material's use is economically justified

Reliable clarification of several of the above-mentioned factors is possible only by constructing full-scale test structures that will be subjected to the correct loadings and actual climatic conditions. In particular, clarifying the effects of climatic conditions (e.g. frost, moisture) requires follow-up measurements over a number of years.

Before building full-scale test structures it would often be appropriate to study the behaviour of the recycled material using smaller-scale structural tests under tightly controlled and controllable conditions (laboratory conditions). However, it is seldom possible to make such tests because of the high costs involved.

3.2. Practical implementation of pilot construction

In many cases it proved to be difficult to link pilot construction with actual building projects. The project schedule from the decision to build to the actual construction stage was often so short that there was not always enough time to carry out the material studies sufficiently thoroughly in cases where these had not be done earlier during the material's product development.

Measurements and other observations made during the construction work hampered and retarded the normal rhythm of building work so that the research project was in some cases regarded as a nuisance by the site workers. In addition, changes necessitated by the use of the recycled material and the pilot construction also slowed down the building work in some cases.

In several cases follow-up measurements of sufficient detail for the purpose of drawing conclusions were made for only one year. However, the behaviour of some structures should be monitored for a number of years in order to draw reliable conclusions. An observation period of just one year is far too short to assess the long-term performance of structures because climatic conditions, especially frost in Finnish conditions, is a very significant factor affecting the long-term condition of structures. In many cases, however, arranging the finance necessary for long-term follow-up has been difficult.

In many cases the structures have been variously instrumented to measure their behaviour. However, after only one year's observation the performance of these instruments and the measurements obtained from them proved to be such that it was not possible to draw unambiguous conclusions about the behaviour of the structure. In many cases visual observations of the structure's behaviour were sufficient for performance assessment, bearing in mind the nature of the projects (demonstrations of the use of recycled materials).

Groundwater and soil samples were taken in order to observe any environmental effects that the use of the recycled materials might have on the soil and groundwater. However, it was difficult to interpret the results of the analyses because, for instance, it was not always precisely known whether some pollutant had actually originated from the recycled material or whether it had come from some other source (e.g. chloride from winter road salting). In some cases the environmental authorities required as a condition of the operating permit the installation of lysimeters beneath the recycled material structures. However, the water permeability of several of the recycled material structures, especially the stabilised courses, is so low that hardly any water seeps through the structure during the first 1–2 years.

It is very difficult to obtain useful cost data on the use of new materials from pilot construction sites. The costs in pilot construction are always higher than in normal construction. It is generally required for the use of recycled materials that their use is not more costly than the use of conventional materials unless the performance of the structure is clearly improved as a result. However, the performance of a structure cannot be reliably assessed until after long-term follow-up measurements have been made. Life cycle cost analyses might promote the use of a recycled material if a sufficiently simple and reliable procedure were available for such analyses.

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Large size tyre chips in structures submitted to traffic loads

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ABSTRACT: In this article some preliminary results from a study of the use of tyre chips as lightweight fill in a yard embankment is presented. In Finland two types of tyre chips are produced. So far only the smaller one has been used in structures submitted to traffic loads. The goal of the study was to investigate if the larger tyre chip also could be used in such applications. In a test area both large and small sized tyre chips were used. The test site is situated in Turku, Finland. Constructions of the layers progressed smoothly for both tyre chips sizes. The tyre chips layers experienced large deformations immediately after the upper layers were constructed. After this the deformations have been very small. Somewhat surprisingly larger bearing capacities were found in the area built using the larger tyre chips. The experience gained showed that the larger tyre chip can be used instead of the smaller one in some applications.

1. Introduction

Old waste tyres is one of the global waste problems of today. In Finland about 2–2.5 million tyres are discarded each year. According to the Finnish legislation (since 1.6.1996) it is no longer allowed to dump old tyres to waste fills while they have to be recycled. The objective is, that 90% of the tyres that are taken out of use annually shall be utilised. Tyres can be used in many ways. They can be retreated or used as energy, construction material or in safety applications like blasting mats. However, new innovation are needed to find good, economical and environmentally safe solutions for the use of old tyres. In principle old tyres represent a potentially cost-effective construction material. Both whole tyres and tyres processed by shredding equipment into smaller can be used. The size of the tyre chips is determined by the design of the shredding equipment and the setting of its cutting mechanism. Small-sized tyre chips can be produced by processing the material more than once through a shredder. In Finland two types of tyre chips are produced; a smaller size chip RR2 (50x50mm^2) and a larger size chip RR1 (300*100mm^2), see Figure 1. So far only the smaller tyre chip (RR2) have been used in structures submitted to traffic loads, while the larger size chip (RR1) have been used in noise banks. However, the costs for producing the larger chip are considerably lower compared to the costs for producing the smaller chip. It would thus be economically beneficial if the larger chip could be used in a more wider range of applications. Herein results from a pilot project where both tyre chips are used as a light weight material under a yard embankment are presented. The goal was to investigate if the larger tyre chip also could be used in structures with higher requirements for bearing capacity.

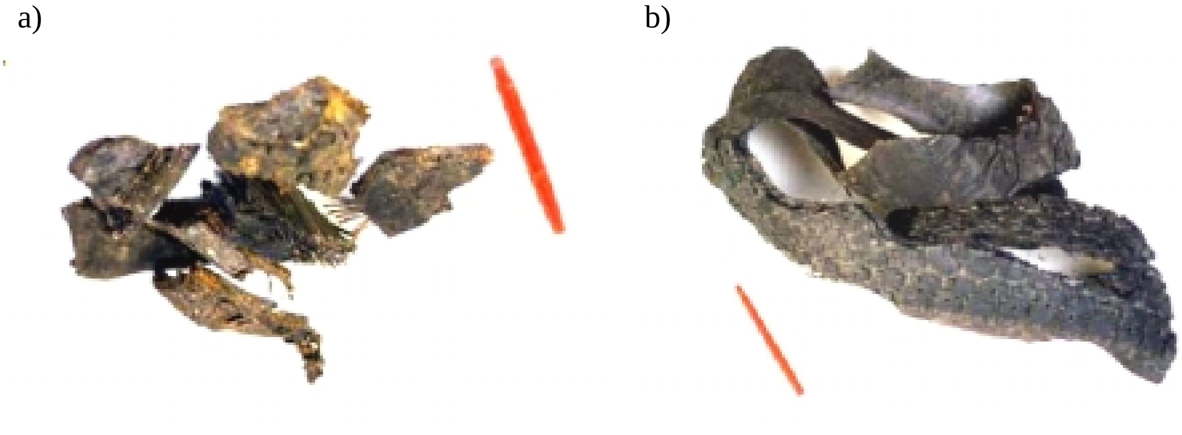

*Figure 1. Tyre chips RR2 (50x50mm^2) a), and RR1 (300*100mm^2) b).*

2. Test field

The test field is a part of an enlargement of the storage yard by Säkkiväline Ltd. and is situated in Saramäki, Turku. The top 5 to 10 meter in the area consists of a soft clay. The traffic in the yard is mainly from heavy trucks and lorries. To reduce the settlements of the storage yard embankment a lighten of the structure with tyre chips was designed. The total area of the new storage yard is 55x110 m^2. RR1 tyre chips was used as lightweight material in a test field 15x32m^2 in size. In the rest of the yard RR2 tyre chips were used.

The thickness of the tyre chip layer in the RR1 test field area and in a comparison test field area with RR2 tyre chips, is 600 mm. To ensure necessary bearing capacity the total thickness of sub-base and basecourse owerlying the tyre chip layers are about 1 m, see Figure 2.

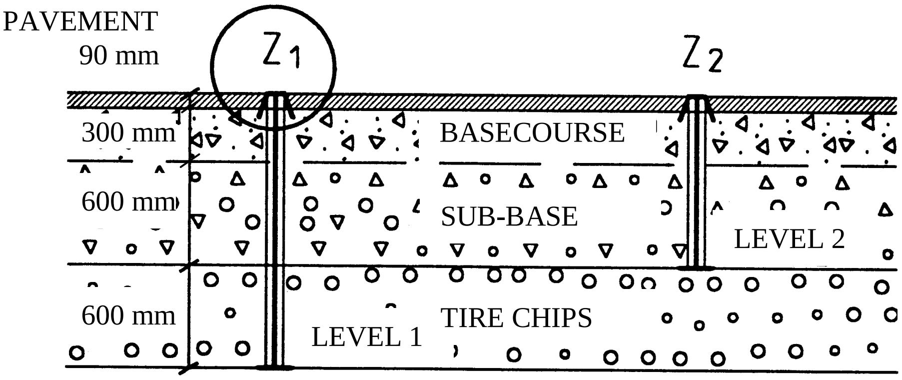

Figure 2. The structure of the yard embankment and the position of the settlement plates.

3. Construction of the yard embankment

The construction of the yard embankment was made in October-November 1998. The construction work progressed smoothly although snow and cold weather delayed the pavement work of the yard. It was faster to build with the larger tyre chips than with the smaller. The larger tyre chip was also easy to compact and it had initially a larger bearing capacity than the smaller one. On the other hand it was easier to build accurate layer thicknesses using the smaller tyre chip. The larger chips also got jammed in the chains of the caterpillar, Figure 3. It would have been easier and faster to spread both materials using a larger pull dozer than the one used (12 t.)

Figure 3. Construction of the RR1 tyre chip layer.

When constructing with tyre chips the upper layers should be laid evenly with relatively thin layers. In the beginning of the construction work a too thick layer was unevenly placed on the top of the tyre chip layer resulting in bulging of the tyre chip layer in the RR2 area, see Figure 4. The compaction of the upper layers were made with a roller.

Figure 4. Construction of the upper layers in the RR2 tyre chip area and the bulging of the tyre chip layer due to uneven overload.

4. Investigations of the test field

4.1 Investigation programme

Since the larger tyre chips (RR1) had not earlier been used in Finland in structures submitted to traffic loads the main goal was to evaluate the bearing capacity of the structure and to monitor the deformations and settlements.

The first measures of the bearing capacity was made with a portable Loadman deflectometer after that 400 mm of sub-base was built. Thereafter a heavyweight deflectometer was used which gives more reliable description of the bearing capacity of the whole structure. The deformations of the tyre chip layers was evaluated using settlement plates mounted at the bottom and the top of the layer, see Figure 2. In addition settlements of the yard was monitored using settlement pins mounted on the pavement layer.

The investigation programme did not include any environmental observations. In earlier investigations made in Finland and in the United States no danger to the environment on the use of old tyres have been found, Repo (1997) and Zelipor (1991).

4.2 Deformations of the tyre chip layer

Four settlement plates were mounted in both the RR1 and RR2 tyre chip areas. The deformations of the tyre chip layer was evaluated from the settlement differences of plates mounted on the bottom an the top of the layer, see Figure 2. The exact initial vertical position of the upper settlement plates were difficult to obtain as the construction of the upper layers caused some disturbances to the position of the plates. The RR1 tyre chip layer was constructed 20% higher than the designed layer thickness and the RR2 tyre chip layer 10% higher than the designed layer thickness to account for the deformation of the tyre chip layer.

According to the measurements the RR1 tyre chip layer deformed about 12–18% and RR2 tyre chip layer about 8–10%. It is worthwhile to note, that the deformations occurred immediately after the tyre chip layers were loaded with the weight of the upper layers. In Figure 5 the measured deformations of the tyre chip layers after the pavement was made are shown. As can be seen, the deformations are very small and close to the measurement accuracy.

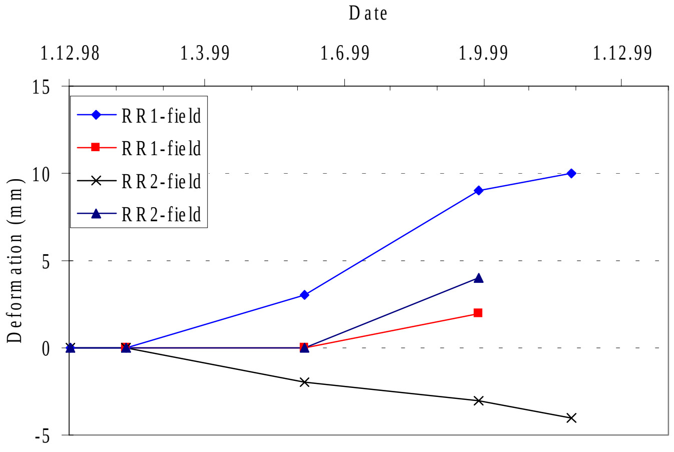

Figure 5. Deformation of the tyre chip layers after the pavement of the yard.

Results from measurements of the settlement pins are shown in Figure 6. As can be seen from the figure the whole area has settled during summer 1999. This consolidation settlement is most likely a result of an additional load due to lowering of the ground water level caused by an exceptionally dry summer.

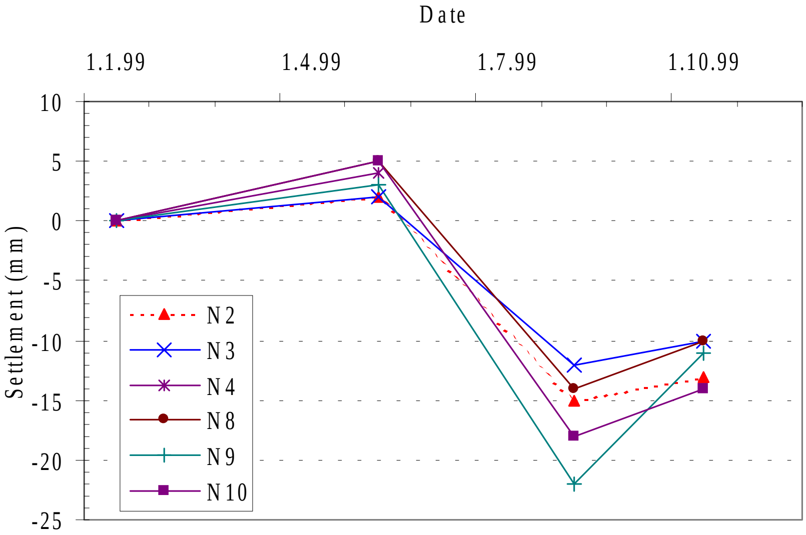

Figure 6. Total settlements measured from the RR1 tyre chip field.

4.3 Bearing capacity

The bearing capacity was evaluated as E2-modulus from the second loading with the deflectometer. The first measurements, made with the portable Loadman deflectometer, are not so reliable as the influence in depth is rather limited for this device. These measurements were made three days after that the upper layer was constructed except for one measuring point at where only one day had elapsed since the construction. The values for the E2 modulus varied between 50 and 74 MPa except for the point in where only one day had elapsed since the construction. In this measuring point the modulus was only 30 MPa due to less compaction work. The ratio between the modulus from the second and the first loading, E2/E1, varied between 1.4 and 1.7.

After that the pavement of the yard was finished the bearing capacity was measured using a heavyweight deflectometer. Measurements were made in the spring and autumn 1999. The average E2 modulus in the RR2 tyre chips area was 80 MPa in the following spring after the construction and 102 MPa in the next autumn. In the RR1 area the E2 modulus were 73 and 68 MPa correspondingly. Maybe somewhat surprisingly the measured bearing capacity was higher in the area constructed with the larger tyre chips. The values are though quite low in both areas compared to what is obtained from conventional yard/road structures. The ratio between the modulus from the second and the first loading, E2/E1 were generally around 1.2.

On the bases of measured bearing capacities back calculations were made to evaluate the E-modulus of the tyre chip layer. The back calculations are only approximate as there is a variation in the realized layer thicknesses of the tyre chip layers. According to the settlement plates the thickness of the tyre chip layers varied between 450 and 730 mm. According to the back calculations the E-modulus of the tyre chip layers varied between 1.5 and 2 MPa. Similar values were also obtained in a previous test road constructed with RR2 tyre chips, Repo (1998). At this site it was found that the bearing capacity increased almost 20% one year after the construction, FinnRa (1999).

5. Conclusions

To reduce the settlements of a enlargement of a storage yard by Säkkiväline Ltd. a lighten of the fill was designed. Tyre chips, produced by Säkkiväline Ltd. was chosen for this purpose. Part of the embankment was constructed using a large size tyre chip RR1 as a pilot test field to investigate the suitability of this material in structures submitted to traffic loads.

The construction work progressed smoothly using both tyre chips. As expected, large immediate settlements occurred after the construction. The RR1 tyre chip layer deformed 12–18% and the RR2 layer 8–12% due to the load from the upper layers. However, the deformations in both areas have been very small after that the work was finished. Somewhat surprisingly the bearing capacity was larger in the area constructed with the larger tyre chip. It can be concluded from the construction work and the measurements that the compaction of the larger tyre chip is not a problem.

The experience from using the larger tyre chip RR1 in this pilot project has been very promising. Further follow-up is though needed to ensure the performance of the material in a longer time period. It should also be tested in structures were the dynamic impact of the traffic load is larger than in storage yards. In addition the environmental impact from using old tyres should be further studied.

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Use of construction and demolition wastes as road sub-base material

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ABSTRACT: In major urban areas, huge generation of construction and demolition wastes comprising of concrete debris creates various problems rendering environmental concern. The debris is produced from demolition of old buildings and structures as well as from new construction projects. The wastes ascertain the need for its proper management so that these can be used effectively and valuably. The paper is the outcome of a research study recently conducted to investigate the possibility of utilizing the concrete debris as road sub-base material. The experimental study to re-use the concrete debris mixed with crushed stone/pebbles (naturally available in abundance in the northern Bangladesh) and waste bricks was carried out in the laboratory and in sites. Defective/unusable waste bricks are available in enormous quantity as industrial waste in the brickfields of the country where brick are manufactured. In this paper, the physical and engineering properties of the compacted mixtures are presented to investigate the feasibility of the materials to use as sub-base course complying AASHTO specification and design criteria. Laboratory and field tests show that the wastes can be used effectively as road sub-base material complying standards and design criteria.

1. Introduction

In Bangladesh, brick aggregates and crushed stone/pebbles are conventional materials for road sub-base. Pebbles/stones are naturally occurring river flown material and available from several rivers in Northern Bangladesh areas. Pebbles/stones are also available in the underground soil layers at shallow depth in some selected areas in a number of districts of Northern Bangladesh, namely, Dinajpur, Panchagar, Sunamganj, Bholaganj, Chattak, Jaflong, Thakurgaon, Nilphamari, Fulbari and Madhaypara. Due to high demand of quality bricks and stones/pebbles for construction works in the country especially in the fast growing cities, these materials are becoming costly. There are brick fields located in a scattered way in the country. Bricks are manufactured in non-rainy and weather-favorable season. The manufacture and supply of bricks are uneven in the context of actual demand, place of need, and time of requirement. Secondly, the limited resources of the stones/pebbles in the country rendering concern about scarcity of the materials in future. Continuous siltation of river bed curtailing the sources of river-flown pebbles/stones and causing difficulties in extraction. So the conventional aggregates are becoming dearth due to difficulties in production, source scarcity and high demand around the country. Thus investigating alternate way for finding road sub-base materials is of great importance.

On the other hand, due to rapid urbanization and scarcity of land especially in the urban areas, old buildings and structures are demolished to build new project. The huge wastes are produced from such demolition works and also during construction of new projects. The increased demolition activities of old structures for rebuilding purpose produces bulk volume of debris which has been identified as an environmental concern associated with unwanted space occupation and other disposing problem as these are discharged haphazardly here and there mostly in the public places. Secondly, every year huge quantities of inferior and unusable bricks are produced from the brick manufacturing fields as waste; these discarded materials also render environmental concern. These waste materials are produced due to insufficient burning, over burning, de-shaping, low strength (caused by low quality/improper raw/composition materials and also get spoiled due to rainfall/precipitation during drying process). Waste bricks are also produced from demolition of old buildings. The construction debris consists of mainly crushed concrete pieces, plaster, concrete hollow blocks, etc., along with other construction wastes (Figure 1). Appropriate management of the debris should be explored so that these can be used as a construction material. The present research was undertaken with a view to investigate and find out a method how the construction debris can be converted into road sub-base material. The research's prime objective is to find out a new material obtained by mixing construction debris, discarded and abandoned waste bricks (obtained from brick manufacturing field as industrial waste) and stone crush in various proportions. A series of comprehensive experimental program was conducted during last two years in the laboratory and in field.

2. New material preparation: experimental study

2.1 Ingredients materials

The new sub-base material was prepared by mixing the following ingredient materials:

1) Concrete debris (Industrial waste): The demolished reinforced and unreinforced concrete structure were crushed (graded smaller than 40 mm diameter).
2) Stones/pebbles: These crushed stone/pebbles were screened to be smaller than 40 mm diameter.
3) Waste bricks (Industrial waste): These were crushed and screened (graded smaller than 40 mm diameter).

Physical properties of the three ingredients are shown in Table 1. These were mixed according to the proportions, CS: CD: WB = 0:3:7, 2:4:4, 3:2:5, 4:0:6, 8:2:0. The mixtures were tested to investigate whether the new sub-base material can suitably be used with respect to modified CBR value and other engineering properties in the laboratory and in field. Grain size analyses, compaction and CBR characteristics with dry densities are shown in Figure 2 to 4.

2.2 Compacted mixtures of crushed stone and waste bricks

Firstly, waste bricks and stone crush mixtures were tested to compare with the engineering properties of stone crush alone. The mixtures had higher unconfined compressive (UC) strength and modified CBR values [AASHTO (American Association of State Highway and Transportation Officials) design criteria for pavement] but lower in compacted densities and CRB values. No significant difference was found in the permeability between the mixtures and crushed stone. Waste bricks and crushed stone were mixed together to form mixes of various properties according to the proportions, CS: WB = 0:10, 2:8, 4.6, 5:5, 7:3, 10:0. A series of laboratory tests were carried out to investigate various properties of the compacted mixtures. Compaction characteristics unconfined compressive strength, permeability, CBR-density relations and modified CBR values are shown in Figures 5 to 9.

Figure 1. Concrete debris / construction wastes.

Table 1. Physical properties of crushed stone, concrete debris and waste bricks.

Materials	Waste brick (WB)	Concrete debris (CD)	Crushed Stone (CS)
Gravel (%)	51	79	52
Sand (%)	42	17	23
Silt (%)	-	-	13
Clay (%)	-	-	-
*D_{60} (mm)	5.0	14.0	6.0
*D_{30} (mm)	0.69	3.9	0.38
*D_{10} (mm)	0.17	0.46	0.023
C_u (uniformity coeff.)	29	30	260
C_c (gradation coeff.)	0.56	2.36	1.05
G_s (specific gravity)	2.718	2.698	2.711

*D_{60}. D_{30}, D_{10} are the diameters through which 10%, 20% and 30% of total mass pass respectively.

3. Laboratory study of the standard composite mixtures

Crushed stone, waste abandoned bricks (crushed) and concrete debris were mixed together. Mixing ratios are shown in Table 2. The mixing was done in such way that it complies with AASHTO specification. Mixture of waste abandoned bricks and concrete debris was taken 85% and 15% respectively of crushed stones. Grading of new material was done in way to satisfy the grading envelopes A or B in Table 2 as determined by AASHTO test method T27. Table 3 shows the specification of AASHTO T27.

Figures 10 and 11 show the processes and the plant facility that were used for crushing, grading, screening and preparation of all materials.

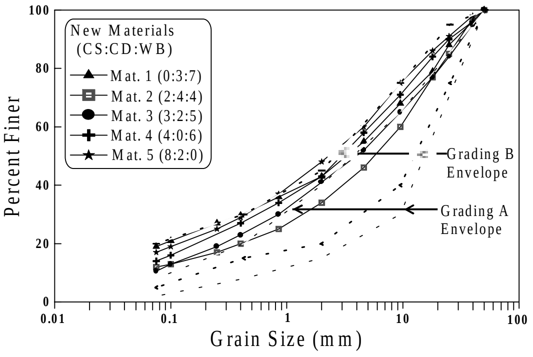


Figure 2. Grain size distribution of new materials.

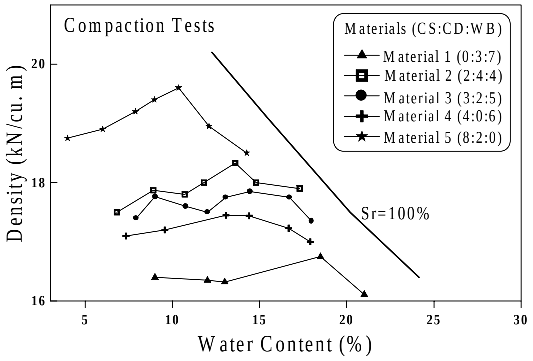


Figure 3. Relationships between Dry Density (ρ_d) and Water Content.

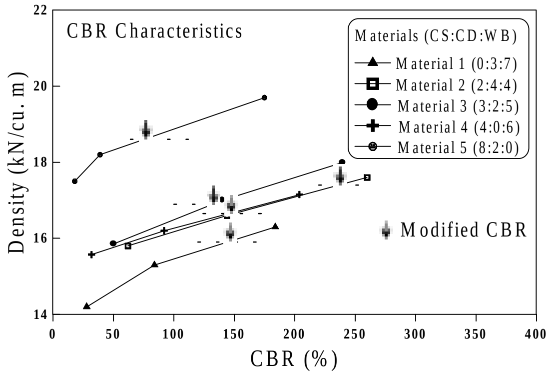


Figure 4. Relationships between Density (ρ_d) and CBR.

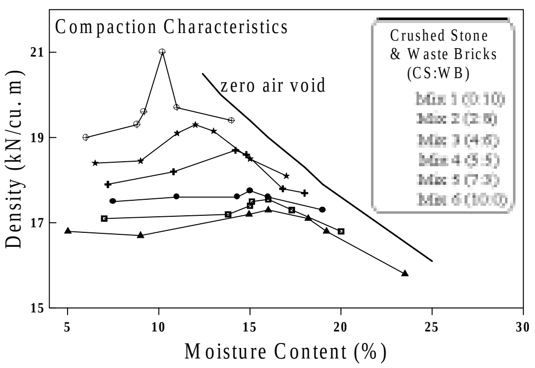


Figure 5. Relationships between Moisture Content and Density (ρ_d).

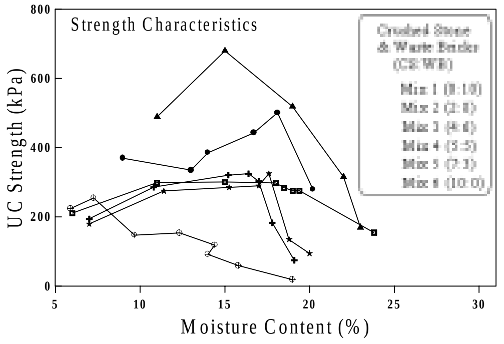


Figure 6. Relationships between Unconfined Compressive Strength (q_u) and Moisture Content (w).

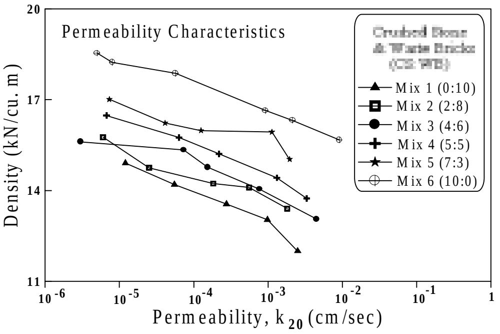


Figure 7. Relationships between Density (ρ_d) and Permeability, k_{20}.

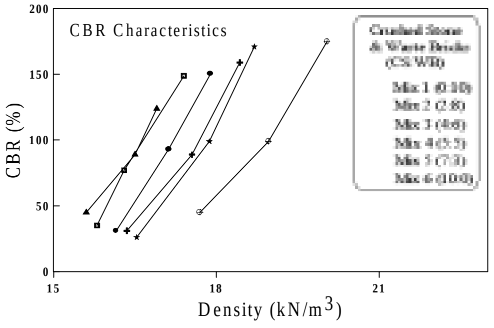


Figure 8. Relationships between CBR and Density (ρ_d).

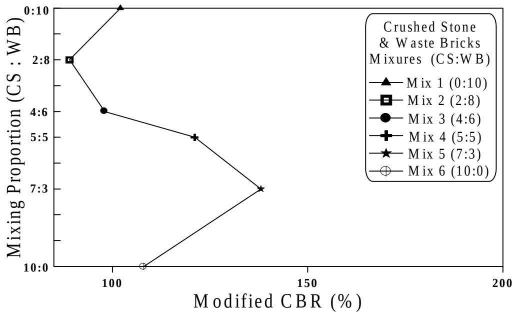


Figure 9. Relationships between Mixing Proportion and Modified CBR.

Table 2. Mixing proportions.

Materials	50–25mm (%)	25–9.5mm (%)	9.5–2mm (%)	2–.425mm (%)	0.425–0.075mm (%)
Grading A	25	35	20	12	8
Grading B	25	30	25	10	10

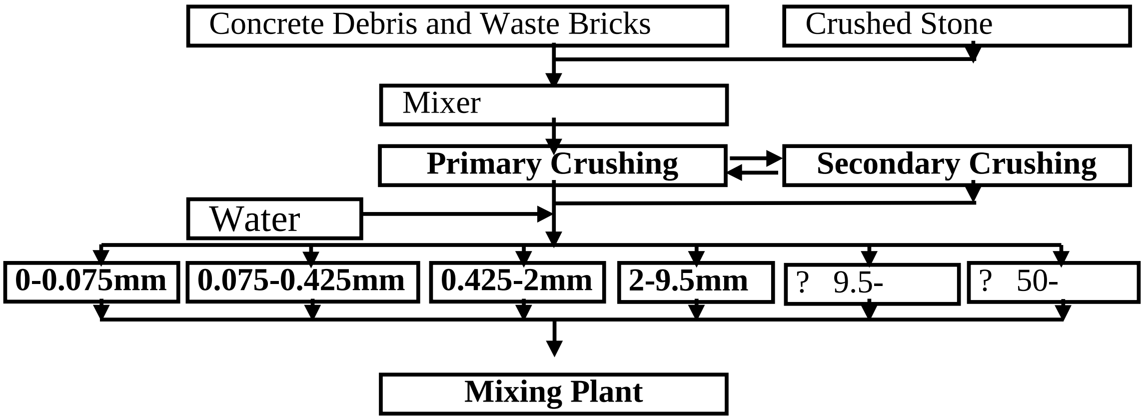


Figure 10. Production process of the new sub-base material.

Table 3. Grading requirement for aggregate base material (AASHTO T27) percentage by weight passing square mesh sieves.

Sieve Designation	Grading A*	Grading B*	Sieve Designation	Grading A	Grading B
2 inch (50.8 mm)	100	100	No. 10 (2 mm)	15–40	20–45
1 inch (24.4 mm)	-	75–95	No. 40 (0.425 mm)	8–20	15–30
3/8 inch (9.52 mm)	30–65	40–75	No. 200 (0.075 mm)	2–8	5–20

*A and B designate the standard grade of sub-base course materials, AASHTO T27 design criteria.

Figure 11. Plant facilities used.

The new composite material satisfied the following AASHTO requirements:

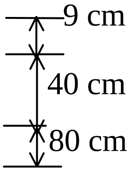
1) The aggregate sub-base mixture satisfied grading limits A & B of AASHTO (Table 3).
2) The fraction passing No. 200 sieve (0.074 mm) was not greater than two-thirds of that portion passing the No. 40 (0.425 mm) sieve.
3) The course aggregate defined as that material retained on the 4.75 mm (No. 4) sieve, had percentage of wear not greater than 40% for 500 revolutions, tested by AASHTO T96.
4) That portion passing the No. 40 sieve of the total mixture had a liquid limit of not more than 25 and a plasticity index of not more than 6% as determined in AASHTO T90.
5) The CBR strength of the whole mixture, as determined in AASHTO T193 was no more than 80 percent after 24 hours soaking, on samples compacted to 95%of the maximum dry density in a moisture range of 4% as determined by AASHTO T180.

Laboratory tests procedures: Tests were conducted as per AASHTO specification and AASHTO Guide for Design of Pavement Structure (1993). Grain size analyses and specific gravity tests was done by AASHTO T88 & T100, Atterberg limit tests by AASHTO T89-86 and T90-86, maximum dry density (compaction test) by AASHTO T180-90 ASTM D1557-70 (Modified Proctor Density) and CBR test by AASHTO T193-81.

4. Tests on model road

Model road section was constructed for feasibility study using above mixtures in the field. In-situ densities were checked by sand-cone method. Complete observation, road test and recording measurements were done for the new materials and were compared with local conventional sub-base material. The investigation is based on performance of flexible Pavement (Asphalt Concrete). Test road was constructed to get equivalent conversion value (design coefficient) according to 'AASHTO pavement design manual' and road was opened for actual traffic. After the designated period, the road surface behavior was examined by extracting samples from the test road. Finally laboratory tests were conducted to find the mechanical properties of the samples extracted from the test road. The road was 30 m in total length and 3.5 m in width. The layout is shown in Figure 12. The vehicles pass was about 10000 per day including about 500 heavy vehicles. The test road along with conventional road was tested for comparative study. Required performances were investigated for a selected Structural Number (SN) for the flexible pavement to withstand a concentration of axle load traffic over a performance period. The investigation involved loading tests, deflection test, surface flat measurements, rutting measurements, etc.

Surface Course + Base Course		Asphalt Concrete (t=9cm)		
Sub-base	Upper	(1)	(3)	(5)
	Lower	(2)	(4)	(6)
Subgrade		**Selected Fill**		



(1) Naturally available pebbles (2) Good quality brick aggregate (3) New materials grading B
(4) Conventional rock aggregate (5) Crushed stone (6) New materials grading A

Figure 12. Details of typical section of model test road. (Total=30 m x 3 sectors=90 m).

5. Road performance in model road section: grain size analyses, compaction tests, durability tests, modified CBR tests, UC tests, permeability & In-situ density tests

Grain size analyses results show that they fit well in AASHTO Grading A and Grading B standards for lower subbase and upper subbase respectively (Figures 13, 14). The compaction curve (Figures 15, 16) shows unique type of shape with half and one peak type; both grading A and grading B materials gradually go down to the bottom (at min. of ρ_d) at about w=8 to 11% and then rise sharply to the peak (at max. ρ_d). In order to check the durability variance, durability tests were carried out by conducting CBR penetration tests on the test section after the permeability tests (Table 4). Result shows that the CBR values are reduced significantly. Modified CBR of grading A and B materials (Figure 17) show some differences because of CBR values for the specified number of blows as per pavement design criteria. Figure 18 shows the relationships between UC tests and moisture content showing strength for 7 days. A range of moisture content was used for each type of sample. The result shows that there are significant difference in strength between Material 5 (crushed stone=80%) and other mixtures. These results provide a preferable and promising property of the mixture as the sub-base material.

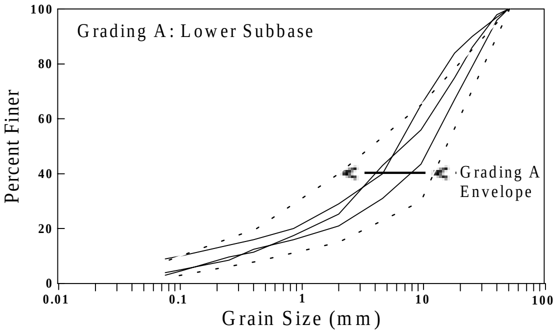


Figure 13. Grain size distribution for lower subbase materials.

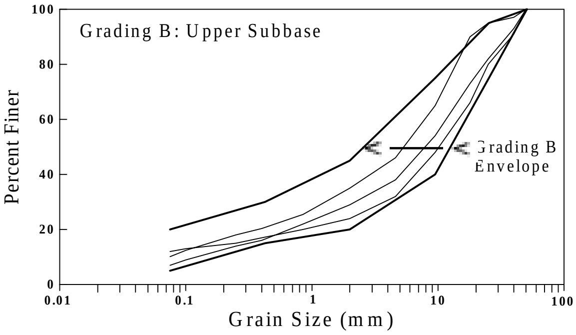


Figure 14. Grain size distribution for upper subbase materials.

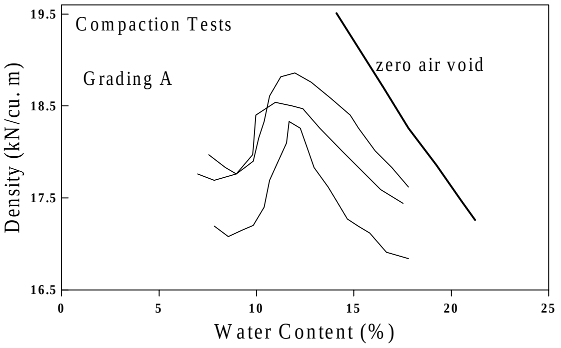


Figure 15. Relationships between dry density (ρ_d) and water content for grading a material.

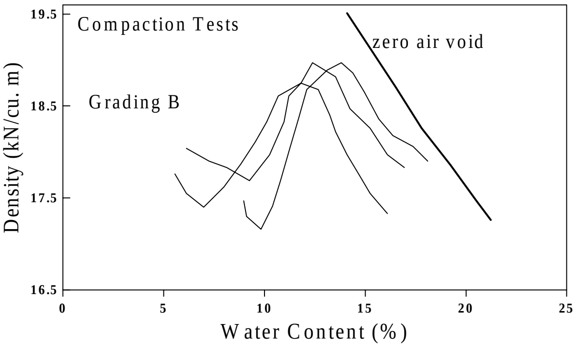


Figure 16. Relationships between dry density (ρ_d) and water content for gradign B materials.

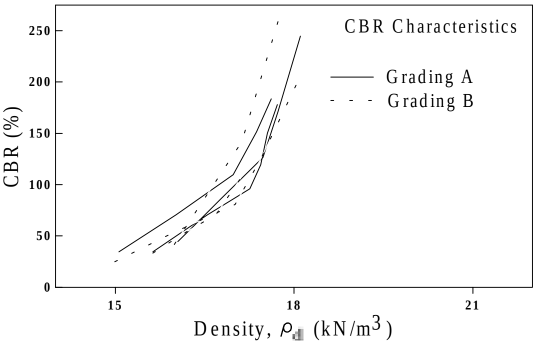


Figure 17. Relationships between CBR and Density (ρ_d).

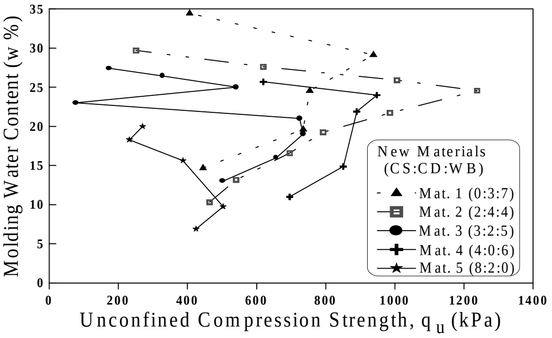


Figure 18. Variation of unconfined compressive strength.

Table 4. Durability test results.

Blows	Material Grading A			Material Grading B		
	CBR(%)	CBR (at later stage) (%)	Reduction (%)	CBR (%)	CBR (At later stage) (%)	Reduction (%)
17	46.2	31.3	32.1	44.3	37.1	28.5
42	107.3	69.3	38.9	117.8	91.9	26.2
92	258.6	193.4	36.6	206.3	168.5	23.5

Figures 19 and 20 show relationships between permeability, k_{20}, dry density, ρ_d and its ratio. From in-situ density of sub-base course at the sites, permeability can be estimated. Field test of in-situ dry (Table 5) shows that in-situ density values are satisfactory with regard to the constructional criteria.

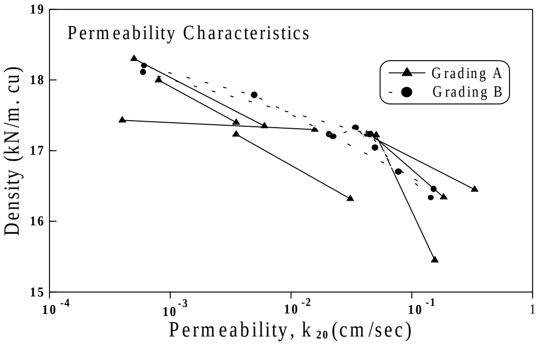


Figure 19. Relationships between permability (k_{20}) and density (ρ_d).

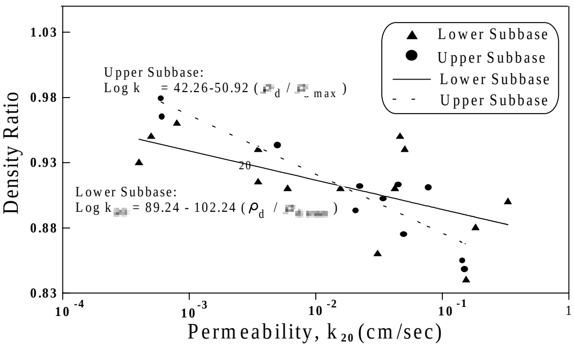


Figure 20. Relationships between permeability and density (ρ_d, ρ_{dmax}).

Table 5. In-situ density tests.

Properties		**Test 1**	**Test 2**	**Test 3**	**Test 4**
Moisture Content (%)		15.31	14.22	14.95	16.82
Dry Density (kN/m^3)		17.61	19.32	17.99	18.32
Degree of Compaction (%)		93.1	99.2	98.3	97.4
Laboratory Tests Results	CBR (Modified) (%)	116	97	114	138
	$\rho_{d(max)}$ (kN/m^3)	19.14	18.35	18.65	18.95
	w_{opt} (%)	14.1	15.2	14.9	12.9

6. Conclusions

A technique is described in the paper to use construction wastes as road subbase material. From laboratory and field tests, it was found that the new material comprising of construction wastes is perfectly suitable to use as road subbase satisfying AASHTO criteria. Road performance on model road section was investigated through grain size distribution analyses, compaction tests, modified CBR tests, durability tests (CBR penetration tests) and strength tests. The new subbase material has no real change in the pertinent mechanical properties with sampling or taking out time. Moisture content was found to be fundamental parameter, which controls the basic behavior of the sub-base. By controlling moisture content in the mixtures, the subbase material can be used effectively for road construction. It was found that there is no difference in compaction characteristics between Grading A and Grading B materials except the modified CBR values. To apply the technique, it is suggested that field tests-loading test (k value) and other tests must be followed for appropriate pre-assessment of the road performance.

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Risk assessment of industrial by-products used in earth construction

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ABSTRACT: Industrial by-products can be used in earth constructions provided their environmental properties are acceptable, e.g. not exceeding defined acceptance values. Risk assessment is needed in cases where the disposal conditions significantly differ from the conditions considered when the acceptance values were set for by-products suitable in earth constructions, for example, in cases of sensitive disposal environments or in cases where the construction consists of several different by-products. It might also be possible through risk assessment to accept higher emission values in cases where more information is available about the properties of the harmful compounds.

A procedure for the risk assessment of industrial by-products to be utilized in earth construction is proposed. The procedure is designed to be as simple as possible to use, yet cover the most important aspects and environmental risks in the assessment. Additionally, the special characteristics of construction and the use of earth constructions were also considered. The risks were primarily related to human health because the background data needed for an ecotoxicological risk assessment is still under development.

The proposed risk assessment concept has also been tested in a case study on the use of coal fly ash in earth construction.

1. Introduction

Industrial by-products may possess detrimental environmental properties, the impacts of which need to be considered before the products are used in earth constructions. Some examples of the most relevant properties to be considered for by-products are the following:

- Direct toxicity of by-product for human, plant, animal, and water organisms
- Leaching properties with special attention paid to all relevant conditions at the disposal site (as a consequence of the transport of toxic metals to the environment)
- Formation of toxic gas emissions, e.g. due to degradation, reactivity
- Dust problems
- Risk for ignition (fire).

Risk characterization means that all the unfavourable properties or conditions are listed and described, and if possible quantified, e.g. as doses or emissions. The risk assessment also covers assessment of the impacts of undesired phenomena. The results of the risk assessment can be used to choose an appropriate way of utilization where the undesired phenomena are minimized or they can be totally eliminated by suitable measurements.

Guidelines for the risk assessment of contaminated sites have been developed. These guidelines are often very broad and general covering all kinds of exposure pathways to humans and the environment. In particular, the future use of the site is considered in the risk assessment.

The guidelines for the risk assessment of contaminated sites have been the basis for this work. Many of the exposure pathways are not necessary to consider for the use of industrial by-products in earth construction. The following exposure pathways, though, are considered relevant with regard to the use of by-products in earth construction:

Human exposure:

- inhalation of dust
- inhalation of volatile compounds
- dermal contact
- intake of by-products and water that has been in contact with the by-product

Environmental risks:

- influence on plants and animal species near the deposit
- influence on the ground and surface water quality

The direct risks to humans are mostly related to the transportation and handling of the by-product. Examples of typical risks are the inhalation of dust, dermal contact, and in respect of children also ingestion of by-products. Risks to the environment may be caused by contamination of the ground and surface water as well as the soil near the site. The risks are significantly dependent on the sensitivity of the surroundings, the geological conditions at the site and also on the use of the site. For examples in an urban area, where drinking water or irrigation water are not taken from wells, the effects on humans from the intake of water or food can be regarded as insignificant. Examples of exposure routes in the utilization of by-products in earth constructions are given in Table 1.

The study is part of a larger research entity aimed at developing a guide for the assessment of the environmental and technical suitability of by-products in the permission and product qualification process.

Table 1. Examples of work stages in the utilization of by-products in earth construction and possible exposure pathways related to these.

Work stage	**Exposure pathway (condition)**	**Target group for exposure and likelihood for occurrence**
Transportation of by-product	Dust can be spread to the environment if the by-products are transported in open vehicles and if the moistening of the powdered by-product has not been sufficient.	Dust emission may cause exposure to the lungs. Furthermore, dermal irritation and ingestion via the mouth are possible. Detrimental compounds in the dust particles may leach out to the soil. The risks are dependent on the amount of dust and the place. The risks are casual and local.
Temporary storage (heap)	In the case of a powder-like by-product, which is stored in a heap without a covering, dust emissions to the environment are likely to occur. Detrimental compounds may leach out from the heap if the by-product is not covered with a water impermeable by-product.	Dust emission may case exposure to the lungs. Furthermore dermal contacts and ingestion via the mouth (small children) are possible. Detrimental compounds in the dust particles may leach out to the soil. The risks are dependent on the amount of dust and the place. The risks are casual and local.
Earth construction	During the construction works dust emission may occur, especially in the case of powder-like by-products. Also leaching from the construction needs to be evaluated if the construction is not covered with asphalt or other by-products for a long time.	Workers may be exposed to dust and dermal contact. If the construction is situated in a residential area, the inhabitants of the area may also be affected by dust and ingestion. The risks are usually occasional.
Use of road	In the case of a non-covered by-product, rainwater percolates the construction layer. In the case of an asphalt construction , the water might find its way through cracks. In both cases detrimental compounds may also leach out to the environment	Human and animals may use the surface or ground water as drinking water near the construction. The background levels in soil and water increase. The increase in the soil near the deposit may have effects on the plant and animal species.
Maintenance and remedial actions at the road/construction	For the maintenance and the remedial actions of the construction, the asphalt layer is often removed and the earth layers are dug up. These activities may lead to dust emission, and the leaching of detrimental compounds to the environment is enhanced.	Humans and animals use the water as drinking water. The background level in soil and water is increased Workers are also exposed to possible dust emission.
Time after the road/construction has been used	The road constructions are usually not removed even if the road is taken out of use. In some cases the road is broadened or reconstructed in such a way that the old road is left beneath the new. Only seldom, is the road construction demolished and the by-products removed. This means that the leaching of detrimental components continues.	Humans and animals use the water as drinking water. The background level in soil and water is increased.
Accidents	Accidents need to be considered, especially for transportation. The by-product may be spread to the surroundings causing dust emissions and leaching of detrimental compounds.	People passing near the accident place are exposed to dust. Also skin contacts or ingestion is possible. The risk is usually very local.

2. Description of model

2.1 Scope and field of application

The procedure is designed to be as simple as possible to use, yet cover the most important aspects and environmental risks in the assessment. The procedure is simplified and gives an overview of the general risk factors involved in using the by-product. The model includes several assumptions and it may not be applicable for all cases. Therefore, special attention needs to be paid to the differences between the conditions of the real case and of the model presented.

The model procedure is mainly based on the properties of the by-product. In particular, the risk factors involved in the handling, and the typical use of the by-product are emphasized. The material properties are also important for the site-specific risk assessment where the site conditions (e.g. geology and hydrogeology) are considered. The sensitivity of the environment and the future use of the site are especially evaluated in an extensive risk assessment.

It is not possible to give general recommendations on how specific environmental conditions should be included in a site-specific risk assessment, and therefore a case-by-case approach is recommended. Only lists of general aspects to be considered can be given.

The procedure is developed for inorganic by-products mainly containing inorganic contaminants, i.e. metals and salts that influence the behaviour of the metals. The environmental assessment of organic pollutants needs to be studied separately taking into account their special properties (degradation, colloid formation).

2.2 Procedure

The risk assessment of the by-product includes the following parts:

1. Description of material properties (origin, processes, raw materials, variations in quality).
2. Identification of detrimental properties during the whole life cycle of the by-product including the most important handling steps.
3. Evaluation of the mobility of contaminants at the site, including the storage of the by-product when necessary.
4. Evaluation of the transportation of the contaminants into the environment (surface and groundwater, soil).
5. Calculation of exposure (doses) for critical target groups.
6. Evaluation of the results of the risk assessment based on the material properties including presentation of the acceptable risk level used.
7. Uncertainty analysis.
8. Site-specific risk assessment (when necessary).
9. Conclusions and recommendations.

2.2.1 Identification of properties detrimental to humans and environment

The first step is to collect all the relevant background information of the material (usually through the origin and chemical analysis) in order to be able to identify the detrimental properties. The content of harmful components is usually compared to the trigger and limit values given for the soils in the assessment of soil contamination. If the concentration of the harmful component is below the trigger value for clean soil, no further assessment is usually needed. On the other hand, if the concentration of some harmful component significantly exceeds the limit values for contaminated soils or exceeds the maximum leaching values, a risk assessment is needed.

2.2.2 Transportation of detrimental compounds to the environment

Usually the leaching of detrimental compounds needs to be considered in the risk assessment. This means that the mobility of the compounds from the by-product layer and also the factors controlling the leaching need to be assessed usually through a full characterization of the leaching behaviour. Suitable test methods for the assessment are now under preparation in the standardization organization of CEN (CEN TC 292). The leaching is either governed by percolation of rainwater (in the case of a non-isolated construction), or through diffusion (in the case of an isolated construction). The leaching rate as a function of time can be modelled by mathematical equations. The proposed time-scale to consider in the model is 50 years, which is the lifetime of a road. During this period, the leached amount during some time intervals of 1, 3, 10 and 50 year is calculated. The magnitude of the water flow in a non-isolated construction is an important parameter and it can be estimated to vary between 70 to 300 mm/year.

The transportation of contaminants in the water to the surroundings of the site from the earth construction containing the by-product can be modelled in many ways. The simplest way is to calculate with dilution factors. Dilution factors of between 1 and 4000 have been suggested in the model.

2.2.3 Estimation of exposure

The most relevant exposure pathway for many powder-like by-products is via inhalation of dust. Unfortunately, suitable models were not found. For this reason, field measurements of dust emissions during different working stages are helpful.

The exposure pathways (e.g. dermal contact, leaching) are evaluated for human, plant, and animal species during the handling of the by-product, and the construction and maintenance of the earth construction (see Table 1). The doses to humans from other exposure pathways are calculated using simple mathematical models developed for the risk assessment of the contaminated site. Several models are available with different kinds of assumptions for the exposure. Usually, intake through e.g. drinking water, and in the case of playing children, direct inhalation of the by-products is estimated. The calculated intake values can be compared to tolerable daily intakes (TDI). In the assessment, the background exposure also needs to be considered, and in some cases other sources may be significant.

The direct contact (intake by animals or uptake by plants) of the by-product can be ignored because the earth constructions are usually covered and compacted. The environmental risk is due to harmful compounds in the leachates from the construction.

2.2.4 Evaluation of risks

The significance of the emissions from the considered scenario is estimated through comparisons to guideline values that indicate minimal risks for human beings and indicator organisms The assessment of ecotoxicological risks can only be made roughly, because only limited suitable reference values for no-observed effect concentrations (NOECs) are available. Moreover, the values are usually derived for certain laboratory conditions and certain chemical compounds. The applicability of these values may be poor and therefore they should be used with caution. The ecological effects on plant and animal species are evaluated by comparing the calculated values with the toxicological values reported in literature.

The environmental risks can also be evaluated by comparing the calculated values in the leachate to the background concentrations or ecotoxicological target values, when available. This gives information on the need for dilution to reach the background concentrations in the environment.

In the risk assessment, also the exposure of several different pathways (e.g. human exposure to dust and one or several heavy metals) should be considered. However, today no guidelines are available for assessing the synergetic effect of several exposure pathways.

2.2.5 Uncertainty analysis

An important part of the risk assessment is to evaluate the impact of critical parameters on the results. Variations in input data and checking the influence of critical assumptions give important information on the sensitivity of the results.

Examples of typical parameters to be checked are:

- material thickness
- chemical composition and leaching behaviour
- assumptions in the calculation of water flow (rate, percolation, surface wash)
- dilution factor for leachate from the earth construction.

2.2.6 Sit- specific risk assessment

The site conditions are taken into account in a more extensive risk assessment. The geology and hydrogeologial conditions of the site are especially considered. The risk assessment may include leachate handling, permeability of surrounding material, and climatic and biological conditions. The background levels of detrimental compounds can also be considered in certain cases (e.g. in urban areas). The future use and the sensitivity of the site are important in the risk assessment.

2.2.7 Conclusions and documentation

The results of the material-specific risk assessment give information about which risks are most relevant. This information can be used to classify by-products into different classes (no risks – some risks in the earth utilization). The risk assessment gives valuable information on the appropriate ways of utilization in which all risks can be minimized. In the site-specific risk assessment, which is more extensive, especially the sensitivity of the site (hydrogeology, geology) and its future use are considered.

It is important that all the steps and assumptions in the risk assessment are well documented and transparent. The conclusions and the chosen acceptance criteria need to be carefully explained. Usually the risk assessment involves a broad expert group.

3. Case study

The developed model has been tested for coal fly ash in earth construction. Two construction-types consisting of a one-metre material layer were studied: a construction isolated by asphalt and a construction covered by soil.

For the most relevant properties to be considered, dust was chosen as well as the following contaminants: chloride, sulfate, chrome, molybdenum and vanadium. The potential exposure routes and target groups for exposure were evaluated for typical handling processes during the whole lifecycle of the by-product. Also the consequences of accidents were checked.

In the risk assessment it was concluded that dust emission might cause problems especially to workers if the fly ash is not moistened and handled according to the instructions given by the power plant. The most relevant risk factor was the mobility of contaminants into the rainwater and transportation of the contaminant with water to the environment.

The assumptions of some parameters in the scenarios are presented in Table 2. An example of the estimated concentrations in the leachate before dilution, which presents the most critical scenario, is illustrated in Fig. 1. The predicted values have been compared to Finnish background values, guideline values or reference values reported in literature. Especially no-observed effect concentrations (NOECs) for water organisms were used when possible. Only a few ecotoxicological values have been presented in the literature. Most values are set for the protection of human health.

The conclusions of the case study were the following:

- For the isolated construction: The concentrations of contaminants in the leachate from the construction were generally near the background concentrations of the Finnish environment or near guideline values for human health. Because the leachate amounts were small, it could be concluded that the environmental impacts on surface and groundwater can be regarded as insignificant. This means, of course, that the isolation layer is without cracks during the lifetime of the construction.

- For the covered but non-isolated construction: The concentrations of contaminants may cause some kind of risk to the environment. The contaminant concentrations in the leachate were momentarily high and clearly exceeded the guideline values, e.g. the drinking-water values given for the protection of human health. A site-specific risk assessment is needed for the evaluation of impacts. Exclusion of the non-isolated construction in sensitive areas is recommended.

Table 2. Examples of input data in the scenarios considered in the case study.

	Non-isolated construction	Isolated construction
Properties of by-product		
Density	2000 kg/m^3	2000 kg/m^3
Porosity of the by-product	0,45	0,45
Content of some elements		
- Cr	120 mg/kg	120 mg/kg
- Mo	6,4 mg/kg	6,4 mg/kg
- V	200 mg/kg	200 mg/kg
Road dimensions:		
Width	10 m	10 m
By-product thickness layer	1 m	1 m
Leaching mechanism	Percolation of rainwater (300 mm/a)	Diffusion (D_e 2 10^{-9}m/s)
Leaching characteristics:	Results from column test at L/S 10	Pore water concentrations:
- Cr	11,6 mg/kg	150 mg/l
- Mo	3,3 mg/kg	15 mg/l
- V	4,9 mg/kg	49 mg/l

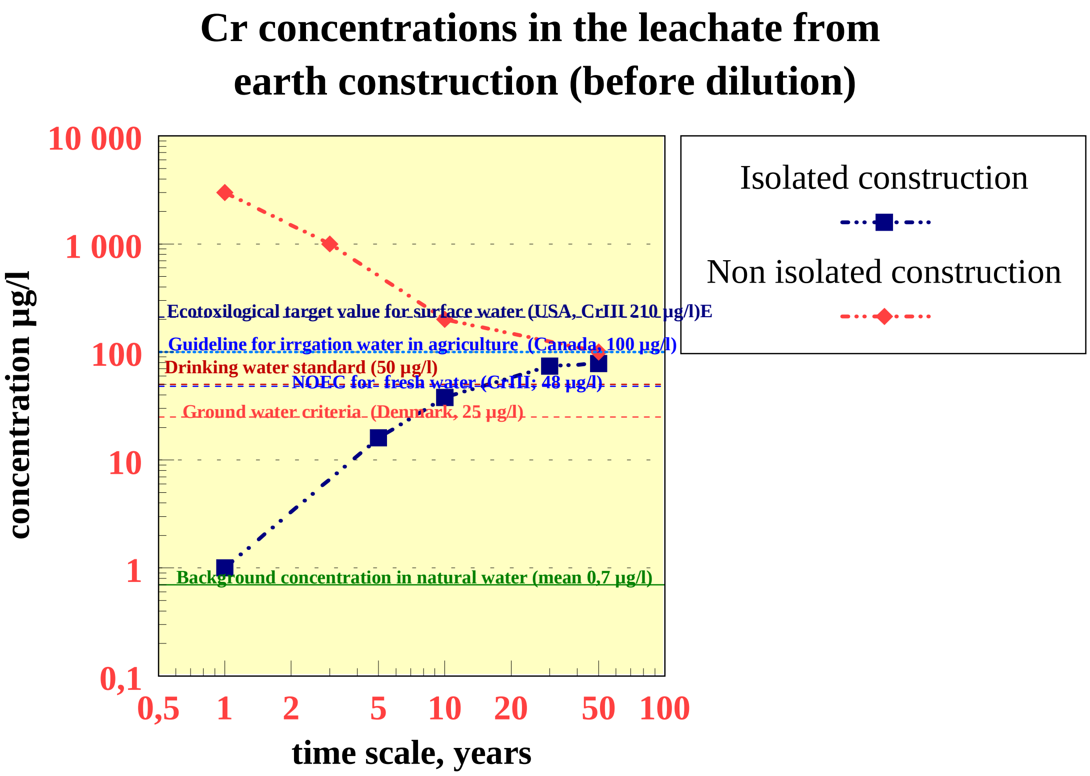

Fig. 1. Estimated Cr concentrations in the leachate from two earth constructions during the lifetime of the road. The values can be compared to following reference values: drinking water standard 50 µg/l, ecotoxicological target value for surface water 210 µg/l (USA), Canadian guideline for irrigation water in agriculture 100 µg/l, Danish ground water criteria 50 µg/l and Finnish background concentration in natural water 0,7 µg/l (mean).

4. Conclusions

The aim of the risk characterization and assessment is to find an environmentally safe way to use by-products in earth constructions. The risk assessment is needed for by-products possessing properties that fall outside the general guidelines for by-products in earth constructions.

Documentation of the input data and assumptions is important for the evaluation of the results, especially if supplementary information should later become available, e.g. from field studies. The report of the work should be as transparent as possible.

The conclusions should at least contain the following information:

- Which risk factors, exposure routes, target groups have been considered
- Time frame of the evaluation
- Which risk level is assumed to be acceptable (motivations)
- Which environmental conditions (e.g. dilution of leachate) are included in the study
- Limitations of the study
- Assessment of the reliability of the input data and reference values (suitability for comparison)
- Expertise record of the experts.

Reference

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Legal aspects concerning the utilisation of by-products (slag) of iron and steel industry in geotechnics

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ABSRACT: When marketing slag to customers one of the main topics *in practice* between the slag marketer and the customer is the question of slag being classified as by-product or waste. This is understandable since utilisation of waste is nationally under strict observation and regulation.

If slag will be classified – even partially – as waste, it will result losses in marketing opportunities and difficulties in recycling by-products with excellent properties. Customers do not wish to be involved in long lasting bureaucratic procedures and there is of course the image impression, too.

It seems that in this respect there is some controversy and interpretation problems in the Community and national legislation concerning the utilisation of slag in geotechnics.

1. Introduction

The history of utilisation of iron and steel industry’s by-products dates back a long way. In many cases it has been mainly the question of solving waste problems. Through awareness of environmental matters, ultimately the concept of sustainable development and the extensive R&D the idea of mere waste handling has been transformed into effective and profitable utilisation of by-products.

As it very often in rapidly developing areas happens, the legislation has to try to keep in pace with the inventions and development. And as far as the environmental legislation of by-products is concerned there have remained two problems. Firstly the burden of the past i.e. even excellent by-products are labelled as “waste” and secondly the dilemma between on one hand the urge to recycle waste and on the other hand the protection of environment (against recycling harmful or even hazardous materials).

It seems that in the future environmental authorities will set still tighter regulations concerning the utilisation of by-products of iron and steel industry.

2. Statutes under observation (italicizations by the author):

2.1

Council Directive 75/442/EEC of 15 July 1975 on waste (amended by Council Directive 91/156/EEC of 18 March 1991**)** states the following:

Article 1

For the purposes of this Directive:
(a) "waste" shall mean any substance or object in the categories set out in Annex I which the holder discards or intends or is required to discard.

The Commission, acting in accordance with the procedure laid down in Article 18, will draw up, not later than 1 April 1993, a list of wastes belonging to the categories listed in Annex I. This list will be periodically reviewed and, if necessary, revised by the same procedure;

…..

Article 3

1. Member States shall take appropriate measures to encourage:
(a) firstly, the prevention or reduction of waste production and its harmfulness …..
(b) secondly:
(i) the recovery of waste by means of recycling, re-use or reclamation or any other process with a view to extracting secondary raw materials, or

…..

Article 4

Member States shall take the necessary measures to ensure that waste is recovered or disposed of without endangering human health and without using processes or methods which could harm the environment, and in particular: - without risk to water, air, soil and plants and animals,

…..

2.2

Commission decision of 20 December 1993 established a list of wastes pursuant to Article 1 (a) of Council Directive 75/442/EEC on waste (94/3/EC). The list was named European Waste Catalogue (EWC).

The Introductory note of the Commission decision states a.o. the following:

1. Article 1 (a) of Directive 75/442/EEC defines the term 'waste' as: 'any substance or object in the categories set out in Annex I which the holder discards or intends or is required to discard'.
2. The second indent of Article 1 (a) requires the Commission, acting in accordance with the procedure laid down in Article 18, to draw up a list of waste belonging to the categories listed in Annex I. This list is commonly referred to as the European Waste Catalogue (EWC), and applies to all wastes, irrespective of whether they are destined for disposal or for recovery operations.
3. 3. The EWC is an harmonized, *non-exhaustive* list of wastes, that is to say, a list which will be periodically reviewed and if necessary revised in accordance with the committee procedure. However, the inclusion of a material in the EWC *does not mean* that the material is a waste in all circumstances. The entry is only relevant when the definition of waste has been satisfied.
4. The waste featuring in the EWC is subject to the provisions of the Directive unless Article 2 (1) (b) of this Directive applies.
5. The EWC is to be a *reference nomenclature* providing a common terminology throughout the Community with the purpose to improve the efficiency of waste management activities. In this respect the European Waste Catalogue should constitute

> the basic reference for the Community Programme on waste statistics launched pursuant to the Council resolution of 7 May 1990 on waste management policy (1).

…..

2.3

The European waste catalogue (Annex to the Commission decision 94/3/EC) states the following:

…..

10 00 00 Inorganic wastes from thermal processes

…..

10 02 00 wastes from the iron and steel industry
10 02 01 waste from the processing of slag
10 02 02 unprocessed slag

…..

10 02 99 wastes not otherwise specified

3. The demand to recycle

As it can be seen from the regulations they include an antithesis.

Firstly there is a clear demand of recycling and secondly there is a demand that this may not endanger human health or harm the environment (Articles 3 and 4 of Council Directive 75/442/EEC of 15 July 1975 on waste).

It can be said that the demand to recycle is a general rule i.e. one must recycle whenever possible. In this sense the demand to ensure human health and protection of environment can be seen as a special rule making restrictions to the general rule. It is of course clear that even if the demand to recycle is – in a contemporary world – a strong rule, the demand to protect human health and environment has supremacy over recycling.

However as the demand *and the benefits* of recycling are so essential one should be quite careful while setting limits to recycling. The restrictions should, as in every judicial and administrative practice, be proportionate and reasonable and most important – reasoned very carefully.

4. Slag and interpretation of the regulations

The slag producers have during the last decades tried to clear the image of slag from waste to by-product. From practical point of view, i.e. marketing of slag products, it is almost vital that slag is not classified as waste.

The technical and chemical properties of slag do not justify it to be classified as waste. The only base for the waste classification of slag is found from Article 1 (a) of Council Directive 75/442/EEC of 15 July 1975 on waste, which states that "waste" shall mean any substance or object [in the categories set out in Annex I] *which the holder discards or intends or is required to discard.*

One can always claim that slag, while originating from the iron and steel making process and without any further processing, is waste.

The interesting question is: does slag - and if it does, in which case and at which point - cease to be waste.

For a lawyer coming from a Roman law based system the answer is unambiguous:

According to the European waste catalogue (paragraph 10 02 02) only *unprocessed slag* is waste.

And from the iron and steel industry’s perspective it is also unambiguous what does slag processing mean; shortly put: it is granulating, crushing, separating metal and sieving (also other forms of processing exist). Through this processing slag will transform from waste to by-product.

However this as such very clear definition has found opposition from some environmental authorities side.

The main argument - as it has been understood – is that the Commission decision of 20 December 1993 which established the European Waste Catalogue (EWC) is only a guideline and a recommended decision. This idea is expressed in the Article 3 of the Introductory note of the Commission decision: "The EWC is an harmonized, *non-exhaustive* list of wastes, that is to say, a list which will be periodically reviewed and if necessary revised in accordance with the committee procedure.

However, the inclusion of a material in the EWC *does not mean* that the material is a waste in all circumstances. The entry is only relevant when the definition of waste has been satisfied."

From this perspective the clear classification of the paragraph 10 02 02 of the EWC has been challenged which can be argued since after this general introductory note there is a specific rule of EWC (10 02 02) concerning *(un)processed* slag

To support the challenge of EWC 10 02 02 there have been attempts to find the answer from certain cases that have been brought to the Court of Justice of the European Communities. For example in the case Euro Tombesi C-304/94 the Court of Justice of the European Communities ruled that the concept of waste (in Article 1 of Council Directive 75/442/EEC) is not to be understood as excluding substances and objects which are capable of economic reutilization, even if the materials in question may be the subject of a transaction or quoted on public or private commercial lists. Furthermore the Court ruled that "The fact that a substance is classified as a re-usable residue without its characteristics or purpose being defined is irrelevant in that regard. The same applies to the grinding of a waste substance".

However this ruling of the Court does not seem to apply to slag products since slag is not "any substance that is capable of economic reutilization" because there is a specific statute (EWC: 10 02 02) that only unprocessed slag is waste.

Somewhat confusing in this regard is the Commission decision 96/660/EC of 14 November 1996 adapting pursuant to Atricle 42 (3), Annex II to council Regulation (EEC) No 259/93 on the supervision and control of shipments of waste within, into and out of the European Community.

According to the Annex II i.e. the Green List of Wastes the shipments of waste for recovery listed on the green list of the OECD Decision shall be generally excluded from the control procedures of the Regulation since such waste should not normally present a risk to the environment if properly recovered in the country of destination.

The Green List has the following condition to exclude slag from the control procedures of the Regulation:

"GC 070 Slag arising from the manufacture of iron and steel (including low alloy steel) excluding those slags which have been specifically produced to meet both *national and relevant international requirements and standards*."

Thus from these basis there also has been drawn a general principle according to which slag would not be waste if it will meet national and relevant international requirements and standards concerning for example quality.

It is however questionable if one could draw a general principle concerning the status of slag as waste from this Decision since it does not apply to national shipments of waste but only international shipments.

5. Slag and environment

The attempts to obscure the position of processed slag as non-waste have to be seen in the light of its environmental aspects. Claiming slag as waste on technocratic bases only would do injustice to an environmentally excellent product.

Firstly the extensive use of slag will solve once and for all the quantitative big waste problem that producing iron and steel would create.

Secondly the technical and chemical properties of slag while utilised in geotechnics (and in agriculture and in construction industry and in civil engineering) are *better* than its competitive materials.

Thirdly – and one of the most important aspect is the double effect – every ton that slag is being used will save at least the same amount (and in geotechnics more than the same amount) unrenewable natural resources.

Fourthly there is no evidence that slag used in geotechnics would harm the environment. The only aspect that has been brought into discussion is the possible effect of slag product to the groundwater right next to the slag material. Even if there is no scientific evidence that there would be any harm, slag producers and environmental authorities have together agreed on protective measures to be taken in these cases. However even this slight voluntarily restriction does not entitle slag to be classified as waste.

Furthermore according to the report by VTT Chemical Technology, Environmental Technology (in Finland) “Life cycle analysis of road and earth construction” (authors Eskola, Mroueh, Juvankoski and Ruotoistenmäki; ISBN 951–38–5446–9) the environmental burden of blast-furnace slag is lower than that of fly ash, crushed concrete waste or *even* natural mineral materials.

The aspects on favour of vast slag recycling are numerous and there should be neither scientific nor practical reason to set artificial limits to the recycling of slag.

6. De lege ferenda

The modern iron and steel industry has always – to maintain its moral right to proceed its activities - favoured environmental matters. Actually in the beginning it was the iron and steel industry itself – partly due to the change in the public way of thinking and without any significant pressure from the authorities side – which started and developed its environmental policies and activities.

In the case of by-products we have come to the stage that the environmental authorities have reached the environmental level where the iron and steel industry has already been before the authorities.

In the future it seems that the regulations created by environmental authorities and especially the interpretations made by them will reach much further than the iron and steel industry has yet been prepared to.

This threatening confrontation will create a challenging task on one hand to the iron and steel industry to develop its activities even further and on the other to the environmental authorities to set and interpret regulations in the way which will be most beneficial from the environmental point of view.

Case study of using shredded tires in a road structure (local road 11863 Ilola-Sannainen pilot structure)

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ABSTRACT: FINNRA (Finnish National Road Administration) and Säkkiväline Oy has used shredded tires as light-weight material in trial road embankment. The road has been constructed in 1930's and has been hampered by flooding especially in spring. The soil under the road is soft clay. The amount of chip needed to impair the settlements was about 3700 m3 and chip thickness varied between 0,34 and 1,4 meters. The total lenght of the trial section is 350 meters.

The pilot structure was analysed for bearing capacity, settlements and environmental impacts by chemical testing of water samples. The designing and construction methods of the pilot structure together with the field and laboratory analysis results with the main stress on environmental monitoring and analysis are presented in the paper.

A solubility test was performed by Technical Research center of Finland before applying environmental permit for the structure. Small amounts of copper, zinc, manganese, iron and PAH's were dissolved. The environmental impact of tires and shredded tire chips has been studied considerably in other countries, such as the USA. According to these studies, depending on prevailing conditions, a certain amount of metals are dissolved from the tires. However, the concentrations are not considered to be harmfull for the environment.

The trial structure was constructed in August - September 1997. Structure included two lysimeters for testing the water filtered through the structure. Also the ground water quality has been analysed for soluble chrome, copper, led, zinc, manganese, iron, sulfates, redox potential, electric conductivity, polyaromatic hydrocarbons and pH.

The results analysed before July 1999 have indicated no hazardous amounts of heavy metals or PAH compounds in the groundwater or in the water filtered through the structure. Evaluation of the resent results is going on and presented in the paper.

1. Introduction

Used tires have to be put in beneficial use in Finland since June 1996 by decision of Finland’s Council of State. Used tires accumulate in Finland at a rate of approximately 30,000 tons per year (2.500.000 pieces). Today the collection rate is appr. 90%. Used tires are primarily recycled by retreading them or otherwise using the material they are made of. Finland has begun to use used tires in road structures, primarily as lightweight embankment filler in lower class roads or in pedestrian ways and in noise barriers. Another promising utilization is to use shredded tires as drainage structures like those used at rubbish dumps. The main reason and goal for use has always been considerable savings in natural resources and construction cost. Secondary use of used tires is energy production by burning shredded tires.

The shredders produce two grades of tire chips: RR1 (10 x 30 cm^2) and RR2 (5 x 5 cm^2). Whole tires are graded as RR0.

First full-scale trial structure of using shredded tires as lightweight filler in lower class roads was constructed in1997. It has been followed by monitoring selected environmental parameters and technical functionality.

2 Properties of shredded tire chips

2.1 Technical and mechanical properties

The weight by volume, strength and deformation properties, water permeability and thermal properties are presented in Table 1. Especially weight by volume, strength and deformation parameters and water permeability depend on the degree of compaction as well as the weight of the fill above shredded tires. Values in table are based on few laboratory tests, field studies and back-analysis calculations made in Finland and other countries. Properties of whole tires and coarser chip (RR1) are not much researched.

The aggregate material of shredded tire chips is slightly heavier (12 kN/m^3) than water, so its underwater weight by volume is approximately 1 kN/m$^{3.}$ Therefore, there is no problem with buoyancy. Tires absorb nearly no water, so material remains lightweight even though it is permanently submerged underwater.

Table 1. Properties of shredded tire chips and whole tires.

Property / Material	Tire chips RR2	Tire chips RR1	Whole tires RR0
Grain size	5 x 5 cm^2	10 x 30 cm^2	
Weight by volume (kN/m^3)	5–6	3.5–5	1.2–2.0
Angle of friction ϕ (°)	20–40	?	?
Cohesion (kPa)	8–10	?	?
The rigidity modulus E (Mpa)	0.8–2.5	?	?
Water permeability k (cm/s)	2–20	?	?
Thermal conductivity λ (W/Km)	0.2	?	?

2.2 Chemical composition

Typical chemical composition of a new tire is presented in table 2.

Table 2. Typical composition of a tire in Finland /Vehkalahti et al. 1989/.

Item	Percentage by weight (%)
Polymer (rubber)	50.8
Zinc oxide	2.1
Sulfur	1.2
Mineral fillings	2.5
Plasticizers and protective compounds	10.2
Steel	6.6
Different kind of textiles	3.6
Carbon black	23.0

2.3 Environmental impacts in literature

The environmental impact of tires and shredded tire chips has been studied considerably in other countries, such as the USA (Repo 1997). According to these studies, depending on prevailing conditions, a certain amount of metals are dissolved from the tires. Metals are dissolved most in acidic conditions. The metals that need to be considered are barium (Ba), cadmium (Cd), chrome(Cr), led (Pb), selenium (Se) and zinc (Zn). The organics that are dissolved are alifatic and polyaromatic hydrocarbons (PAHs). Laboratory tests performed in different pH have indicated that these organics dissolve most in alkaline conditions.

3 Pilot structure

3.1.Location and basic facts of pilot structure

Pilot structure locates at local road 11863 near Porvoo, about 50 kilometers east from Helsinki. The road was first constructed in 1930's. Road section closer to river had suffered nearly every year from flooding river and grade line of road has to be raised. Subsoil is 10 to 25 meters thick, consisting of very weak and compressible clay, silty mud and fat clay. Raising had to be done by lightening the structure to prevent too large settlements and failure of subsoil. Structure was designed so that 200 mm settlement in twenty years is acceptable and that in year 2007 the surface of road still is above the high water level. Pilot structure was constructed August - September in1997.

Pilot structure is 350 meters long and maximum raising of grade line was 800 mm. Cross-section of structure is presented in figure 1. Superstructure is 1160 mm thick with 60 mm thick soft asphalt concrete pavement (PAB-V1500). In last 170 meters a steel net was installed between sub-base and basecourse. Thickness of shredded tire chip layer varies between 350–1350 mm. Chip size RR2 was used. Chips were wrapped around by filter cloth. Altogether some 3740 m^3 (1914 tons) of chips were used. The amount equals to 320 000–340 000 pieces of used tires.

An environmental permit was applied from the Porvoo municipality before constructing the pilot structure. The permit requires that environmental conditions need to be followed during ten years after the construction. The environmental monitoring parameters include from heavy metals chrome, cadmium, copper, zinc, lead, rom the organics PAHs and sulfur as sulfate. Other important parameters like pH, electric conductivity and redox potential are also measured. Sampling is performed for the groundwater and for the water filtered into the lysimeter wells below the structure.

In shortly, constructing the test road was implemented very well with conventional road construction machines and conventional construction methods too. Shaping the tire chip material was easy and the compaction was done by bulldozer and power shovel with treads (Figure 1). When constructing shredded tire structure it must be noticed that because compaction and the weight of superstructure, chips compress 10–15% from its original height.

Figure 1. Constructing the pilot structure.

3.2 Instrumentation and monitoring

Observations of test road includes measurements of bearing capacity by heavy weight deflectometer and settlements by levelling the road surface. To observe the contraction of shredded tire two potentiometers were installed in to the structure. Environmental impacts are monitored by chemical testing of the water samples. Water samples are taken from lysimeter well and standpipe (Figure 2 below). Standpipe was drilled below the soft clay layer to depth of 19,5 meters. Two lysimeters were installed in the road structure to measure the water filtered through the structure. Results of bearing capacity, settlements and contraction of chips are presented in Chapter 4 and the results of environmental monitoring in Chapter 5.

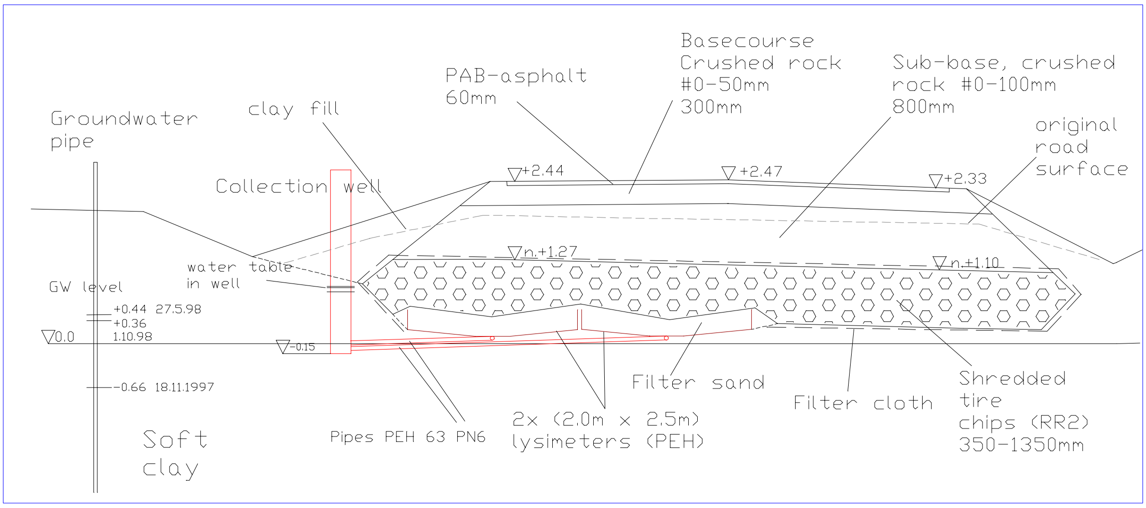

Figure 2. Cross-section (1062) of the pilot structure, water collection system and standpipe at test site.

4. Bearing capacity and settlements of pilot structure

4.1 Bearing capacity

Bearing capacity has improved after construction quite remarkably, by about 50%. In autumn 1999 mean values were 160 MN/m^2 (section without steel net) and 180 MN/m^2 (section with steel net). All the reasons for improvement are not well known. One of the reasons is that viscosity of bituminous asphalt layer has increased and moreover, shredded tire layer has compressed and stiffened under traffic load.

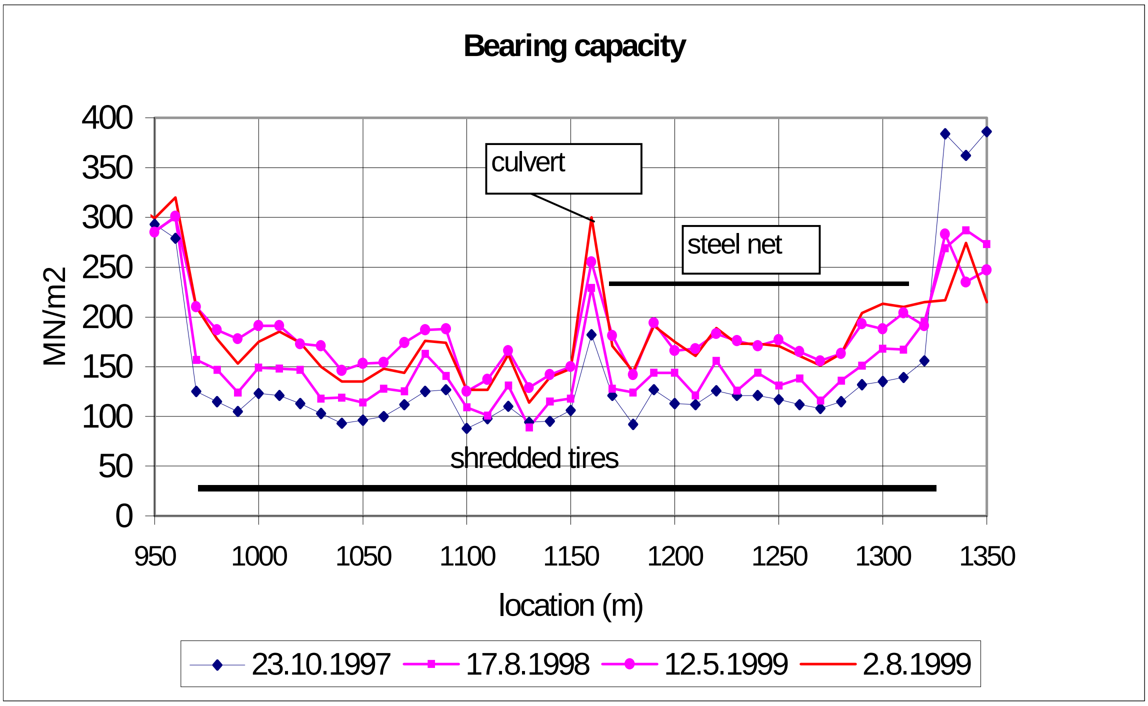

Figure 3. Bearing capacity (heavy weight deflectometer) of structure.

4.2 Settlements and contraction of structure

Measured settlements after construction have been similar to estimation. On the average settlements have been between 40…85 mm in 2.5 years. Steel net seems to reduce settlements. Reason for this might be that steel net makes the structure stiffer and reduce horizontal movements. Around culvert there is no lightening so that part of road is settling faster.

Contraction of shredded tire layer has been 10–13% after construction of the superstructure. After paving contraction has been only 0–0.7% (< 10 mm) in 2.5 years.

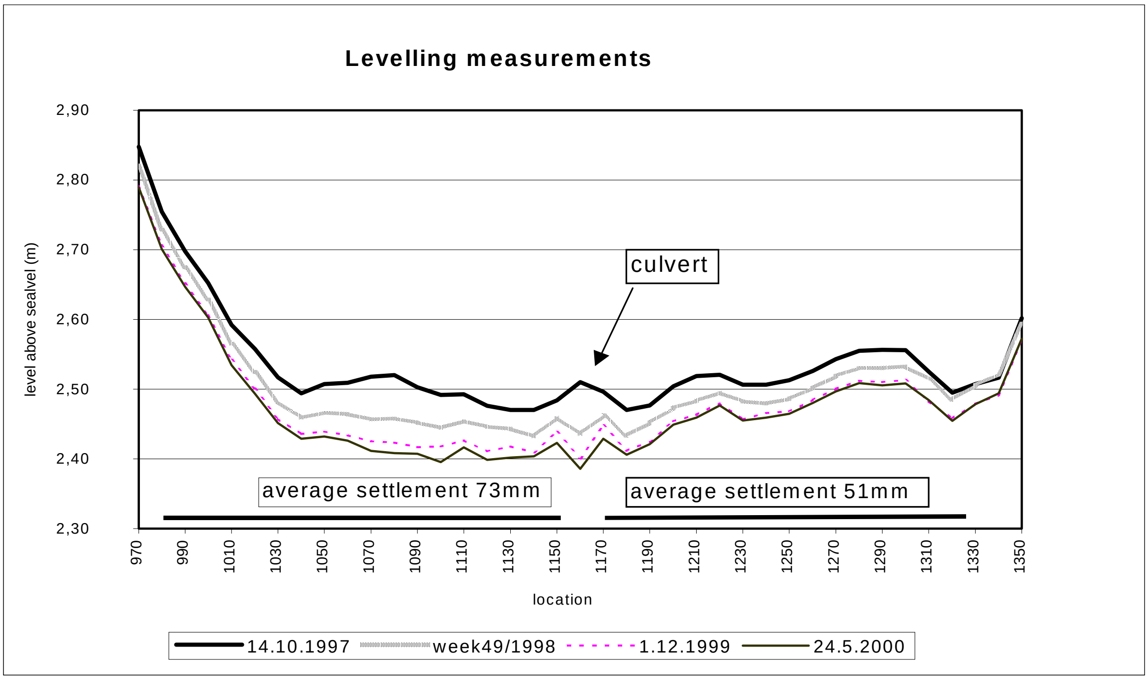

Figure 4. Settlements of test road.

5. Environmental results

5.1 Solubility tests

A leaching test was performed by Technical Research center of Finland before applying environmental permit for the structure. Dutch column test (cumulative L/S 10) and shaking test for 7 days and 30 days (L/S 10) were used. The metals were analysed with FAAS (flame absorption spectrophotometer) and GFAAS (graphite flame absorption spectrophotometer) and the polyaromatic hydrocarbons with GC-MS (gas chromatograph and mass spectrometry) using stantardised methods. Also pH , redox-potential and electric conductivity were measured. Small amounts of copper, zinc and manganese were dissolved. Quite small amounts of PAH's were dissolved. Some methyl-isobutylketone was also detected. Some of the concentrations were increasing with the increasing shaking time. There are no limit values for methyl-isobutylketone in the test and it is not harmfull to the environment in small amounts. Based on the results, it was concluded that the material may be use in earthworks not situating in the important groundwater areas.

5.2 Water quality results of Ilola-Sannainen pilot structure

Table 3. Water samples from lysimeter well.

Element tested	Unit	11/97–1*	11/97-2*	5/98	10/98	5/99	10/99	2/00	Finland limits / quality demands for drinking water**	
									Health	Technical esthetical
Chrome, Cr	mg/l	0.005	0.005	0.004	0.005	<0.002	<0.001	0.006	0.05	
Copper, Cu	mg/l	0.044	0.031	0.025	0.047	0.13	0.01	<0.002	--	1
Zinc, Zn	mg/l	0.12	0.068	0.91	0.15	0.17	0.01	0.005	--	3
Lead, Pb	mg/l	<0.001	<0.001	0.005	0.004	<0.002	<0.001	<0.0005	0.01	
Manganese, Mn	mg/l	1.2	1.2	4.7	3.7	1.7	2.2	0.003	--	0.05
Iron, Fe	mg/l	0.23	0.22	84	6.5	0.005	20	21	--	0.2
Sulfate, SO_4^{2-}	mg/l	370	380	600	590	215	79	63	--	150 (<50)
pH	-	7.5	7.4	6.46	5.93	6.5	7.0	7.0	--	6.5-9.5 (7.0-8.8)
Electric conductivity	mS/m	152	152	146	128	58	74	80	--	--
Redox-potential	mV	222	223	108	164	-	-114	77	--	--
PAH compounds	ng/l	174.2	184.6	98.6	207.2	200	804	815.19	200**	
PAH compounds (5)**	ng/l	11.2	10.1	5.6	8.3		72.87	ND	200**	

ND not detected

* 11/97 two samples were taken from collection well

** Decision of Ministry of Social Affairs and Health on drinking water, 74/1994, Finland. Values in brackets are guidance values. PAH compounds included in the decisision are (5): fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(123-cd)pyrene ja benzo(ghi)perylene

The lysimeter as well as the groundwater results indicate that very small amounts of chrome, copper, cadmium and zinc have been detected in the water samples. Led concentration has been low in the lysimeter well. In the groundwater the concentration in the beginning was 0,084 mg/l which exceeds the limit for drinking water. In 1999 the concentration was below the limit value and in February 2000 it was not detected. It was concluded that high concentration in the groundwater in the beginning was caused by close situation to the main road and the leaded fuel used before year 1995.

Manganese and iron concentrations are high in the lysimeter well. The concentrations have been also at elevated level in the groundwater before construction and after the construction but no effect of the construction can be detected.

Sulfate in the groundwater was also at elevated level before construction and has gradually decreased showing no effect of the construction.

Polyaromatic hydrocarbons have been detected both in the groundwater and in the lysimeter well at elevated levels. In the lysimeter the concentration of total PAHs has been gradually increasing. Sum of five PAH compounds included in the decision of Ministry of Social Affairs and Health on drinking water has been below the limit value for drinking water. In the groundwater the concentration was already at elevated level before construction. After construction the level increased but was still lower than the limit for PAHs in the drinking water. In 1998 and in the spring 1999 the concentration decreased gradually until in the autumn 1999 the concentration for total PAHs was high, 582 ng/l. In February 2000 the concentration was 289 ng/l. Sum of five PAHs has been below the limit value for drinking water.

5.3 Discussion and conclusions of the water quality results

The source of polyaromatic hydrocarbons in the groundwater is not known. The groundwater is not in connection to the perched ground water or to the water in the lysimeters because it lays below 19-25 metres thick soft clay layer. The main sources of PAHs are anthropogenic, but also biological sources for PAHs have been concluded to results for background levels in soil and water, even in remote areas (Cerniglia 1990, Searle 1976). The concentration in the groundwater was at elevated level before the construction and therefore, other anthropogenic source than shredded tires or even biological source may be found. There are implications of possible anthropogenic sources in the same groundwater area situating close to the pilot structure and investigations have already begun.

Results indicate that heavy metal concentrations dissolved from the structure have been small. Manganese, iron and sulfate are dissolved from the structure to a greater amount. Dissolving of polyaromatic hydrocarbons has been increasing since October 1999 sampling. The structure is not in hydraulic connection to the groundwater and no increasing concentrations of the monitored substances have been detected in the groundwater due the structure. The anthropogenic source for polyaromatic hydrocarbons in the groundwater area is under investigations.

6. Conclusion

Test road has functioned so far well. There are no visible damages in road surface and bearing capacity of the structure is increasing. Settlements have been similar to estimation. Steel net in superstructure seems to have a good influence to the behavior of the structure; it stiffens the structure and that reduces and evens the settlements and increases bearing capacity.

The environmetal effects of the structure have been monitored for three years. Monitoring will continue to the end of year 2007. The results indicate that pilot structure has not had any adverse effect in the groundwater quality in the groundwater area. Monitoring results indicate that heavy metal concentrations dissolved from the structure have been small. Manganese, iron and sulfate are dissolved from the structure to a greater amount. Dissolving of polyaromatic hydrocarbons has been increasing since October 1999 sampling.

In the future the road surface will be levelled (measure settlements) one or two times a year and bearing capacity will be measured once a year.

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CONTAMINATED SOILS

Rehabilitation options for a Finnish copper mine

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ABSTRACT The Luikonlahti Copper mine is located near the town of Kaavi in eastern Finland, approximately 30 km northwest of Outokumpu. The copper sulphide ore deposit formed the northern most part of the Outokumpu assemblage. During 15 years of operation, between 1968 and 1983, a total of 33 km of underground tunnels and 5.5 km of underground shafts were excavated in the mining of 6.85 million metric tons of ore. The underground working are now flooded with 2 million m^3 of contaminated water and three open pits contain over 1 million m^3 of contaminated water. Five separate waste rock piles exist and are actively forming acid mine drainage (AMD).

This paper will examine the basic structure of the remediation plan, including remediation techniques that are applicable to the geology and climate of the mine site. Techniques include proven and innovative methods such water covers, wet barriers, composite capping layers and in-pit disposal. Treatment methods for AMD will be discussed including the role of passive treatments, such as wetlands and permeable barriers. The role of risk assessment in the rehabilitation plan, plus the importance of an ecological risk assessment, will be discussed.

1. Acid Mine Drainage (AMD) generation

Acid Mine Drainage is the product formed by the atmospheric oxidation (i.e. by water, oxygen and carbon dioxide) of the relatively common iron sulfide minerals pyrite (FeS_2) and pyrrhotite (FeS) in the presence of (catalysed by) bacteria (Thiobacillus ferrooxidans), and any other products generated as a consequence of these oxidation reactions (i.e. heavy metals solubilized by acidic solutions). The following chemical reactions describe the oxidation of pyrite (FeS_2) to the products that constitute the contaminants generically termed Acid Mine Drainage, although similar equations may be written for the oxidation of pyrrhotite (FeS) (Shaw and Mills, 1998).

Table 1. Chemical reactions involved in the oxidation of pyrite to form AMD (Shaw and Mills, 1998).

$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O = 15FeSO_4 + 8H_2SO_4$	**(1)**
$FeS_2 + Fe_2(SO_4)_3 = 3FeSO_4 + 2S$	**(2)**
$4FeSO_4 + O_2 + 2H_2SO_4$ bacteria $= 2Fe_2(SO_4)_3 + 2H_2O$	**(3)**
$2S + 3O_2 + 2H_2O$ bacteria $= 2H_2SO_4$	**(4)**
$4FeS_2 + 15O_2 + 2H_2O = 2Fe_2(SO_4)_3 + 2H_2SO_4$	**(5)**
$S^0 + 3Fe_2(SO_4)_3 + 4H_2O = 6FeSO_4 + 4H_2SO_4$	**(6)**

The stable pH developed (2.5 to 3.0) and the products of sulphuric acid and ferric sulphate create conditions where the ferric iron ion itself can act as an oxidant (above about pH 3 the ferric ion is itself hydrolyzed to ferric hydroxide, which precipitates as the familiar rust-coloured stain associated with AMD). In the absence of ferric iron at pH 2.5–3.0, sulphuric acid will dissolve some heavy metal carbonate and oxide minerals, but has little reactive effect on heavy metal sulphides. However, ferric iron ion is capable of dissolving many heavy metal sulphide minerals, including those of lead, copper, zinc, and cadmium , by the general reaction: $\mathbf{MS + nFe^{+++} = M^{n+} + S + nFe^{++}}$ **(7)**

Where: MS = solid heavy metal sulphide; Fe^{+++} = aqueous ferric iron ion; M^{n+} = aqueous heavy metal ion; S = sulphur; Fe^{++} = aqueous ferrous iron ion (Mills 1995).

It is by this process that significant amounts of heavy metals maybe solublized by AMD. It has been customary to call Acid Rock Drainage (ARD) with the dissolution of metals by equation 7, **Acid Mine Drainage**, even though this term implies that the process occurs only in association with mining activity.

2. Prediction of AMD

The prediction of AMD generation can be broadly divided into three categories: static tests, kinetic tests and, mineralogy and surveys (Papastavrou and Georgopoulou, 1997). The standard international approach for the prediction of AMD chemistry involves the “Wheel” approach (Figure 1) in which types of static and kinetic tests are conducted and compared (Morin and Hutt, 1998).

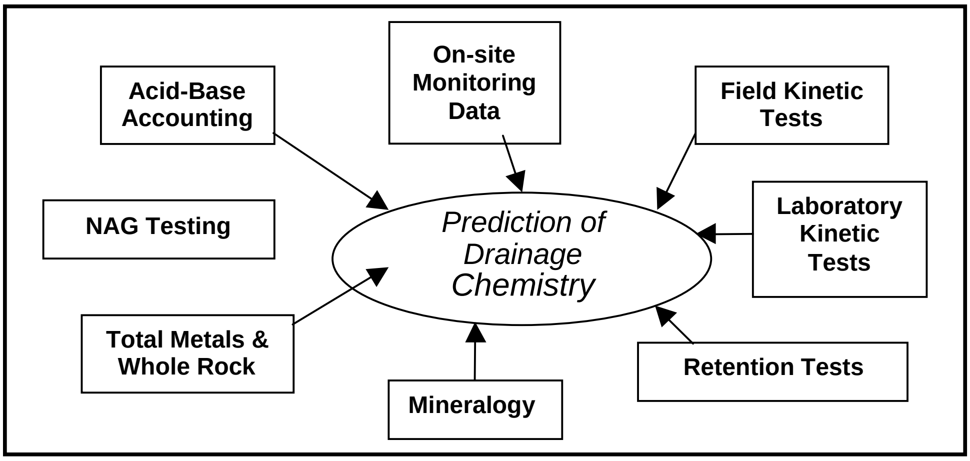

Figure 1. The “Wheel” for Acid Mine Drainage Chemistry (Morin and Hutt, 1998).

Static Tests: These attempt to define the balance between the acid producing components of the material (acid producing AP) which usually are sulphide minerals and the acid consuming components (neutralization potential NP) which usually are carbonate minerals (Morin and Hutt, 1998)

Kinetic Tests: These consist of repetitive cycles of leaching and monitoring either under field or laboratory conditions, and they are used to predict long-term generation rates of metals, non-metals, and parameters such as acidity. These tests can also evaluate the effect of biological reactions (Lawrence and Sheske, 1997).

Mineralogy and Surveys: Surveys such as magnetic surveys and IP/resistivity measurements may also be applied to locate zones of increased sulphide concentrations (Papastavrou and Georgopoulou, 1997). A sample's mineralogy is a critical aspect in the prediction of its acid generation, acid neutralisation, and metal leaching (Morin and Hutt, 1998).

3. Risk assessment

Risk assessment is an analytical tool used to identify the potential adverse effects to humans and ecosystems resulting from exposure to environmental hazards. Health risk assessment deals with effects on humans and ecological risk assessment with effects on ecosystems. Risk assessment is a tool providing a basis for site-specific decisions (e.g. one criterion for choosing remediation/rehabilitation techniques, identifying chemicals of concern, prioritizing sensitive receptors). It can also be used to assess acceptable contaminant levels in the environment (Kuusisto, 1999).

Health risk assessment (HERA) methodologies and techniques are firmly established. The most commonly used framework involves the following steps: hazard identification, exposure assessment, dose-response assessment and risk characterization (EPA 1989). HERA produces measures of risks, which contain the probabilities of the possible adverse outcomes and the uncertainties involved.

Ecological risk assessment: Ecological risk assessment (ERA) is the process of estimating the likelihood that adverse ecological effect (e.g. reduced species diversity) will occur as a result of exposure to a physical, chemical or biological stressor (e.g. elevated metal concentration). ERA includes three primary steps: problem formulation, analysis and risk characterization (EPA 1998). In problem formulation, goals are evaluated and assessment endpoints selected. Also, a conceptual model is prepared and an analysis plan developed. In the analysis phase, exposure to stressors is evaluated (exposure assessment) and the relationship between stressor levels and ecological effects is estimated (toxicity assessment). Finally, in risk characterization, risk is estimated through integration of exposure and stressor- response profiles (Kuusisto, 1999).

Table 2. Data that will be collected as a part of ERA. (Adapted from VEPA 1997).

ERA COMPONENT	DATA THAT MAY BE COLLECTED	RESPONSIBLE PARTY
Problem formulation	**Extent and degree of contamination**	**TUT / Mondo Minerals**
	Identification of contaminants of concern	**Risk assessor**
	Distribution of biota of ecological value at the site (biological survey)	**Ecologist/biologist?**
Exposure assessment	**Fate and transport modeling of chemicals of concern**	**Risk assessor**
	Literature-based inhalation, ingestion and absorption rates	**Risk assessor**
	On-site environmental properties that affect contaminant mobility/availability (e.g. *foc*, pH, bulk density, porosity)	**TUT / Mondo Minerals**
	Bioavailability factors	**Risk assessor**
Toxicity assessment	**Literature review of relevant toxicological studies**	**Risk assessor**
	Laboratory toxicity tests	
Risk characterization	**Integration of preceding steps**	**Risk assessor**

AMD with elevated metal concentrations from the Luikonlahti mine drains to the nearby lakes and to groundwater. Water ecosystems are known to be susceptible to metals and, therefore, ecological risk assessment is warranted.

The risk assessment process in Luikonlahti case will contain the following steps (Kusisto, 1999):

- Establishing a planning group, which will meet prior to and during the risk assessment process. ERA planning team could include e.g. representatives of Mondo Minerals, environmental authorities, risk assessors, local communities and environmental groups.
- Data collection
- Risk assessment (health and ecological)
    1. Risks caused by the current state
    2. Risks caused by the different remediation options
- Reporting

4. Rehabilitation options

The rehabilitation options for the Luikonlahti site revolve around the principals of prevention and control. Regarding the fundamental processes governing the generation of AMD and metal release from mine water, methods for prevention and control of AMD in general aim at either:

- Changing the chemical properties of the waste prior to disposal by, for example, separation of pyrite or blending of waste rock with acid consuming material,
- restricting the transport of oxygen and/or water into the waste dump or
- treating the leachate (MiMi1998).

Prevention and control methods can be divided into four different groups:

1. Treatment of waste which includes altering the chemical properties of the waste but also altering the physical properties of the waste in order to limit the transport of oxygen or air into the waste dumps.
2. Flooding of the waste, i.e. a water table is established above the disposed waste as a barrier in order to limit the transport of oxygen or air into the waste.
3. Dry covering of the waste in order to limit the transport of oxygen and/or water into the waste dump.
4. Treatment of AMD with the purpose to reduce the metal concentrations and neutralized the water that is discharged for the site.

Water Covers: Water cover is considered the most effective of all AMD prevention and control measures (MEND 2.18.1, 1997). The maximum concentration of dissolved oxygen found in natural waters is approximately 25,000 times lower than that found in the atmosphere.. The solubility of oxygen in water is quite low (11 mg/L at 20^oC) and the diffusion rate of oxygen through water is about 10,000 times slower than through air. This means that the rate of oxygen transported through water is sufficiently slow to be of no significance in acid generation.

Major factors influencing the application of a water cover include the availability of water and the cost of maintaining the required depth of water in the long term. The cover maybe achieved by the disposal of wastes into natural water bodies, into engineered impoundments (such as dykes or dams) or into flooded underground mine workings and open pits (ARD Tech. Guide, 1989).

Sub-aqueous disposal: The principal of water cover applies if acid producing material is deposited in a deep water body such as lakes or marine places. Possible environmental impacts related marine or lake disposal are the toxicitry of heavy metals, the increased turbidity due to suspended solids and direct physical impact on inhabitants. (ARD Tech. Guide, 1989).

In-pit disposal: Open pit mines that have ceased production are increasingly being considered for the permanent and environmentally acceptable disposal of mine waste rock and tailings that are, or have the demonstrated potential to become, sources of acidic drainage. There are four basic concepts for the placement of wastes in pits:

Option 1 - Underwater disposal
Option 2 - Elevated water tables
Option 3 - Dry disposal
Option 4 - Perched water tables (MEND,1995).

Soil Covers: Soil covers (or dry covers) are placed over mine wastes to reduce oxygen diffusion and water infiltration (MEND, 1994). The effectiveness of a soil cover as an oxygen barrier is dependent on its moisture content. A cover that can be maintained in a saturated condition will be more effective because of the low diffusivity of oxygen in the pore water and absence of desiccation cracking (MEND 2.35.2b, 1997). In general, soil covers can be classified according to their function as shown in Table 3.

Table 3. Soil cover classification (adapted from MiMi 1998).

Cover Type	Primary Function
1. Oxygen diffusion barriers	To limit the transport of oxygen by acting as a Barrier against the diffusion of oxygen to the waste
2. Oxygen consuming barriers	To limit the transport of oxygen by consumption of which penetrates into the cover
3. Low permeability barriers	To limit the transport of oxygen and the formation of leachate by acting as a barrier against the diffusion of oxygen as well as the infiltration of precipitation
4. Reaction inhibiting barriers	To provide a favourable environment to limit reaction rates and metal release

In Finnish winter conditions, the effects of freezing and thawing on a saturated soil cover is a major design factor. Another major factor in selecting the appropriate cover material is the availability of local soil types. Cost is a limiting factor in the soil cover design process. Local soils are much cheaper to use than soils that have to be transported distances (MEND 2.35.2b, 1997). The final factor in regard to soil cover design for the Luikonlahti site is climate. The net water balance delivered to the ground surface of the site is a positive value, and therefore the site can be considered a “wet” site. This is a key feature regarding the performance of the cover system that will be selected for use and allows for a system that utilizes a saturated condition.

Innovative Covers: Innovative "dry" cover research is indicating that several materials, including waste materials from other industries provide excellent potential at lower cost for generating moisture-retaining, oxygen-consuming surface barriers. Recent studies have shown that clean (non-acid generating) tailings, often available close to problematic sites, can be used as a lower cost alternative for the fine material in layered cover systems (MEND, 1996, MEND, 1999).

Single layer covers: To meet the requirements of an oxygen transport barrier, a single layer cover should be constructed of a material with mainly fine pores, which is generally true for fined grained materials (clays, clayey silts) and well graded materials with a high content of fines (clayey and silty tills) (MiMi, 1998). A single layer cover can be an efficient oxygen transport barrier particularly at sites where the ground water table is close to the ground surface and conditions are favourable to maintain a high degree of saturation in the cover.

Composite covers: Composite cover systems consist of several layers (up to six) and may include synthetic membrane covers, compacted layers and drainage layers. Composite covers provide good medium-term control but they are sensitive to long term degradation (ARD Tech. Guide, 1989, MiMi, 1998).The basic cover design rationale for composite covers design is:

- base granular material draining to residual saturation before fine grained till layer,
- fine grained glacial till with low hydraulic conductivity as a moisture and oxygen barrier,
- overlying coarse grained granular layer as a recharge layer to the underlying till layer, and
- surfacial coarse grained layer for erosion protection.

5. Treatment of AMD

Passive Treatment of Acid Mine Drainage: Passive treatment systems have been developed that do not require continuous chemical inputs and that take advantage of naturally occurring chemical and biological processes to cleanse contaminated mine waters. The primary passive technologies (Figure 2) include constructed wetlands, anoxic limestone drains (ALD), successive alkalinity producing systems (SAPS), limestone ponds, open limestone channels (OLC) and permeable reactive barriers (PRB).

Natural wetlands are characterised by water-saturated soils or sediments with supporting vegetation adapted to reducing conditions in their rhizosphere. Constructed wetlands are man-made ecosystems that mimic their natural counterparts. Often they consist of shallow excavations filled with a flooded gravel, soil, and organic matter to support wetland plants, such as *Typha*, *Juncus*, and *Scirpus* sp. Treatment depends on dynamic biogeochemical interactions as contaminated water travels through the constructed wetland

ALDs are abiotic systems consisting of buried limestone cells that passively generate bicarbonate alkalinity as anoxic water flows through. SAPS combine treatment concepts from both wetlands and ALDs. (Skousen and Ziemkiewicz, 1995). PRBs are installed in aquifers down gradient of contaminated source areas and are designed to stimulate sulfate reduction and metal sulphide precipitation reactions (Papastavrou and Georgopoulou, 1997).

Selection of an appropriate passive system is based on water chemistry, flow rate and local topography and site characteristics (Hyman and Watzlaf, 1995), and refinements in design are ongoing. In general, aerobic wetlands can treat net alkaline water; ALDs can treat water of low Al, Fe^{3+}, and DO; and SAPS, anaerobic wetlands and OLCs can treat net acidic water with higher Al, Fe^{3+}, and DO.

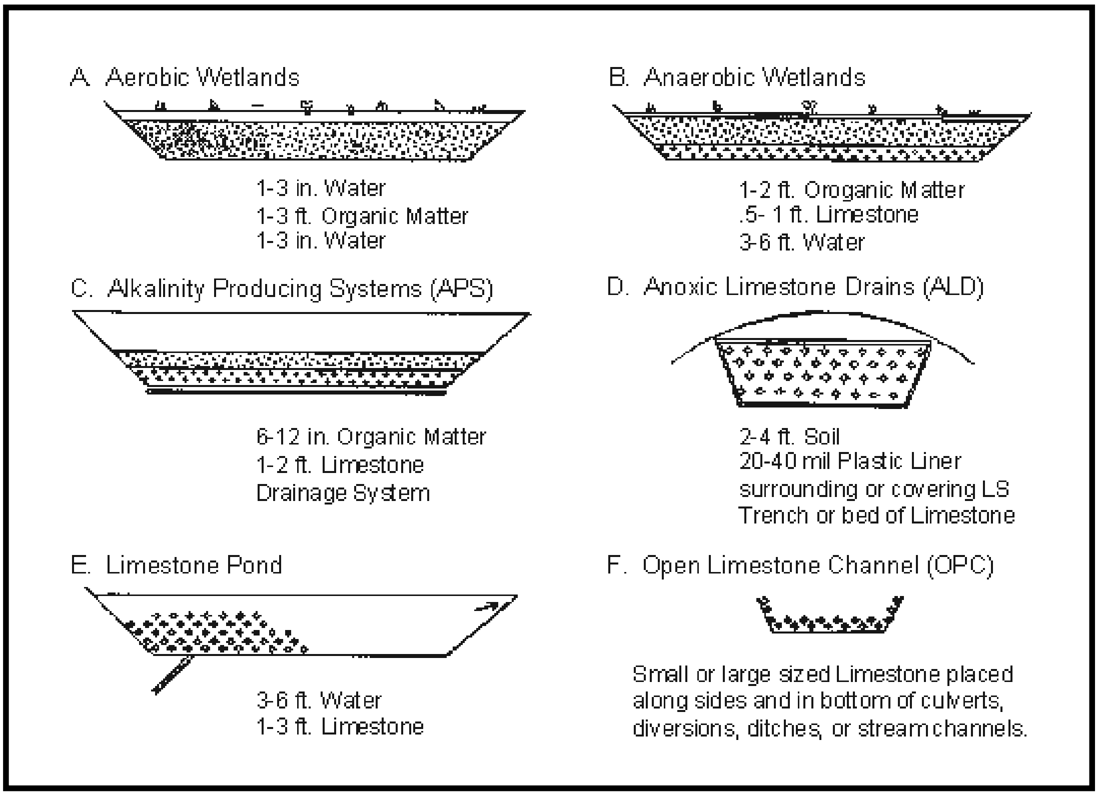

Figure 2. Passive treatment options for AMD (Skousen and Ziemkiewicz, 1995).

Chemical Treatment of Acid Mine Drainage: Six primary chemicals have been used to treat AMD (Table 4). Each chemical has characteristics that make it more or less appropriate for a specific condition. The best choice among alternatives depends on both technical and economic factors. The technical factors include acidity levels, flow, the types and concentrations of metals in the water, the rate and degree of chemical treatment needed, and the desired final water quality. The economic factors include prices of reagents, labor, machinery and equipment, the number of years that treatment will be needed, the interest rate, and risk factors (Skousen et al, 1990).

Table 4. Chemicals available to treat AMD (Skousen et al, 1990).

Common Name	Chemical Name	Formula	Conversion	Neutralization
			Factor[1]	Efficiency[2]
Limestone	**Calcium carbonate**	**$CaCO_3$**	**1**	**30%**
Hydrated Lime	**Calcium hydroxide**	**$Ca(OH)_2$**	**0.74**	**90%**
Pebble Quicklime	**Calcium oxide**	**CaO**	**0.56**	**90%**
Soda Ash	**Sodium carbonate**	**Na_2CO_3**	**1.06**	**60%**
Caustic Soda (solid)	**Sodium hydroxide**	**$NaOH$**	**0.8**	**100%**
20% Liquid Caustic	**Sodium hydroxide**	**$NaOH$**	**784**	**100%**
50% Liquid Caustic	**Sodium hydroxide**	**$NaOH$**	**256**	**100%**
Ammonia	**Anhydrous ammonia**	**NH_3**	**0.34**	**100%**

[1] The conversion factor may be multiplied by the estimated tons acid/yr to get tons of chemical needed for neutralization per year. For liquid caustic, the conversion factor gives gallons needed for neutralization.

[2] Neutralization Efficiency estimates the relative effectiveness of the chemical in neutralizing AMD acidity. For example, if 100 tons of acid/yr was the amount of acid to be neutralized, then it can be estimated that 82 tons of hydrated lime would be needed to neutralize the acidity in the water (100(0.74)/0.90).

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Possibilities for biotechnical *in situ* -remediation of groundwater contaminated by sulfite pulp mill effluents

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ABSTRACT: Biotechnical *in situ* -remediation of groundwater contaminated by sulfite pulp mill effluents was examined in laboratory scale. The contaminated groundwater and soil consisted mainly of organic substances dissolved from wood and formed during sulfite pulping. The contaminants consume oxygen in the groundwater. *In situ* -simulation with air-lift percolators and a semi-continuous reactor were performed in dark at 9 ^{o}C. The highest DOC -concentration was 8400 mg/l and the average DOC reduction rate was 56.7 mg/d. The DOC reduction achieved was 13–17%. The effects of pH and presence of the original soil material were studied. There was no significant difference in the performance of the percolators at the ambient (4,3–4,5) or adjusted (6,5–7,5) pH. Neither was the DOC-reduction of the percolators containing the original soil material higher than the one containing only burned and washed sand. The possibility of maintaining a stable DOC-reduction was studied with a semi-continuous reactor test. Average DOC-reduction of 20 and 7.8% with hydraulic retention times of 7.6 and 1.6 d, respectively, were achieved.

1. Introduction

A lot of organic contamination of soil and groundwater has occurred earlier years by industrial activity. Because of carelessness and lack of knowledge large amounts of industrial waste has been led in the environment without any treatment. Under today's environmental regulations a restoration of contaminated environment is often demanded.

The restoration can be based on physical, chemical or biological processes. The use of biological remediation technologies has been getting more popular as an increasing number of micro-organisms has been found with the capacity of degrade organic compounds earlier classified as non-biodegradable.

The aim of the work was to study the possibilities for biological *in situ* -stabilisation of the polluted groundwater.

2. Materials and methods

2.1 Site description and sampling

The study area is located in Central Finland about 20 kilometres east from Jyväskylä. The groundwater and the soil of the area are contaminated by old sulfite pulp mill effluents. The effluents consist mainly of organic substances dissolved from wood. A large part of the organic substances are lignin derivatives (probably lignosulfonates) formed during the pulping process (Vilén 1993). The contaminants increase the consumption of oxygen when released in the water system. The contamination was occurred in 1935–1967. The total amount of waste water released in the area is approximately 2.9 millions m^3 (Suvilampi and Rintala 1999). The estimated total area of contaminated soil is about 225 000 m^2 of which the area of the pond where the effluents have been released has been about 95 000m^2

(Mäkelä 1994). The water used in the experiments was taken from a well, situated about 200 meters south-east from the pond. Water samples were stored at 9^{o}C in dark.

2.2 Air-lift percolators

The *in situ* -bioremediation simulation was performed in glass air-lift percolators in the dark at 9^{o}C. (Puhakka and Tuovinen 1986, Langwaldt *et al.* 1998) (Fig. 1). The percolator was filled with two layers of sand. The sand was dried at 180 ^{o}C for 3 hours. Dry sand was passed through a sieve with a mesh size of 0.5 mm (fine grained sand) and 1.68 mm (coarse-grained sand). The fractionated sand was heated at 550^{o}C for 1 h and then boiled for 1 h in 5mM HCl to remove organic matter. 200 g of coarse-grained sand was added in the bottom of the percolator and 1000g fine-grained part on the top of it.

The liquid phase of the percolators was replaced with new waste water sample and nutrient solution when the degradation was getting slower (three times) or at the end of the experiment every two weeks to see if the velocity of degradation is still increasing. The liquid level in the percolator was held above soil level to simulate saturated subsurface conditions. The amount of water added at the time was 1000 ml. The total time of the experiment was 149 d.

The effects of pH and presence of the original soil material were studied simultaneously in parallel percolators.

The oxygen concentration in the liquid was maintained at 5 mg/l by aeration of the recycle flow.

Samples were taken from the sampling port at the bottom of the percolators. The parameter monitored was dissolved organic carbon (DOC).

At the end of the experiment NaN_3 (200 mg/l) was added in the water to show non-biological removal.

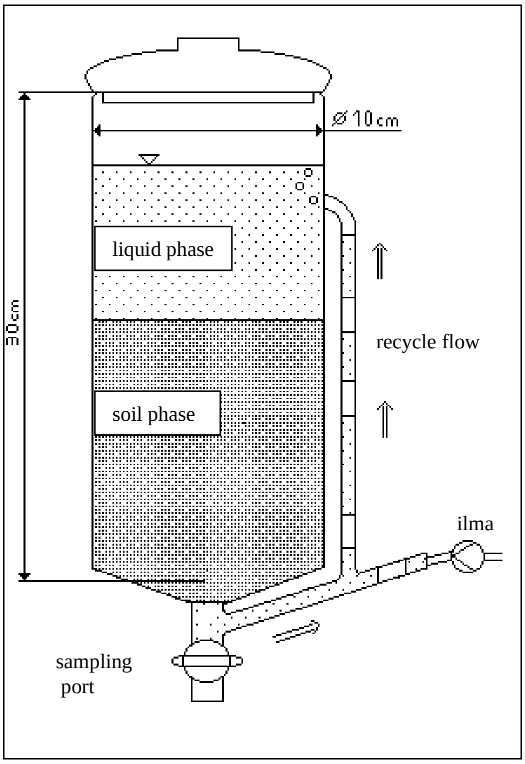

Figure 1. A schematic diagram of an air-lift percolator.

2.3 Semi-continuous flow reactor

The principle of the semi-continuous reactor is shown in Figure 2. The total liquid volume of the reactor was 7.4 l. 1000 g of gravel was added in the bottom of reactor. On the top of this layer were added 5000 g of gravel (mesh size > 5 mm) mixed with 3000 g of the soil from the polluted area. The gravel was heated at 550^0C (1 h) before the experiment. The water was neutralised with 10% NaOH and a sufficient amount of nutrients were added.

The oxygen concentration in the reactor was kept at 10 mg/l.

The water was first circulated in the rector during 18 d to enrich a microbial population. The circulation flow was about 6 l/d. After the enrichment period a flow of 970 ml/l of water was led through the reactor for 35d. After that period the flow was increased to 4500 ml/d for 9 d. The hydraulic retention times in the reactor were 7,6 and 1,6 d respectively. DOC -concentration and pH of the inflow and the outflow were monitored.

The experiment was performed at 7,5 ^{o}C in dark.

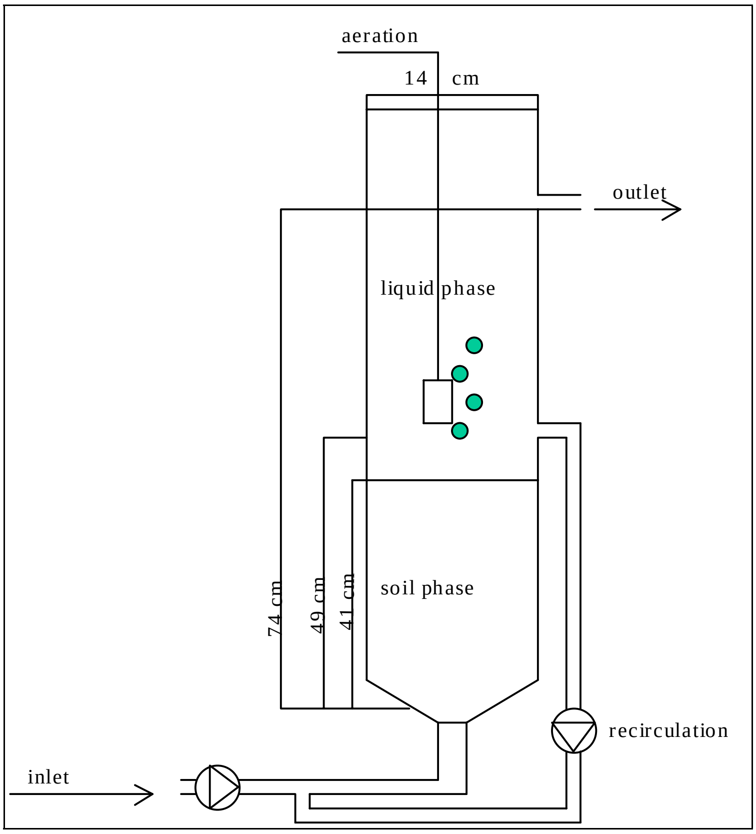

Figure 2. A schematic diagram of the semi-continuos flow reactor.

2.4 Analyses and the nutrient media

The pH of the water was determined with SenTix 97T electrode (WTW Ltd. Weilheim Germany).

The oxygen concentration was determined with an oxygen sensitive electrode EO96 (WTW Ltd. Weilheim Germany).

The dissolved organic carbon (DOC) concentration was analysed with Shimadzu TOC-5000 analysator connected with Shimadzu ASI-5000 autosampler. Diluted (1:100) samples were filtered before analysis with 0.45 µm Whatman Puradisc^{TM} 25 AS filters.

In the experiments a buffered nutrient solution based on Ortega-Calvo *et al.* (1995) was used. The nutrient solution was added in the water to achieve DOC:N:P -relation 100:5:1. The initial BOD_7/DOC -ratio of the water was 0,86.

3. Results and discussion

3.1 Air lift percolators

The aim of the air-lift percolator experiment was to simulate the bioremediation of the polluted groundwater. The liquid phase of the percolators was replaced with new ground water sample and nutrient solution when the degradation slowed down or at the end of the experiment every two weeks to see if the velocity of degradation was still increasing. The liquid level in the percolator was held above soil level to simulate saturated subsurface conditions. The amount of water added was 1000 ml. The total time of the experiment was 149 d. The results are shown in Figure 3.

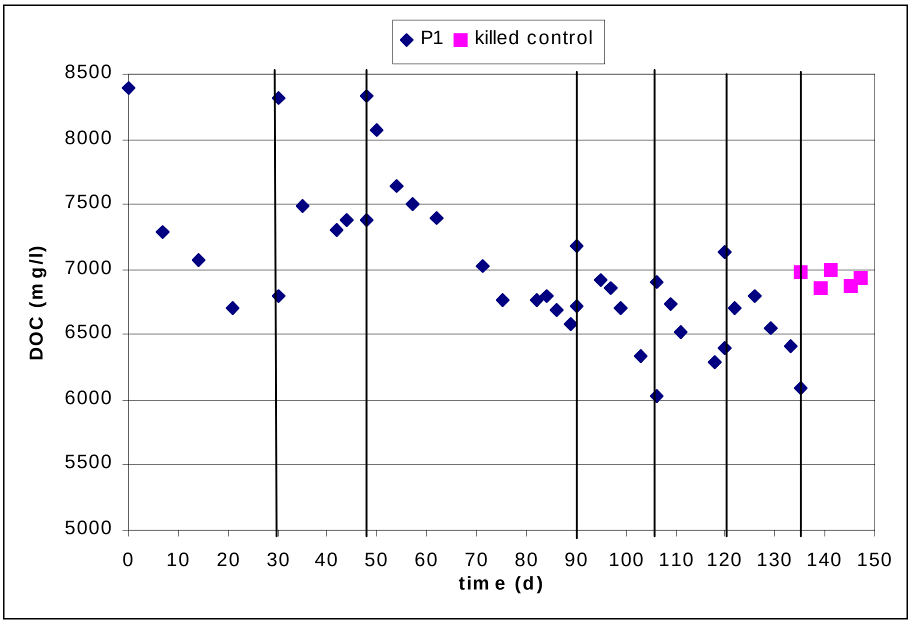

Figure 3. Groundwater DOC removal in air-lift percolator. The vertical lines show the times of groundwater replacements. The percolator was operated at ambient groundwater pH.

The highest initial DOC -concentration was 8400 mg/l and the average DOC reduction was 56,7 mg/d. The DOC reduction was between 13–17%.

At the end of the experiment 200 mg/l of NaN_3 was added in the water which stopped biodegradation (Figure 3).

The effects of pH and presence of the original soil material were also studied. There was no significant difference in the performance of the percolators of the original (4.3–4.5) or regulated (6.5–7.5) pH. Neither was the DOC-reduction of the percolators containing the original soil material higher than the one containing only burned and washed sand.

The biodegradation rate did not increase during the experiment. This may be due the strong biomass accumulation in the percolator, which decreased the recirculation rate of the water.

3.2 Semi-continuous flow reactor

The aim of the semi-continuous flow reactor experiment was to find out the possibility of maintaining stable DOC-reduction. The effect of retention time was also studied.

The water was first circulated in the reactor for 18 d to enrich a microbial population. The circulation flow was about 6 l/d. After the enrichment period a flow of 970 ml/l of was led through the reactor for 35d. After that period the flow was increased to 4500 ml/d for 9 d. The hydraulic retention times in the reactor were 7,6 and 1,6 d respectively. DOC -concentration and pH of the inflow and the outflow were monitored. The results are shown in Figure 4.

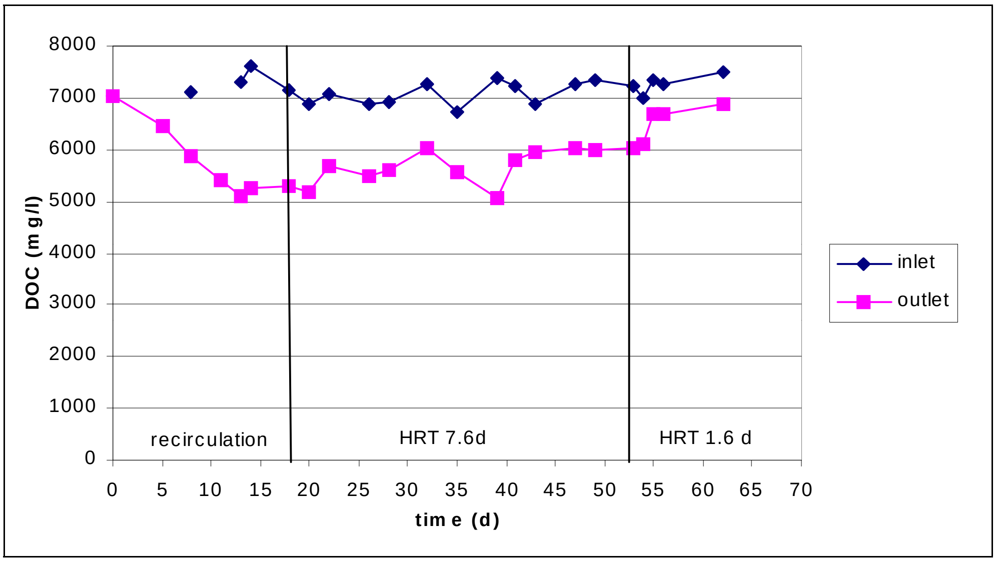

Figure 4. Degradation of DOC in continuous-flow reactor.

During the recirculation period the DOC -concentration decreased by 25%. Average DOC-reductions of 20 and 7.8% with hydraulic retention times of 7.6 and 1.6 d, respectively, were achieved. In previous tests at the room temperature (Anttila 1999) 46% of the DOC was biodegradable. Rintala and Suvilampi (1999) reported similar results when testing the biodegradability of the water of the bottom layers of the pond. With 4 days aerobic biodegradation tests in a lab-scale batch reactor they measured soluble chemical oxygen demand (SCOD) reductions of about 46±2% at 20^{o}C.

4. Conclusions

Over 20% reduction of groundwater DOC was achieved in a lab-scale in-situ simulation system at ambient groundwater temperature in dark when nutrients and air is added into the system. A stable DOC -reduction of 20% was achieved at a hydraulic retention time of 7,6 d.

The better results with semi-continuous test than with percolator tests were mainly due to better recirculation of water in the reactor. That was because of higher flow rate and bigger soil particle size in the reactor.

In field circumstances the biomass accumulation is a limiting factor for biotechnical *in situ* remediation.. On the other hand, the biomass accumulation could be used for controlling the water flow in the aquifer.

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The risk assessment of PCB contaminated soil and water – calculated and perceived risk

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ABSTRACT: Polychlorinated Biphenyls (PCBs) are both toxic and carcinogenic contaminants that bioaccumulate within the food chain and are persistent for long periods of time. This means that the receptors (or targets) identified as at risk from a particular source can be numerous over the time period that the PCBs remain in the environmental media. A Risk Assessment therefore has to consider a wide range of pollutant linkages and complex scenarios as the PCBs are transported through the environment.

The perceived risk from PCBs is heightened in relation to many contaminants as they are banned substances under UK law and EC Directive 76/464/EC on Dangerous Substances, where they are classified as List 1, Black List chemicals, and therefore “require clean-up”. However, remedial action has few choices, so is both difficult and expensive with most PCB contaminated sites having to undergo exsitu incineration. The calculated risk may show that although present, PCBs do not require action, but this must be balanced by the perceived risk which may actually become the driving force for clean-up. Therefore a sensible balance has to be sought between industry, the Regulatory Authority and local people who all identify risk differently.

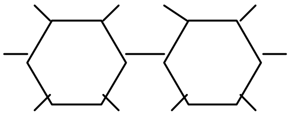
The problems associated with PCB risk assessment and the interpretation of source-path-receptor will be illustrated with reference to studies taken from the UK.

1. Introduction

Polychlorinated Biphenyls (PCBs) are banned substances in the UK, due to their ability to bioaccumulate and remain persistent in the environment, as well as due to their toxic and carcinogenic effects. PCBs are man-made chlorinated aromatic hydrocarbons, which historically, have been used as dielectrics in transformers & capacitors, used in hydraulic systems, in lubricating oils, and as plasticisers and solvents in paints and plastics. The environmental implications of PCBs were first identified in Sweden in 1966, and in the UK sale of “open application” PCBs was banned in 1972 (e.g. plastics, varnish, cutting oils). Production in the UK ceased in 1977, and in 1979, all uses of PCBs were banned. However, PCBs are now found world-wide, including Polar Regions thousands of miles from the original sources, due to the persistence and mobility of these compounds.

2. Composition of PCBs

PCBs are aromatic chemicals, manufactured by the chlorination of biphenyl. The chemical formula is $C_{12}H_{10-n}Cl_n$, where the chlorine number ranges from 1 to 10.



There are theoretically 209 congeners (individual PCBs), although only 130 are generally found to occur in commercial products. PCBs were generally sold in mixtures of a number of different isomers and congeners, generally under the trade name “Aroclor”; the Aroclor number varying according to percentage by weight Chlorine, e.g. Aroclor 1260 contains 60% chlorine.

Individual congeners are colourless, often crystalline compounds, but commercial PCB mixes form yellow oily liquids to resins, with properties varying with the mixes. PCBs have a high degree of chemical stability under normal conditions, (19 PCBs are stable at room temperature), with low water solubility. PCBs however are lipophilic; they have high fat solubility, and are also soluble in organic matter. These properties govern PCB fate and transport in the environment - coupled with their resistance to breakdown by a wide range of oxidants and other chemicals - this means that metabolism in an organism is very slow, therefore bioaccumulation occurs in the adipose (fatty) tissue.

3. Toxicology

PCBs are classified as both toxic chemicals and carcinogens for humans as well as other animals, with 12 of the 209 congeners considered dioxin-like. A further 9 are considered highly toxic, and 25 have been commonly identified bioaccumulated in milk or fish. Less research has been carried out on vegetation, although this is contaminated from soils generally due to adsorption onto the outer surface of the plant, although some absorption may occur onto the waxy outer cuticle of the plant. There is no evidence for PCBs being particularly phytotoxic (except for a slowing of growth at very high concentrations); however this is an uptake route for herbivorous animals, and thus to higher mammals. Aquatic life is especially prone to bioaccumulation, with the PCB concentrations increasing up the food chain. In the UK the Ministry of Agriculture, Fisheries & Food (MAFF) has measured concentrations of PCBs in fish-liver oils for human consumption as well as PCB concentrations in many other foodstuffs (MAFF 1989). Cod liver oil was found to contain between 0.9 and 1.2mg/kg PCB, and Halibut Liver oil 7mg/kg. It should be noted that for a risk level of 1 in 1 million, the US Food and Drug Administration (FDA) consider the concentration of PCBs in water should be below 0.1μg/l and the safe limit in foodstuffs to be between 0.2 and 3mg/kg. There are no limits for PCBs in food stuffs within the UK.

Human studies relate to commercial mixtures, rather than individual congeners, and are generally based on those that worked in the manufacture or use of PCBs, and those that have ingested high levels of PCBs through contaminated foodstuffs. Two highly publicised incidents in particular, both in Japan, (Yusho and Yu-Cheng), involved contaminate rice bran oil. Victims showed acute toxic effects, such as Chloracne, pigmentation and death; long term chronic effects, e.g. liver cancer, respiratory problems and Central Nervous System Damage, and finally developmental damage to children born of the victims. However, it should be noted that in the two incidents PCBs plus other impurities such as Polychlorinated Dibenzo-Furans (PCDFs) (which are known carcinogens), were present.

4. Risk analysis

As demonstrated in Sections 2 and 3 above, the main driving forces behind PCB focussed environmental assessment are the toxicity and carcinogenity of PCBs, and their ability to bioaccumulate and remain persistent in the environment. Due to their hydrophobic and lipophilic nature they remain relatively immobile in soil, but due to media attention as Polar contaminants', PCBs are perceived as highly dangerous chemicals, achieving the same reputation that pesticides such as DDT did, after "*Silent Spring*" was published.

4.1 Source characterisation

The calculated assessment of risk is complex for PCBs firstly due to their persistence. This means that firstly the receptors identified as at risk from a particular source can be numerous over the time period that the PCBs remain in the environmental media. A Risk Assessment therefore has to consider a wide range of pollutant linkages with greater uncertainties in the risk analysis model data for historic and potential future pollutant linkages. Secondly, it is difficult to accurately characterise the PCB source. This is due to several factors; certain PCB congeners are difficult to analyse for, the original Aroclor used is not known, and commercial PCB mixtures, have, through transformation, partitioning and biological metabolism, altered greatly in congener profile. Unfortunately much of the laboratory work with regard to toxicity has been carried out on "pure" commercial mixtures, and a few selected individual congeners. In many cases, the environmental mixture analysed will be relatively more toxic overall than the commercial mixture, since it is generally the most toxic and most dioxin-like congeners that have the greatest persistence.

Therefore for a credible risk assessment, with limited uncertainties, a number of points have to be considered to assess the environmental mixture. Firstly the composition of the mixture as individual congeners will vary in toxicity and carcinogenity (required for human and ecological risk assessment), and secondly the mobility and migration rate of individual congeners additionally varies (the less chlorinated congeners are more water soluble, whilst the higher chlorinated congeners sorb more to particulates and sediments). Therefore although calculating risk based on Aroclor type is acceptable, a more accurate estimation of risk can be calculated using individual congeners as part of an environmental mixture.

In a water environment it is therefore often expected that given the properties of PCBs there should be a "chromatograph" like effect away from the original source. However, work done by IERC for the Environment Agency (EA) (EA 1997) and GeoDelft on contaminated streams and estuaries in the UK, has shown that although a few of the more soluble congeners may be found in the water near the source, the pattern of congeners does not seem to relate strongly to chlorination. For the site in Figure 1 below, there was a slight increase of the more toxic, more chlorinated, congeners with distance from the source, and a slight decrease of the lightest, most soluble congeners (di & trichlorobiphenyls such as IUPAC congener numbers 4 and 30). Many of the mid range congeners showed no pattern at all (including one of the most toxic congeners, IUPAC Number 77), although they did show more direct correlation with other environmental factors.

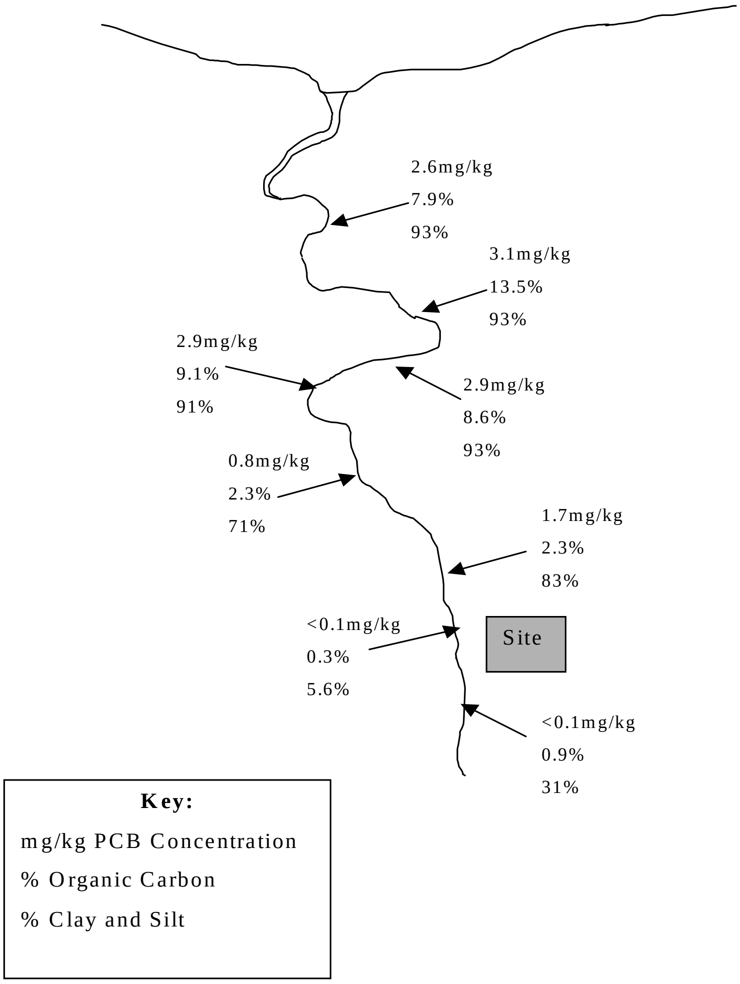


Figure1. Showing relation between PDB sediment content & organic content and fine sediment.

For mid-range congeners and overall total PCB concentration, there was strong correlation against organic matter and to some extent clay content in stream sediments. Thus PCB contamination may be found away from the source, concentrated in slow moving/depositional environments and/or organic environments. This can lead to confusion in the interpretation of the source area (See Figure 1). As can be seen in the accompanying figure, the concentrations of PCBs were low close to the main source due to the stream sediments being mostly sand. The highest concentrations correlated to the organic content. This organic matter was highest in a large bend in the water-course, where flow rates were low, and in addition there was nutrient input from a fertiliser factory. This lead to the increase in organic content. However, although the bend was the area of highest concentration, it was not linked with the industry on this bend.

It should also be noted that for the three sample locations upstream of the alleged site, that the background total PCB content of the sediment varied from 1.3µg/kg to 21.9µg/kg. This, it can be assumed, is from aerial deposition, via run-off from the land. This highlights the fact that the presence of PCBs on a site does not necessarily indicate a site source, but may in fact indicate the local or national background concentration.

A second example concerning the difficulty of identifying a historic PCB source area, also occurred in the UK, where a major river and estuary was contaminated at low levels by PCBs. However, prior to the site being identified, elevated concentrations of PCBs had been found in eels by the Regulatory body, upstream of the input from the site. No PCB input was identified near the eel sampling area, and downstream was not considered. However, due to the migratory habit of eels, the PCB input did not have to be upstream of the sampling area.

Finally, the identification of PCBs on a contaminated site may be missed altogether and therefore a source not identified. This is because PCBs may not have been used directly on site. PCBs were often contaminants of reclaimed oil, and therefore may be found in scrap yards and oil reclamation centres where there is no obvious site-held or desk study evidence of their presence. Therefore sites contaminated with PCBs do not just include the more obvious sites, such as electrical sub-stations, cable and capacitor manufacturers, but also railway depots, scrap yards, paint and paper manufacturers, for example.

4.2 Transport pathways

Given their chemical properties, it is often believed that PCBs will be attenuated by soil and sediments, and transported via surface water. However, even with such low volatility, PCBs are mainly distributed within the environment via air, particularly due to incineration, the drying out of sewage sludge and the burning of scrap and waste at low temperature. Once in the atmosphere PCBs adsorb onto particulates or water droplets, and although the mono and dichlorobiphenyls have relatively short half lives (days/weeks) in sunlight, most are transported and deposited at distance from source, commonly within 2-3 days from the area of origin. Work carried out to characterise the background PCB and Dioxin contamination across the UK by the HM Inspectorate of Pollution (HMIP 1989 & 1995), found PCBs at all sampling points on 50km grid squares with concentrations between 1 and 141µg/kg. The national and local background around a contaminated site requires consideration when carrying out a risk assessment. For a PCB contaminated industrial site, with particular reference to nearby residents, the overall *current* risk from the nearby site may pose a low overall risk, but the low level chronic exposure from “background” historically deposited in and around their property, may be a lot higher. They are therefore at risk from their own environment, contaminated historically, rather than current contaminant conditions at the site. However, the risk to local residents from historic contamination is generally perceived to be from the site only, by both the site and the residents, since long-term effects are rarely noticeable and obviously attributable; most long term health effects can be attributed to a number of other factors.

The main other transport pathway is by sorption to clay-rich suspended solids or colloids (especially organic acids) in surface water. Drains are a “special case” of this pathway, but often ignored. In fact on the majority of PCB contaminated sites investigated by GeoDelft in the last 3 years, storm water drains and foul sewers have all contained PCBs often in significant concentrations. This is mainly due to the partial silting of drains and the relatively high organic matter content often associated with them – therefore any PCBs washed in as soils or dust, or spilt directly into the drains, often collects there at significant concentrations. This can additionally then become a disjointed source characterisation problem, when elevated concentrations are identified further down the drainage network at sewage works.

Groundwater transport is not usually significant due to the attenuation of the PCBs by soil, the solubility of PCBs and due to pore sizes/connectivity of the soil media. Sorption processes include adsorption, cation exchange and chemisorption. The amount of sorption is dependant on the amount of organic matter and clay within the soil, the effective porosity and bulk density of the soil and rock material. However, on contact with water, sediments will act as a reservoir of PCBs and not just as a sink, as the PCBs desorp into the clean water. Desorption will also occur if there is subsequent contamination of PCB contaminated soils and sediments by other organic solvents such as BTEX hydrocarbons, alcohols and bipolar esters.

4.3 Exposure pathways

As with the majority of environmental contaminants, the main exposure routes to humans and other animals are via inhalation, ingestion and dermal contact. For humans, the pathways are relatively simple, and exposure normally considered as a chronic cancer risk. Inhalation of vapours from historic contamination is extremely low, with inhalation of particulates higher, although proportional to the amount of bare soil and the surface concentrations. Ingestion can vary greatly and is effected by the behaviour patterns of the individual for on and off site contamination. On site, this is less of a concern, as occupational hygiene protocols can be enforced. However, at least one study, summarised in WHO 1993, showed that wives of workers exposed to PCBs, had raised levels of PCBs in their blood due to bad industrial hygiene and cross contamination of the home. However, it should be noted that many foodstuffs contain PCBs, although there has been a steady drop in concentration over the last 20 years. PCBs identified in foodstuffs are mostly sourced from bioaccumulation up the food chain, packaging material, and cross-contamination. The average intake of PCBs is approximately 0.01 to 0.04mg per day, which should be considered as part of the Total Daily Intake of PCBs alongside that sourced from contaminated land. In the UK there are no limits set for PCB content of food, although there are limits set in the US by the FDA (See Section 3).

Dermal Adsorption, along with ingestion is the main exposure route for uptake from contaminated soils and waters. Quantitative studies have been carried out on shaved rats etc (WHO 1993), and qualitative studies on capacitor workers. Uptake is believed to be due to the lipophilic nature of PCBs, and thus the adsorption to the uncovered skin surface area. However, it should be noted that the degree to which the skin comes into contact with the soil (e.g. digging, rather than walking on it) affects the amount of PCBs adsorped, and therefore behaviour patterns of receptors require consideration.

Non-human exposure pathways, particularly for grazing animals, have to account for soil and herbage uptake, since the grazing pattern (whether the animal cuts through the grass stalk or whether grass is pulled up with soil on the roots) is significant. For sheep, the main exposure route, given their coat helps prevent elevated dermal contact, is through ingestion of soil rather than grass. On contaminated sites studied by GeoDelft in the UK, the PCB concentration of grass is generally about 4% of that of soil. The HMIP (1989 & 1995) studies of UK contamination identified grass concentrations of between 7–16μg/kg in rural areas. The implications of this mean that for a full risk assessment to be carried out, the assessor has to consider not only the internal uptake processes of PCBs within the animal but also the grazing habits and patterns of the specie of concern.

Although uptake by grazing animals is not generally considered of importance to the animals themselves, it is of consideration to the human food chain, as meat or milk.

4.4 Receptor characterisation

The significance of the receptor is identified by legislation and “shareholder value”. Legislation prevents contamination or demands clean-up of certain receptors. In the UK the PCB contamination of surface and groundwater is legislated at zero concentration. Therefore any contamination likely to cause “significant harm” of receptors, or impact water resources is prosecutable and has to be cleaned-up, although in practice the interpretation of the law usually takes into account the historic nature and past good working practices. As a result areas in the UK where PCB contamination is significant e.g. Mersey Estuary/Liverpool Bay, remedial actions are unlikely to be considered as sites where the “polluter pays”, but instead will be considered and assessed from the public purse. This is because the sources of the PCB present are many, discharge followed past good practice, and much of the contamination is historic. Sewage sludge too contaminated to be spread to land was disposed of within the Bay (approximately 0.5 to 1.8 million tonnes/year), contaminated industrial waste (0.05 to 0.3 million tonnes/year), dredged spoil from docks and harbours (3.5 to 5.7 million tonnes/year), (Norton et al 1984) plus there are historical manufacturing sites in the area that used PCBs and discharged many other contaminants, notably mercury. Fish in this area contain concentrations of PCBs in the 23 to 130µg/kg range (Leah et al 1997), being a receptor for contamination in their own right, and as a pathway to PCB uptake to human health. Therefore although there is harm being caused to receptors, the positioning of blame becomes difficult to assess or prove with so many potential sources. It is therefore unlikely that remedial measures will be taken.

Shareholder value is the main driver to clean-up and the identification of other receptors. This is the perceived and actual risk of PCB contamination becoming interlinked. The bad publicity of actual risk, or the perceived risk from a site to a nearby receptor such as a school, all cause bad publicity with an associated drop in share value and possibly a local/national boycott on the products manufactured at a site. Although clean-up is often associated with a calculated risk to human health, this is rarely done as simply a “duty” to the community, but a reaction to the likelihood of prosecution and the resulting publicity. Once off site risk is determined, risk communication is of the utmost importance both to the site owners, the Regulatory body, and the local community to keep the risk in context and to prevent the risk being perceived as a larger or smaller problem than it technically is. It should be remembered that any contaminant risk is an involuntary risk and therefore treated very differently to a voluntary risk, e.g. the risk of driving to work may be a higher risk than that of living next to a chemical dump, but the risk of driving is being controlled by the individual and thus is more acceptable. Therefore for clear communication work, it has been shown by Freudenburg et al (1994), that the biggest barrier to risk communication is the “trustworthiness” of those communicating the risk.

5. Risk based clean-up

PCBs are classified as List 1, Black List chemicals, and therefore “require clean-up”. However, remedial action has few choices, due to the physio-chemical nature of PCBs, so this is both difficult and expensive with most PCB contaminated sites having to undergo exsitu high temperature incineration. A number of techniques have been studied such as bioremediation, soil washing, etc, but very few techniques have passed the laboratory or pilot stage, and most work under very site-specific conditions. Therefore most clean-up is based on soil excavation and landfilling (up to 50mg/kg) or incineration in the UK.

However, given the sorptive properties of PCBs to soil, the calculated risk of leaving the contaminated soil insitu, and the risk of the clean-up process has to be considered as part of the overall site management. Excavation produces dust, and excavation usually involves large quantities of soil that need to be moved on lorries away from the site. This may spread contaminated PCB dust, and poses an increased vehicular hazard, both directly, and indirectly from fumes. Finally, clean soil has to be brought in to replace what has been removed, posing a second vehicular hazard.

GeoDelft have been involved in two cases where the risk of clean-up was greater than leaving the contamination insitu. The first, involved the water course, discussed in Section 4.1, where dredging would have remobilised fairly static sediment, which increased in PCB content with depth. Secondly the increase in traffic across a recreational area of marshland near the estuary would have posed significant risk to the public.

A second site involved contaminated grazing land with potential access to the public (it was surrounded on two sides by housing and commercial properties), and was contaminated by PCBs from an adjoining site. However to excavate the contaminated soil would have produced bare earth (increasing the risk of dust), and the lorries would have had to leave the gazing land via a small cul-de-sac with residential housing, and then pass on through the village concerned. The increased traffic (approximately 200 lorry loads) posed a considerable risk to local residents. Since PCBs are strongly sorped to soil and the contamination was associated with drainage ditches in the field, comprising the top 0.3m of soil, it was agreed by the site and the Regulatory body that the overall risk of leaving the material in the field was less than transporting it a way. However, the level of contamination did pose a potential risk, albeit small, so the final remedial option for the field was deep ploughing (locking the PCBs at depth), with the end-use determined as wildlife habitat – thus it removed the grazing receptor and as a wildlife habitat reduced the likelihood of people accessing the field.

The calculated risk to local residents from the grazing land, prior to remediation, was such that, although a risk was present, it was low enough not to require action, but this was balanced by the perceived risk of both the site owner and the Regulator which actually became the driving force for considering clean-up, and after much consideration, the option of deep ploughing and biodiversifying the area. The risks were explained to local residents, but the perceived risks by the public were considered low, probably because many of the villagers had worked on the nearby manufacturing site where the PCBs had originated, were currently working on that site or had relatives there. Thus the problem became one of “rational selfishness”, where the benefits of the manufacturing site appeared to outweigh the risks caused by the site, and because (due to the employment of local people), the site owners were seen as “trustworthy” and “credible” in the communication of risk. (Freudenburg et al 1994).

6. Conclusion

Thus it can be seen that the risk assessment of any contaminated site that involves particularly a persistent chemical, has to take into account a vast range of considerations when studying the source-path-receptor scenarios; many of which are extremely complex. The technical assessment has additionally to take into account the perceived risk, which is the attitude to that risk from individuals. The scientific environmental community has progressed a long way into statistical risk assessment, with the risk to receptor from a contaminant or contaminants better understood than ever before. The fields of toxicology, chemistry and biology have been integrated in the last few years into the fields of environment and geotechnics and this has led to a greater understanding of the source-path-receptor linkage. However, it is now time that the scientific community integrated the social scientists, because particularly with contaminants with a public high profile, the calculated risk is not enough. This is especially true for “emotive” contaminants such as PCBs where the perceived risk is often of greater importance than the calculated technical risk, and as can be seen from the above examples, where the remedial strategy drivers have been direct legislation or perceived risk rather than just the calculated risk scenario. This does not make the assessment of risk any less scientific or important, it just has to be considered within the wider framework.

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Polychlorinated biphenyl (PCB) contamination of apartment building surroundings by construction block sealants

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ABSTRACT: Due to their superior properties polychlorinated biphenyl (PCB) containing sealants have been used in constructions in 1960´s and 1970´s. The PCB content and distribution of individual PCB-congeners in sealant and soil samples were determined using gas chromatography (GC) with selective-ion monitoring mass spectrometry (MS-SIM). In the case study, total concentration of extractible PCBs in sealant samples ranged from 8 300 mg/kg to 108 700 mg/kg. The concentrations were the highest in the Northern side of the building studied. In soil samples the concentrations ranged from 0,03 mg/kg to 6,62 mg/kg. The concentrations were the highest in the immediate vicinity of the building and declined by distance.

The risk assessment carried out was not based only on the total PCB concentrations but the congener specific analyses. Toxicity of specific congeners was estimated on the basis of 2,3,7,8-TCDD equivalents. The highest deterministic risk value with congener specific information and exposure pathway as soil ingestion was $4{,}90*10^{-5}$. Using probabilistic assessment along with lognormal distributions for the parameters the 95 percentile value for the toxicity risk was $3{,}02*10^{-7}$. For the purpose of this study, only PCB exposure by dermal contact and ingestion of soil was evaluated. There was no significant toxicity risk for the children.

1. Introduction

Several million kilograms of polychlorinated biphenyls (PCBs) have been used worldwide since their invention in 1929. Since then millions of kilograms of PCB have been released to the environment (Zwiernik et al., 1998) and adsorbed to organic soils and sediments where they still persist (Bedard & May, 1996). Due to their chemical properties PCBs are extremely difficult for living organisms to excrete (Lanting et al., 1998). Thus they tend to bioaccumulate in the food chain. Despite their ban in 1970s, PCBs are still found in the environment for decades.

Sediments are the main sink of PCBs (Hansen, 1987). In Finland, for example, PCB-contaminated lake sediments have been found to be very persistent (Hurme & Puhakka, 2000). A new type of PCB source for environmental contamination has been observed from apartment building houses (Jansson, 1997; Pyy & Lyly, 1998; Hellman, 2000). PCB mixtures were used as sealing paste additives in prefabricated constructions from 1960´s to late 1970´s. PCBs may pose a risk to people especially to the children living in houses with PCB-containing sealants.

The aim of this work was to study the problems in apartment buildings in Tampere. The concentration and composition of PCBs in sealants and in soil next to the building were determined followed by toxicity risk assessment.

2. Materials and methods

2.1 Site description and sample collection

The building studied was located in Tampere, Finland. It was built in 1971 and had the original sealants. Sealant samples were collected in each quarter of the building using cluster sampling. Soil samples were taken using systematic grid sampling. The distances were 0,1 m, 0,5 m, 1 m, 2 m, 5 m and 10 m away from the vertical joint of elements.

2.2 Extraction of soil and sealant samples

Hexane was used as a solvent with the sealant samples. Samples were cut into small pieces and placed in 15-ml test tubes sealed with teflon lined rubber septas and screwed-caps. The solvent was added and the test tubes were mixed with a vortex mixer. The test tubes were placed into ultrasonic bath for one hour. The procedure was repeated twice. Finally, the elutes were diluted with hexane.

Hexane-acetone (1:1) was used as a solvent for the soil samples. The pretreated soil samples were placed into test tubes. The solvent was added. After vortex mixer the test tubes were placed into ultrasonic bath for one hour. The tubes were centrifuged and the elutes were transferred into clean test tubes. The procedure was repeated twice. Acetone was removed from the extracts by reverse partitioning into distilled water. The remaining hexane fractions were concentrated under nitrogen stream and passed through a Florisil solid-phase extraction column.

2.3 PCB analysis

PCBs were analyzed in a HP 6890 Series GC equipped with a HP-5MS (length 30 m, diameter 250 µm, film thickness 0,25 µm). Helium served as the carrier gas (1 ml/min). The initial oven temperature was 80 °C from which it was ramped at 30 °C/min to 150 °C, 5 °C/min to 250 °C, 15 °C/min to 300 °C and finally held for 1 minute. PCB-congeners were identified by using Aroclor 1260 mixture as an external standard. The twenty-three different PCB-congeners were used in quantitative analysis.

The concentrations of individual congeners in standard samples were calculated from the total PCB content and the weight-% distribution of congeners in the Aroclor 1260 mixture according to Schulz *et al.* (1989). The relation between the response area and concentration was determined. The total PCB content for each sample was the sum of the peak concentrations.

2.4 Risk assessment

The risk assessment considered children between 1 to 6 years who are exposed to surface soil while playing on the ground. According to U.S. EPA (1996) cancer dose-response assessment was performed. The parameters were chosen from U.S. EPA´s Exposure Factors Handbook (U.S. EPA, 1997). In quantitative risk assessment the deterministic approach, which uses a single point value for each estimate of the input variables, thus yielding a single output value, was used. This seldom represents a real life situation. Most of the input variables are random variables. If the input variables are random then the output variable is random as well.

Probabilistic approach was used to incorporate the uncertainty into the exposure assessment calculation. Using commercial software (Crystal Ball with Monte Carlo simulation) the distribution of the health risk for the case study was estimated. The distribution was compared to the point estimate of the risk. The 95th percentile value was estimated.

In order to perform a specific risk assessment the toxicity of specific congeners was estimated on the basis of 2,3,7,8-TCDD equivalents. The total PCBs but also congener specific results were included in exposure assessment. Exposure parameters having the greatest impact on the result were identified.

3. Results and discussion

3.1 Quantification of PCBs

The sealant samples were analyzed for PCBs and the results are presented in Figure 1. Total concentrations of extractible PCBs in the sealant samples ranged from 8 300 mg/kg to 108 700 mg/kg. The PCB concentrations were the highest in samples from the Northern side of the building. This indicates that the climate conditions, including sunlight, have less effect on PCBs in the sealants in the Northern side of the building.

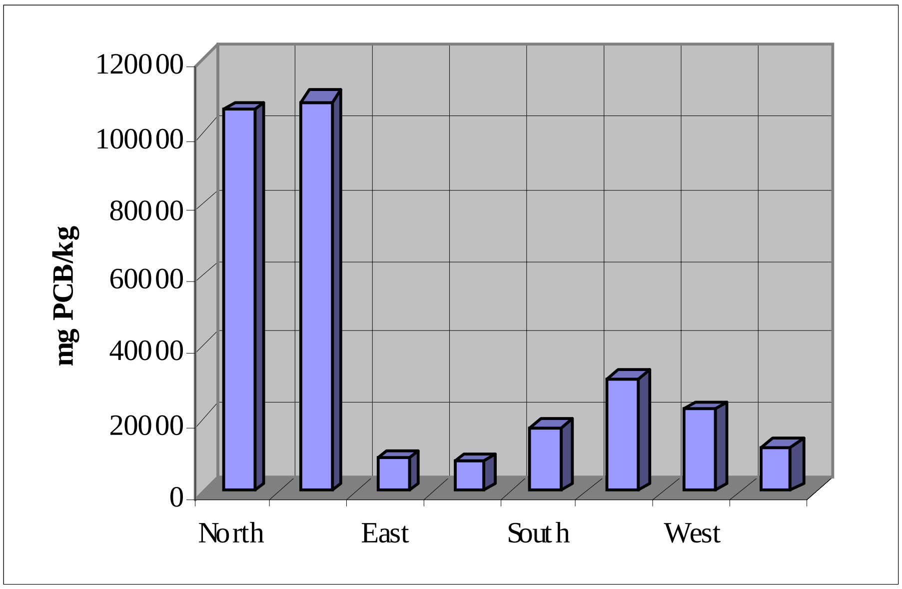
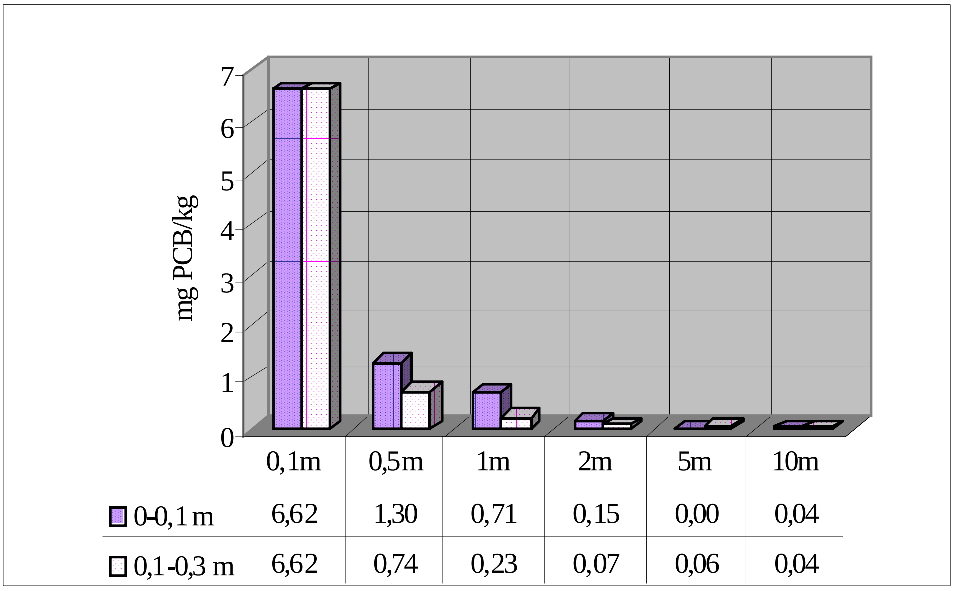


Figure 1. The PCB concentrations in apartment building sealant samples.

The distribution of PCBs in the surroundings of the building were studied. The total PCB concentrations in the soil samples ranged from 0,03 mg/kg to 6,62 mg/kg. The PCB concentrations were the highest adjacent to the building and declined by distance. Figure 2 shows an example of a sampling line of soil samples in the Southern side of the building.



	0,1m	0,5m	1m	2m	5m	10m
▨ 0-0,1 m	6,62	1,30	0,71	0,15	0,00	0,04
☐ 0,1-0,3 m	6,62	0,74	0,23	0,07	0,06	0,04

Figure 2. The PCB concentrations of the soil samples collected from the Southern side of the apartment building.

The composition of the PCB product did not change significantly over the years in the sealant; the peak patterns followed closely that of Aroclor 1260. Examples of the ion chromatograms of one soil sample and the Aroclor 1260 standard is shown in Figure 3.

The most toxic coplanar congeners (IUPAC #77, #126, #169) were studied but not detected. The most persistent congeners (IUPAC #153, #180) differentiated well in all ion chromatograms.

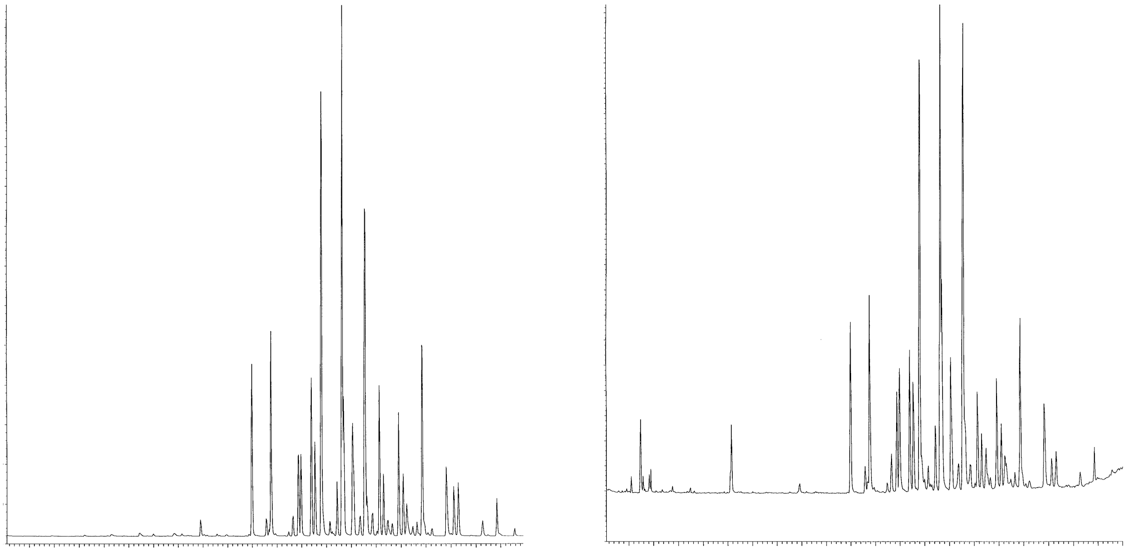
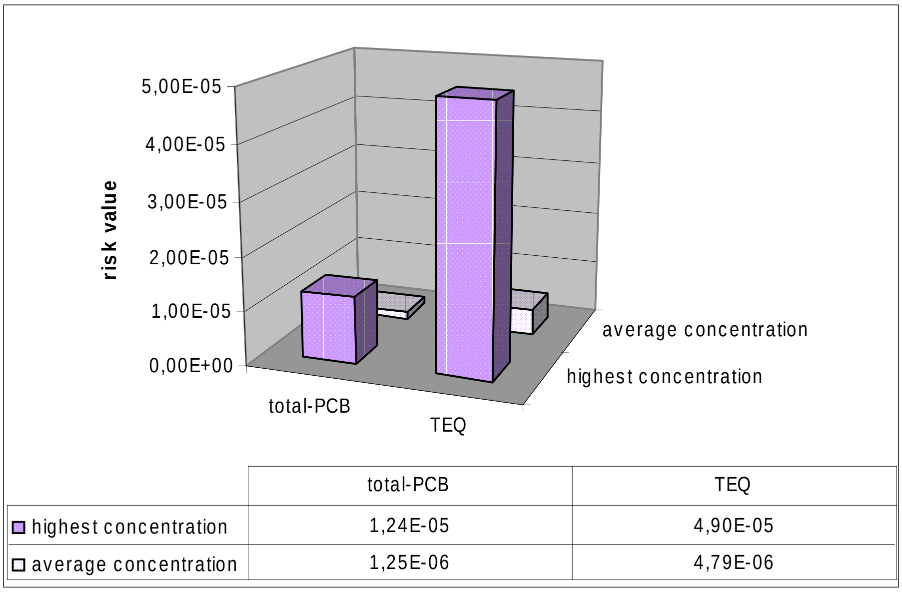


Figure 3. Ion chromatograms for a soil sample (on the right) and the Aroclor 1260 –standard. The scale in Y-axes is more accurate with the soil sample than with the Aroclor standard, that causes the background to be higher on the right hand side ion chromatogram.

The results from the risk assessment when exposed by soil ingestion are shown in Figure 4. Figure 4 shows the difference between the risk assessment based on the total PCBs and the one calculated with the congener specific information.



	total-PCB	TEQ
■ highest concentration	1,24E-05	4,90E-05
□ average concentration	1,25E-06	4,79E-06

Figure 4. The risk values for the children between 1 to 6 years of age when exposed to PCB by soil ingestion from the apartment building surroundings.

The highest risk value with the congener specific information and the exposure pathway as soil ingestion was $4{,}90*10^{-5}$. Using lognormal distributions for the assumed parameters the 95th percentile value for the toxicity risk was $3{,}02*10^{-7}$. These results show that there is no significant risk for the children in the case.

A risk based cleaning goal was calculated using the case specific parameters. The risk based cleaning goal in the case was 0,56 mg PCB/kg. It is very close to the given limit value for PCBs in soil (0,5 mg PCB/kg), which shows that the limit value is applicable in the case.

4. Conclusions

Apartment building sealants may contain high concentrations of PCBs. The sealant itself used in the case study building was classified as hazardous waste.

Apartment block PCBs are spread from the constructions into soil next to the building. In this case study the concentrations in soil were lower than those in sealants but exceeded the given limit value for PCBs in soil (0,5 mg PCB/kg).

The case building did not exhibit significant toxicity risk for the children. The risk assessment was based on the specific exposure parameters (e.q. exposure factors and pathways, average weight for children, average soil ingestion volume) which were then approximated by probability distributions found from the literature. The most important parameter for the assessment was the PCB concentration of soil (56%). The assessment was case specific and results do not apply to all cases. With good site-specific knowledge the results from the risk assessment can be improved.

The risk assessment protocol for apartment building sealants and soils contaminated by these materials should not be based on the total PCB. The congener specific information with chosen standard congeners is needed for the assessment. How detailed information is required and how accurate the assessment should be depends highly on the case but the basic rules should be discussed.

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Remediation of soils contaminated by lead- and copper-containing rifle bullets

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ABSTRACT: The possibilities of using mineral processing techniques to remediate rifle range soils were evaluated. The studied soils originated from two Finnish rifle ranges, Viikinmäki and Utti, and were heavily contaminated by lead- and copper-containing bullets and their disintegrated fine-grained weathering products.

Most of the lead and copper in the soil samples is in the form of coarser particles, which can be easily recovered mechanically by combining wet sieving with consecutive gravity concentration stages. In this process, 83–85% of the total lead and 91–99% of the total copper can be recovered into a ca. 90% pure bullet product.

The fine soil fraction contains 14–17% of the total lead, mainly as fine-grained carbonaceous weathering products of the bullets, and 1–3% of the total copper. Due to the higher solubility of the lead carbonates and the high surface area of these particles, they form a significant source of contamination for the environment. Complex-forming leaching was used to recover the lead and copper from the fine soil fractions with recoveries of 95–98%. By combining the mechanical and leaching processes, lead and copper recoveries higher than 99.4% can be reached.

1. Introduction

As big cities are expanding, the lack of suitable areas for new housing is becoming a problem of ever-increasing importance. Abandoned industrial estates and shooting ranges often cover several hectares of prime building land in the vicinity of new suburbs of the growing cities, but due to the former activities these areas are often contaminated and call for remediation measures before being used for housing purposes.

Until now the most popular, option in Finland, as in many other countries, for managing the problem of contaminated soils has been the encapsulation and isolation of the contaminated material. However, this solution does not meet the requirements of sustainable development and an active treatment to remediate the contamination is to be preferred. In an earlier work (Hintikka et al. 1999) we evaluated the possibilities of using conventional mineral processing technologies—such as screening, heavy medium separation, and complex-forming leaching—in the remediation of soils contaminated by lead-containing shotgun pellets. In this work, we extend the research to include rifle range soils, which along with lead are heavily contaminated by copper, but the contaminants are restricted to smaller areas. In addition to the concentration methods used for shotgun shooting range soils, in this work we evaluate also the possibilities of shaking table concentration. As all the studied methods are already highly developed and used on an industrial scale in extractive metallurgy, the treatment prices are expected to be low compared to the emerging, innovative technologies, e.g. electro-dialysis, for the remediation of soils polluted by heavy metals.

2. Experiments

2.1 Research material

A typical rifle range consists of a firing line, a target line, a target berm, and an impact berm, the distance from the firing line to the target line being normally from 50 to 300 m. The impact berm is designed to capture the fired projectiles containing mainly lead, along with copper, zinc and sometimes nickel originating from the jacket of the bullet. The soils studied in this work originated from the berms of the Viikinmäki rifle range in Helsinki and from the Utti rifle range in Kouvola.

The first step in the characterization of the soils was to screen them into a series of size fractions. The oversize fraction was separated (and rejected from further studies) by a screen with 20 mm aperture. The coarse fraction in the Viikinmäki case was made by screening on 2.8 mm aperture, while in the Utti case a screen with 5.1 mm aperture was employed. In both cases the medium and fine fractions were separated employing a screen with 1 mm aperture. The distribution of the soils in each particle size fraction are given in Table 1, while the results of the chemical analyses of the soil fractions are given in Tables 2 and 3. The fine and medium size fractions were analyzed by XRF. However, due to sampling and sample preparation problems of material containing particles as coarse as bullets, the metal contents of the coarse fractions were estimated as follows. The whole bullets were first separated by the heavy medium apparatus as described below. The purity (as bullets) of the product was estimated by density measurement and pure bullets were assumed to contain 80% Pb and 20% Cu. After grinding, the remaining bullet-free coarse soil fraction was analyzed by XRF to take into account the small metal particles and metal dust attached to the soil. Based on the analyzed and estimated metal contents, also the calculated average concentrations in the bulk samples and the distribution of the metals in the various particle size fractions are given in Tables 2 and 3.

Finnish environmental authorities have proposed reference values for lead and copper concentrations in soils (Puolanne et al. 1994). In the case of lead the figures are 60 mg/kg and 300 mg/kg, while in the case of copper the corresponding figures are 100 mg/kg and 400 mg/kg. Although discretion can be exercised, generally, concentrations below the lower values, referred to as guideline values, are considered harmless, while concentrations exceeding the higher values, referred to as limit values, call for clean-up measures. As can be seen from Tables 2 and 3, the lead and copper concentrations in the studied soils exceed the limit values even thousandfold.

Table1. Distribution of the studied soils in the various particle size fractions.

Sample	Mass of the soil in the oversize fraction (%)	Mass of the soil in the coarse fraction (%)	Mass of the soil in the medium fraction (%)	Mass of the soil in the fine fraction (%)
Viikinmäki	1.4	37.3	8.3	53.0
Utti	0.1	13.0	15.2	71.7

Table 2. Concentrations and distribution of lead and coppers in the various particle size fractions of the Viikinmäki sample. Calculated average concentrations of the bulk sample are given as well.

Element	Minus 20 plus 2.8 mm size fraction, the coarse fraction		Minus 2.8 plus 1 mm size fraction, the medium fraction		Minus 1 mm size fraction, the fine fraction		Calculated mass-weighed average concentration (mg/kg)
	Concentration (mg/kg)	Percentage of total amount	Concentration (mg/kg)	Percentage of total amount	Concentration (mg/kg)	Percentage of total amount	
Pb	237 000	73.3	135 000	9.4	39 000	17.3	120 000
Cu	59 000	87.6	34 000	11.2	600	1.2	25 000

Table 3. Concentrations and distribution of lead and copper in the various particle size fractions of the Utti sample. Calculated average concentrations of the bulk sample are given as well.

Element	Minus 20 plus 5.1 mm size fraction, the coarse fraction		Minus 5.1 plus 1 mm size fraction, the medium fraction		Minus 1 mm size fraction, the fine fraction		Calculated mass-weighed average concentration (mg/kg)
	Concentration (mg/kg)	Percentage of total amount	Concentration (mg/kg)	Percentage of total amount	Concentration (mg/kg)	Percentage of total amount	
Pb	588 000	67.4	139 000	18.6	22 000	13.9	113 000
Cu	146 000	80.7	25 000	16.2	1 100	3.1	24 000

It has been shown (Tanskanen et al. 1991, Lin 1996, Jörgensen and Willems 1987) that lead of the bullets after shooting into berm begins to transform into secondary lead compounds, which may be found as surface coatings on the lead particles or as fine-grained weathering products in the surrounding soil. In our earlier work, we conducted detailed mineralogical studies in order to identify the lead-bearing solid phases in the fine fraction of the Viikinmäki sample (Hintikka et al. 1999) and found the lead to exist mainly as hydrocerussite, $Pb_3(CO_3)_2(OH)_2$, and cerussite, $PbCO_3$, associated with minor amounts of anglesite, $PbSO_4$, and massicot, PbO. Also in the Utti sample the transformed lead is present mainly as carbonates. The mineralogy of the copper phases has not yet been studied.

By studying Tables 1–3, it is obvious that the major part of the metals in the berms exist as whole bullets or their coarse parts, which were concentrated in the coarse soil fractions containing 37.3% (in Viikinmäki) or 13.0% (in Utti) of the total mass, but 73.3% (in Viikinmäki) or 67.4% (in Utti) of the total lead. However, 17% (in Viikinmäki) or 14% (in Utti) of the total lead was found in the fine soil fractions emphasizing the significance of the weathering and transformation processes.

2.2 The remediation methods used

2.2.1 Heavy medium separation

In this study, we used heavy medium techniques employing the so-called Erickson's cones to separate whole bullets and coarse bullet parts from the coarse and medium soil fractions. This technique is a standard method for separating minerals of different specific gravity, particularly when rather big difference between specific gravities occurs. Heavy liquids or suspensions of suitable density are used, so that the minerals lighter than the medium float, while the denser minerals sink. In this study, the heavy medium was an aqueous suspension of finely ground ferrosilicon (an alloy of about 82% iron and about 16% silicon) having a pulp density of about 3.4 kg dm^{-3}. In this medium, the bullets and their coarse parts sink, while the metal-poor soil floats. During the heavy medium separation, the secondary lead and copper phases attached on the surface of the bullets partly loosened and the fine-grained weathering products ended up in the middling product, i.e. the medium suspension. The magnetic properties of the ferrosilicon medium are utilized to separate it from the nonmagnetic lead and copper phases, which can be combined with the original fine fraction and processed as described below.

2.2.2 Shaking table concentration

Shaking table is a gravity concentrating device consisting of a slightly inclined deck shaken with a differential movement in the direction of the long axis and washed at a right angle to the direction of motion by a stream of water. The minerals, fed as ca. 25% suspension, at the upper corner of the table are thus subjected to two forces — that due to the table motion and that, at right angles to it, due to the flowing film of water — causing size and specific gravity classification. The net effect is that the smaller denser particles, in our case small metal particles and their transformation products, can be separated as concentrate from the larger lighter particles constituting the tailings. Along with a high-grade concentrate, denoted by C_1 below, and tailings, often also a middling product, denoted by C_2, is separated for further processing. In this study, shaking table was used in the treatment of the fine soil fractions and the float products of the heavy medium separation.

2.2.3 Complex-forming leaching

In hydrometallurgy, leaching is a standard method for extracting valuable metals from solids into an aqueous solution. It is necessary that the particle size of the solid is small enough (<1 mm) in order to liberate the leachable material, that the waste material has a solubility low enough to yield an acceptable separation during the leach, and that the leaching agent can be regenerated. In the practical leaching systems, complex ion formation in the solution is often utilized to increase the solubility of the concerned metal. Based on our earlier studies (Hintikka et al. 1999), we used hot (70 °C) concentrated (470 g dm^{-3}) calcium chloride solution at low pH (1.0 achieved by HCl addition) to remove lead and copper from the fine soil fraction into the solution. After leaching, the lead- and copper-poor fine soil fraction, i.e. the remediation product to be deposited, is separated by filtration and washing. The solution is taken into a subsequent process stage, in which the leaching agent is regenerated by sulfide addition liberating the chloride ions bound to the complexes and converting the dissolved lead and copper into corresponding solid sulfides. The metal sulfides are separated by filtration or flotation and recycled to metal production along with the bullet scrap recovered by the heavy medium separation.

3. Results

3.1 Heavy medium separation

The coarse and medium soil fractions obtained by screening were introduced to heavy medium separation in order to remove the whole bullets and their coarse parts as the sink product. As can be seen from Table 4, in the Viikinmäki case practically all of the lead and copper present in these soil fractions could be recovered in the sink product at a grade of 720 000 mg Pb / kg and 180 000 mg Cu / kg, which means that the sink product was 90% pure bullets. No copper could be analyzed in the float product, while the analyzed lead concentration of the float product was 300 mg/kg indicating the attachment of minor amounts of lead to coarse soil particles.

Table 4. Heavy medium separation tests on the coarse and medium fractions of the Viikinmäki soil.

	Percentage of the soil	Pb concentration (mg/kg)	Percentage of total Pb	Cu concentration (mg/kg)	Percentage of total Cu
Sink product					
coarse soil fraction	12.3	720 000	73.3	180 000	87.6
medium soil fraction	1.6	720 000	9.3	180 000	11.1
both fractions combined	13.9	720 000	82.6	180 000	98.7
Float product					
coarse soil fraction	25.0	300	0.1	0	0.0
medium soil fraction	6.7	200	0.0	0	0.0
both fractions combined	31.7	300	0.1	0	0.0

In the case of the Utti sample, the performance of the heavy medium separation was not as good as can be seen from Table 5. Although the sink product was also in this case 90% pure bullets, considerable amounts of copper and lead remained in the float product at significant grades. Especially the float product of the medium soil fraction was problematic containing 12.2% of the total lead and 8.3% of the total copper at grades of 98 000 mg Pb / kg and 13 800 mg Cu / kg.

The reason for the different behavior is supposed to be the different ways of screening the samples. The Utti sample was easily dry-screened, while the Viikinmäki sample had to be wet-screened due to the high amount of vegetation-oriented material. While screening the Utti sample, probably clods of fine-grained soil remained on the screen but decomposed later in the heavy medium apparatus. This increased the viscosity of the suspension and, consequently, decreased the selectivity of the separation.

Table 5. Heavy medium separation tests on the coarse and medium fractions of the Utti soil.

	Percentage of the soil	Pb concentration (mg/kg)	Percentage of total Pb	Cu concentration (mg/kg)	Percentage of total Cu
Sink product					
coarse soil fraction	10.5	720 000	66.7	180 000	80.5
medium soil fraction	1.0	720 000	6.4	180 000	7.7
both fractions combined	11.5	720 000	73.1	180 000	88.2
Float product					
coarse soil fraction	2.5	36 000	0.8	1 100	0.2
medium soil fraction	14.2	98 000	12.2	14 000	8.3
both fractions combined	16.7	89 000	13.0	12 000	8.5

3.2 Shaking table concentration

The float products of the heavy medium separation and the original fine soil fractions were mixed in mass-weighed ratios (25.0:6.7:53.0 in the Viikinmäki case and 2.5:14.2:71.8 in the Utti case) and introduced to the shaking table concentration. In the Utti case, shaking table concentration proved to be successful in recovering the bullet weathering products. 12% of the total lead could be recovered in shaking table concentrate and middling product at a grade of 345 000 mg/kg in the high-grade concentrate C_1, with the corresponding figures for copper being 2.9% and 16 000 mg/kg. The grade of concentrate C_1 was high enough for combining this product with the sink product of the heavy medium separation. Hence, 85.1% of the total lead could be recovered in the combined gravity separation process at a grade of 620 000 mg/kg. The corresponding figures for copper were 91.1% and 140 000 mg/kg.

In the Viikinmäki case, the concentrations of lead and copper in the float products of the heavy medium separation were negligible and, consequently, no significant recoveries could be achieved by employing the shaking table. In conclusion, we can note that, when needed, shaking table concentration should be used to complement the performance of the heavy medium separation.

3.3 Complex-forming leaching

The middling product, C_2, and the tailings from the shaking table separation were taken separately into complex-forming leaching for removing the lead and copper from the fine disintegrated bullet weathering products. The leaching experiments were carried out in the same way as in our earlier study (Hintikka et al. 1999) and the results on leaching the lead from the Viikinmäki samples are illustrated in Figure 1. The kinetic data given in this figure indicate that a major part of the lead dissolves immediately and that leaching times longer than one hour do not contribute significantly for the the performance of the process. In the case of the shaking table middling product of the Viikinmäki sample, 98% of the lead could be recovered into the solution resulting in a residual lead concentration of 350 mg/kg in the soil. High lead recovery, 96.7%, was observed also when leaching shaking table tailings, but due to the high initial lead concentration of 69 000 mg/kg, the residual concentration in this soil fraction was still over 2000 mg/kg. However, shaking table tailings form only a minor part of the total soil and, in any case, better results will be obtained after further optimization of the leaching conditions.

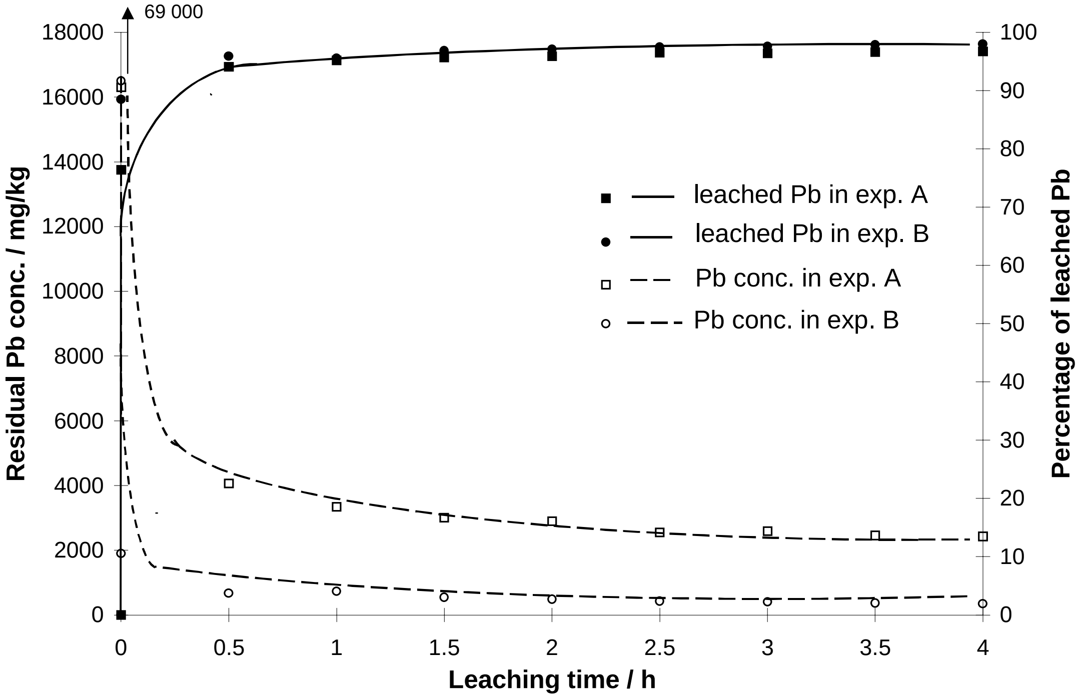

Figure 1. The recovery of lead into solution and the residual lead concentration in the soil as a function of time in the course of the leaching experiments A (• , • , shaking table tailings of the Viikinmäki sample) and B (•, o*, shaking table middling product of the Viikinmäki sample). The solid lines and filled symbols refer to the right y axis, while broken lines and open symbols refer to the concentration axis (left y axis). The initial Pb concentration in experiment A is out of scale, 69 000 mg/kg.*

4. Conclusions

Bench-scale tests on the soils from the Viikinmäki and Utti rifle ranges show that mineral processing techniques can be successfully used for their environmental remediation. Most of the lead and copper in the soil samples is in the form of bullets and their coarser parts, which can be easily recovered mechanically by combining screening with a consecutive gravity concentration stage. In the Viikinmäki case, 82.6% of the total lead and 99% of the total copper could be recovered as a 90% pure bullet product by wet-sieving followed by heavy medium separation. In the Utti case, the sample was dry-sieved making the performance of the heavy medium separation worse. This could, however, be compensated by a subsequent shaking table concentration stage resulting in a lead recovery of 85.1% at a grade of 620 000 mg/kg, the corresponding figures for copper being 91.1% and 140 000 mg/kg.

The metals present as disintegrated weathering products in the fine soil fraction (particle size below 1 mm) represent the greatest risk to the environment due to the higher solubility of these products. As in our earlier study dealing with shotgun shooting ranges (Hintikka et al. 1999), complex-forming leaching proved to be efficient in removing the lead and copper from the fine-grained soil fraction.

By considering the composite process — consisting of wet-sieving, heavy medium separation, an eventual shaking table concentration, and a leaching stage — a total lead recovery of 99.4% can be achieved resulting in an average residual lead concentration of 700 mg/kg in the remediated soil. However, the experimental conditions have not yet been fully optimized and, most probably, a lower residual lead concentration can be achieved allowing the remediated soil to pass the limit value of 300 mg/kg set by the Finnish authorities (Puolanne et al. 1994).

5. Acknowledgements

The authors thank Professor Jussi Rastas for valuable discussions, proposing the chloride leaching method, and introducing three of the authors to the fascinating field of aqueous lead chemistry. Messrs. Hannu Karhu and Markku Kervinen are acknowledged for skillfully carrying out the experiments. This investigation was financially supported by TEKES, the National Technology Agency of Finland, VTT Chemical Technology, the Finnish Defence Staff, Oy Ekokem Ab and the City of Helsinki, who are also acknowledged for permission to publish these results.

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Start-up of sulfate-reducing suspension and biofilm reactors for acidic zinc and ferrous iron containing wastewaters

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ABSTRACT: The start-up of sulfate-reducing suspension (SR) and fluidized-bed reactors (FBRs) for treatment of synthetic acidic wastewater containing sulfate, Zn and Fe(II) was studied. Lactate was added as electron donor. With SR, Zn and Fe removal of 98.9–100% and 99.6–100%, and effluent pH of 7.4–8.5 were maintained until Zn load was increased to 405 mg/l*d and feed pH decreased to 2.3. With FBRs, Zn and Fe removal of 96.4–100% and 99.3–100% respectively, and effluent pH of 7.2–8.5 were maintained over the 156 days of continuous operation. Maximum sulfate reduction of 80.9–87.5% and 81.5–85.7% were achieved in SR and FBR (10% fluidization) respectively, with loads (mg/l*d) of 1500, 375 and 195 for sulfate, lactate-DOC and Zn respectively. For FBRs with 20 and 30% fluidization rates, maximum sulfate reduction of 68.7–78.3 and 64.7–71.3% were achieved with loads (mg/l*d) of 2425, 600 and 405 for sulfate, lactate-DOC and Zn respectively. The start-up of SR process and the FBR with the lowest fluidization were superior to the FBRs with higher fluidization. However, the higher recycling rate became an advantage with higher loads and lower feed pH. In summary, the processes both precipitated metals and neutralized acidity from the water.

1. Introduction

Wastewaters from mining and mineral processing are characterized by low pH and high metal concentrations. These wastewaters may be toxic to many organisms and result in changes in the food web. Traditionally, metal containing wastewaters have been neutralized with alkaline material, such as calcium carbonate. The chemical treatment has high operational and maintenance costs and produces large quantities of chemical sludge, which must be disposed of. Treatment of metal containing wastewaters with sulfate reducing bacteria (SRB) has promise as an alternative over chemical methods. Potential advantages of metal sulfide precipitation include production of lower sludge volume and lower solubility products as compared to hydroxide precipitation (El Bayoumy et al. 1999).

The purpose of this work was to study the start-up of sulfate-reducing suspension and biofilm processes for zinc and iron containing wastewaters. Experiments were carried out in two lab-scale anaerobic suspension reactors (SR) and three anaerobic fluidized bed reactors (FBR). The effects of carrier fluidization percent on start-up of FBR-process were studied Also the effects of increasing loads and decreasing feed pH on reactor performance were demostrated.

2. Materials and methods

2.1 Suspension reactors

In the preliminary experiment, the start-up of a suspension reactor (SR1, V = 2.35 l) was studied by inoculation with methanogenic granular sludge (0.56 g VS) and sediment (0.50 g VS) from mining areas. The reactor (Figure 1) was operated at 35 °C. Synthetic wastewater was a modified Postgate B medium (Postgate 1979)(Table 1) with pH 7.0–7.1, containing sulfate (151 mg/l) and lactate (95 mg/l). The start-up HRT was 14 h and the upward flow velocity was adjusted with recycle flow to 4.1 m/h. Sulfate load was 250 mg /l*d and DOC load of lactate 65 mg /l*d. After 13 days HRT was increased to 18 h and upward velocity adjusted to 5.5 m/h. After 27 days of operation sulfate load was increased to 0.8 g /l*d and DOC-load of lactate to 0.2 g/l*d. Biomass washout was determined as VS in the effluent.

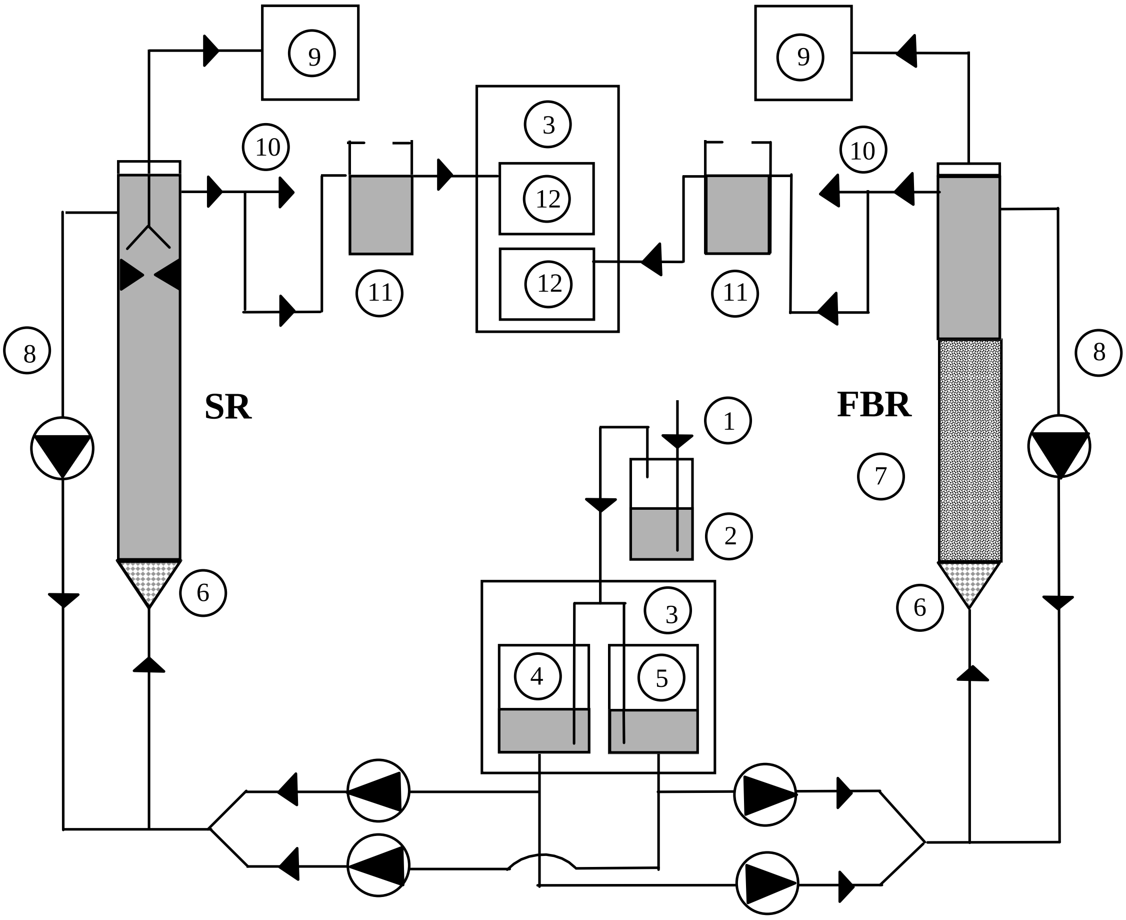
A second suspension reactor (SR2, V = 2.35 l) was inoculated with sludge (5.94 g VS) from the SR1 and with laboratory enrichments cultures (0.46 g VS). Upward velocity was optimized to minimize washout before starting the experiment. Synthetic wastewater, a modified Postgate B medium (Postgate 1979) (Table 1) contained sulfate (1.0–1.6 g/l), zinc (15–270 mg/l), ferrous iron (57 mg/l) and lactate (0.62–1.0 g/l) as electron donor. The process was started with HRT of 79 h. Initially the loading rates (mg/l*d) were 300 for SO_4^{2-}, 76 for DOC-load of lactate, 4.6 for Zn and 17 for Fe(II). The upward flow velocity in the reactor was 2.6–3.3 m/h. The synthetic wastewater was during the first 10 d in one feed container that was located in a refrigerator. After that the feed was divided into two solutions: one containing lactate and yeast extract, and the other the rest of the substances. Sulfate, lactate and Zn loads were gradually increased and feed pH decreased, until a process failure occurred. To recover the process, the sludge was allowed to settle on the bottom of the reactor, and 2.0 l of water were taken out of the reactor and changed to effluent from FBR-3 (containing total of 0.11 g VS). Reactor pH was adjusted to 6.8 with NaOH, and 1 ml of 0.25 M Na_2S was added to bind oxygen from the water. Sulfate, lactate and Zn loads were decreased and feed pH increased. The operational conditions of SR2 and FBRs are presented in Figure 2.

Table 1. Synthetic wastewaters used in the experiments. The changes in the composition of the feed for SR2 and FBRs are presented in Figure 2.

	Feed for SR1		Feed for SR2 and FBRs
	Initially	After 27 days	
Sodium lactate (mg/l)	120	470	778–1258
Yeast extract (mg/l)	38.5	154	11–111
KH_2PO_4 (mg/l)	19.3	77	56
NH_4Cl (mg/l)	38.5	154	111
Ascorbic acid (mg/l)	3.85	15.4	11
Thioglycolic acid (mg/l)	3.85	15.4	11
$Na_2SO_4*10H_2O$ (mg/l)	505	2020	1429–3619
$MgSO_4*7H_2O$ (mg/l)	-	-	1130
$FeSO_4*7H_2O$ (mg/l)	-	-	283
$ZnCl_2$ (mg/l)	-	-	31–563
pH	7.0–7.1	7.0–7.1	2.3–5.6

2.2 Fluidized bed reactors

The FBRs (FBR1 V = 0.5 l, FBR2 V = 0.5 l and FBR3 V = 1.3 l) were inoculated with the sludge (0.40 g, 0.40 g and 0.50 g VS) from the SR1 and laboratory enrichment cultures (0.18 g, 0.18 g and 0.23 g VS). Silicate clay mineral (∅ 0.5–1 mm) was used as carrier material. The FRBs were operated at 10, 20 and 30% fluidization at 35 °C. The synthetic wastewater for the FBRs was as for the SR2, except for the last week. The HRT based on the fluidized carrier volume was initially 24 h. The suspension and biofilm processes were monitored for sulfate reduction, DOC degradation, soluble Zn and Fe removal and sulfide production. Feed and effluent pH and alkalinity were also monitored.



LEGEND:

1. Nitrogen gas
2. Water
3. Refrigerator
4. Feedtank I
5. Feedtank II
6. Glass beads
7. Fluidized bed
8. Recycle flow
9. Gas bag
10. Effluent sampling port
11. Water level adjustor
12. Effluent tank

Figure 1. Schematic diagram of the suspension (SR) and fluidized bed reactor (FBR) set-up.

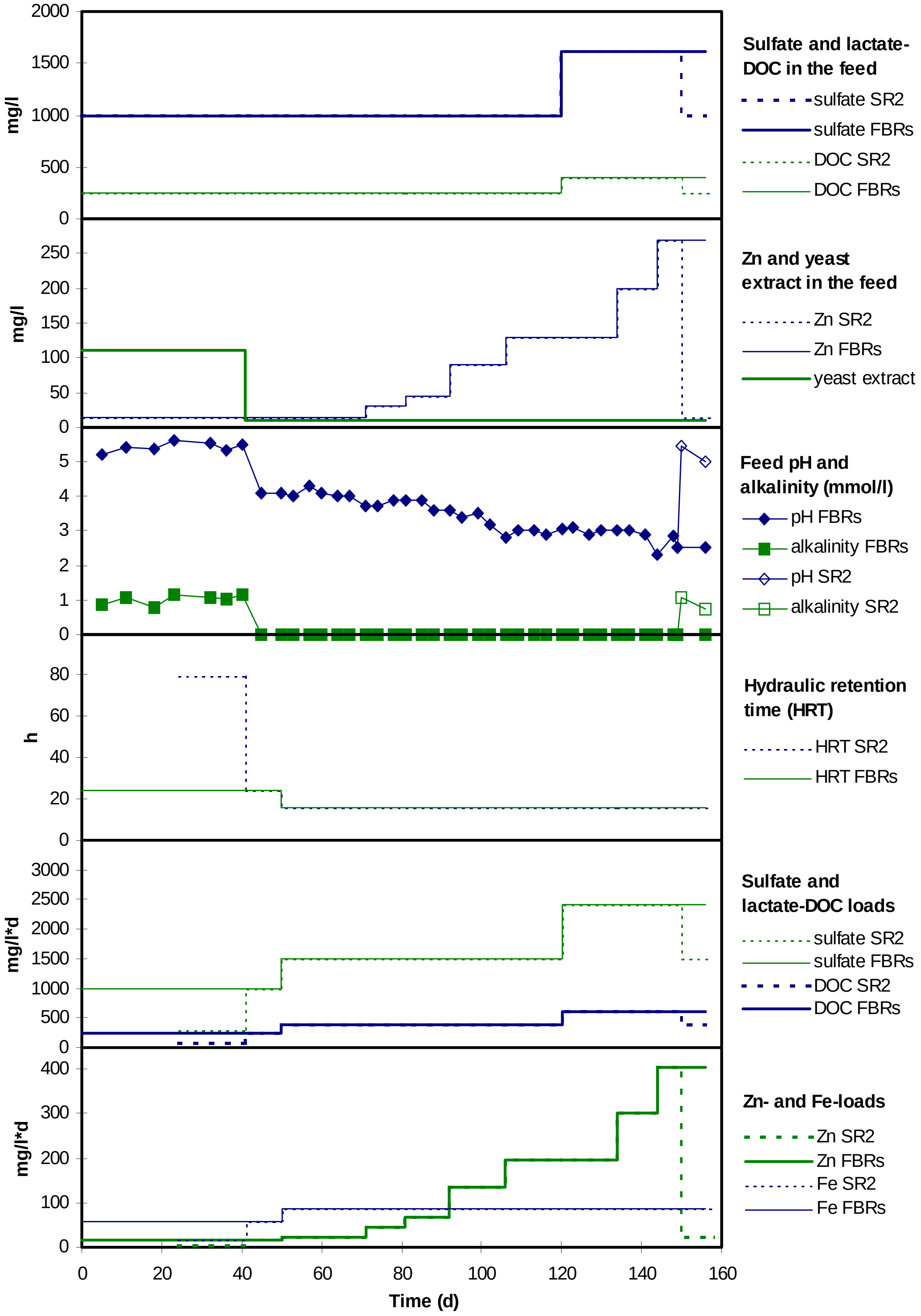


Figure 2. Operational conditions of SR2 and FBRs.

2.3 Analytical methods

Integrated samples of 3–8 d were collected from the effluent containers for sulfate, DOC, metal, pH and alkalinity analysis. Sulfide samples were taken directly from the sampling port indicated in Figure 1. For sulfate, DOC, metal and sulfide analysis the water was filtered through polyethersulfone membrane filters (∅ 0.45 μm). Sulfate was initially (in the preliminary experiment with SR1) determined by barium chloride precipitation, and later by HPLC with an ion column. In the first method, the samples (pH adjusted to 4.5–5.0) were warmed to boil and sulfate was precipitated as barium sulfate with excess of barium chloride. The samples were kept at 80–90 °C for at least 2 h, and after filtration with 0.45 μm membrane filter, soluble barium was determined with AAS. DOC was measured by TOC-5000 analyzator and metals by AAS according to standard SFS 3044. Sulfide was determined with the methylene blue method (Trüper & Schlegel 1964). Alkalinity was determined by potentiometric titration with 20 mmol HCl to pH 4.5 according to the standard SFS-EN ISO 9963-1.

3. Results and discussion

3.1 Suspension reactors

The purpose of the preliminary experiment with SR1 was to study the start-up of a sulfate-reducing suspension reactor with methanogenic granular sludge and sediments from mining areas. After 28 days of continuous operation sulfate reduction of 30–70% and DOC-degradation of 88–98% were achieved with sulfate and lactate-DOC loads (g/l*d) of 0.8 and 0.2 respectively (results not shown). When the upward flow velocity (m/h) was increased from 4.1 to 5.5, biomass washout increased as observed in effluent VS concentrations. This was due to the disintegration of the sludge granules. When testing the suspension reactor with increasing recycle flow rates, upward flow velocities over 4.8 m/h resulted in increasing sludge washout. This shows that high initial upflow velocity results in failure of the process operation.

With the SR2 a different start-up approach was chosen: the reactor was fed with metal-containing synthetic wastewater and the upward flow velocity was decreased. Zn and Fe removal efficiencies were 98.9–100% and 99.6–100%, and effluent pH 7.4–8.5 until the Zn load was increased from 300 to 405 mg/l*d and feed pH decreased from 3.0 to 2.3 (Figures 3 and 4). Maximum sulfate reduction of 80.9–87.5% was achieved, with feed pH of 3 and loads (mg/l*d) of 1500, 375 and 195 for sulfate, lactate-DOC and Zn respectively. Up to these conditions, DOC degradation of over 90% was maintained. With higher loads and lower feed pH, DOC degradation decreased. Effluent sulfide concentration and alkalinity varied with different loads, reflecting the potential to precipitate additional metals and neutralize acidity.

After increasing the Zn load (mg/l*d) from 300 to 405 and decreasing the feed pH from 3.0 to 2.3, a process failure occurred. However, it was possible to recover the sulfate reduction within two weeks. In summary the suspension process both precipitated metals and neutralized acidity from the water.

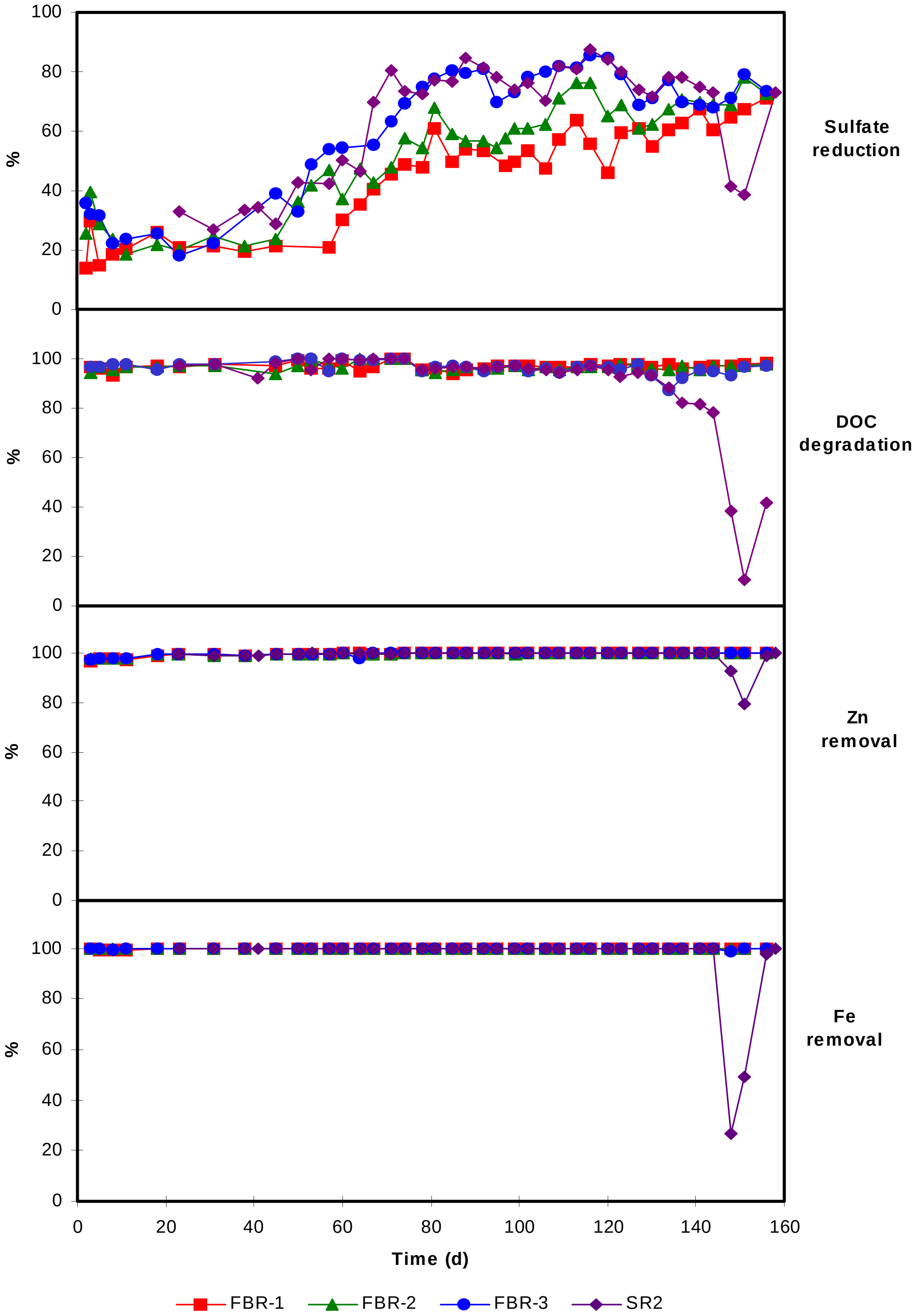


Figure 3. Sulfate reduction, DOC degradation, and Zn and Fe removal in anaerobic treatment of synthetic wastewater in suspension (SR) and fluidized bed reactors (FBRs).

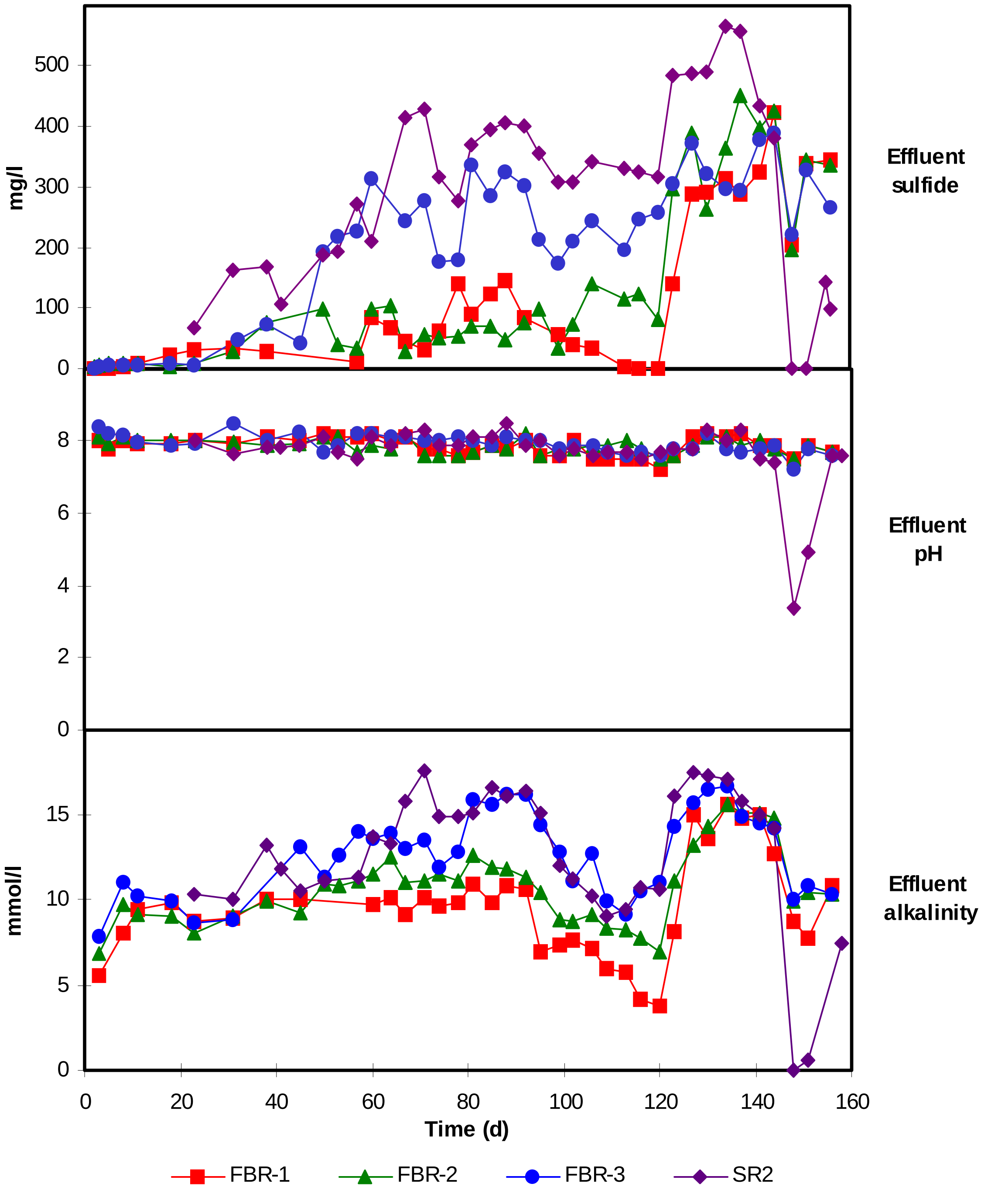


Figure 4. Effluent sulfide, pH and alkalinity in anaerobic treatment of synthetic wastewater in suspension (SR) and fluidized bed reactors (FBRs).

3.2 Fluidized bed reactors

The effects of carrier fluidization percent on start-up of FBR-process was studied. DOC-degradation of 87.3-100%, soluble metal removal of 96.4–100% and 99.3–100% for Zn and Fe respectively, and effluent pH of 7.2–8.5 were maintained in all FBRs over the 156 d operation (Figures 3 and 4). Maximum sulfate reduction of 81.5–85.7% was achieved in FBR3 (10% fluidization) with loads (mg/l*d) of 1500, 375 and 195 for sulfate, lactate-DOC and Zn respectively. For FBRs with 20 and 30% fluidization rates, maximum sulfate reduction of 68.7–78.3 and 64.7–71.3% were achieved with loads (mg/l*d) of 2425, 600 and 405 for sulfate, lactate-DOC and Zn respectively.

The results show that the sulfate reducing biofilm processes were started-up quickly in all FBRs. The lowest fluidization rate (10%) was most successful, as indicated by sulfate reduction, sulfide production and increase in alkalinity. The superiority may have been caused by smaller attrition that allowed faster biofilm formation. However, with increasing loads and decreasing feed pH, the performance of the reactors approached each other. The reason for this may be the advantage of more effective dilution of high metal concentrations and neutralization of the feed pH by higher recycling rates. Low recycling rate may also have caused the suspension reactor to be more susceptible to sudden decrease in feed pH and increase in metal concentration

4. Conclusions

Successful enrichment of SRB from a mixture of methanogenic granular sludge and sediments from mining areas was achieved with suspension and fluidized bed reactors. The processes both precipitated metals and neutralized acidity from the water. High upward flow velocities in suspension reactor resulted in increasing biomass washout. In terms of sulfate reduction, sulfide production and effluent alkalinity, the start-up of suspension process and the fluidized bed reactor with the lowest fluidization rate were superior to the fluidized bed reactors with higher fluidization rates. However, with increasing sulfate, lactate and metal loads and decreasing feed pH, the advantage of the higher recycling rate became obvious.

5. Acknowledments

This research was funded by Technology Development Centre (TEKES), Finland and Outokumpu Research Oy.

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Potential for *in situ* reductive dehalogenation of chloroethylenes

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ABSTRACT: Tetrachloroethylene (PCE) and trichloroethylene (TCE) from a former dry cleanery have contaminated the groundwater in Oitti, Finland. The AOX-analyses of this and former studies suggest a DNAPL-source in the aquifer. The DNAPL is a continuous source of groundwater contamination. The aquifer was investigated for redox conditions. The objective of the study was to estimate if the groundwater conditions would be suitable for the reductive dehalogenation of PCE and TCE. Transformations of PCE were studied in anaerobic microcosms, which were fed with revised anaerobic mineral medium, PCE and either lactate, ethanol, glucose, H_2 or their mixture as the electron donor. The control bottles were made without added electron donor or they were injected with NaN_3 as killed controls. The bottles were incubated at 8 and 25 °C. The results suggest reductive dechlorination of chlorinated ethylenes in contaminated groundwater in Oitti if a suitable electron donor is provided. Pilot-scale experimentations are being started to study the design criteria of in situ bioremediation.

1. Introduction

Tetrachloroethylene (PCE) and trichloroethylene (TCE) are common groundwater contaminants. PCE and TCE have been widely employed as dry-cleaning and degreasing solvents (Mroueh 1993). PCE and TCE from a former dry cleanery have contaminated the groundwater in Oitti, Finland. Approximately 8–10 million m^3 of groundwater has been contaminated with the average concentration of the solvents being 100 µg/l (Silvennoinen 1999). The concentrations in Oitti exceed the limit values given by the World Health Organisation (Savolainen 1998).

For PCE, the reductive dechlorination is the only known biodegradation mechanism. By reductive dehalogenation a halogene substituent is removed from a molecule with concurrent addition of electrons to the molecule. The reductive dehalogenation requires an electron donor. (Mohn and Tiedje 1992)

The electron donor may affect the rate and extent of dechlorination (Holliger 1995). In many cases dechlorinators use H_2 as the electron donor, even though it is not always the only electron donor (Ballapragada *et al*. 1997). Several studies have demonstrated that no single substrate can be recommended for all sites (Holliger 1995). However, various studies indicate that dechlorination can only be sustained supplying an electron donor (Holliger 1995).

The bioremediation of the sites contaminated with chlorinated ethylenes is a young technology. Many field applications are still unaccomplished. The environmental conditions at the contaminated sites vary. In Finland a low temperature may be a limiting factor for the use of bioremediation. However, many field scale studies demonstrate the reductive dehalogenation under anaerobic conditions (Tschistowskaja and de Kreuk 1999; Dooley *et al*. 1999; Litherland *et al*. 1999).

The objective of the study was to estimate whether the groundwater conditions in Oitti are suitable for the reductive dehalogenation of PCE to TCE, DCE, VC and ethene (Figure 1).

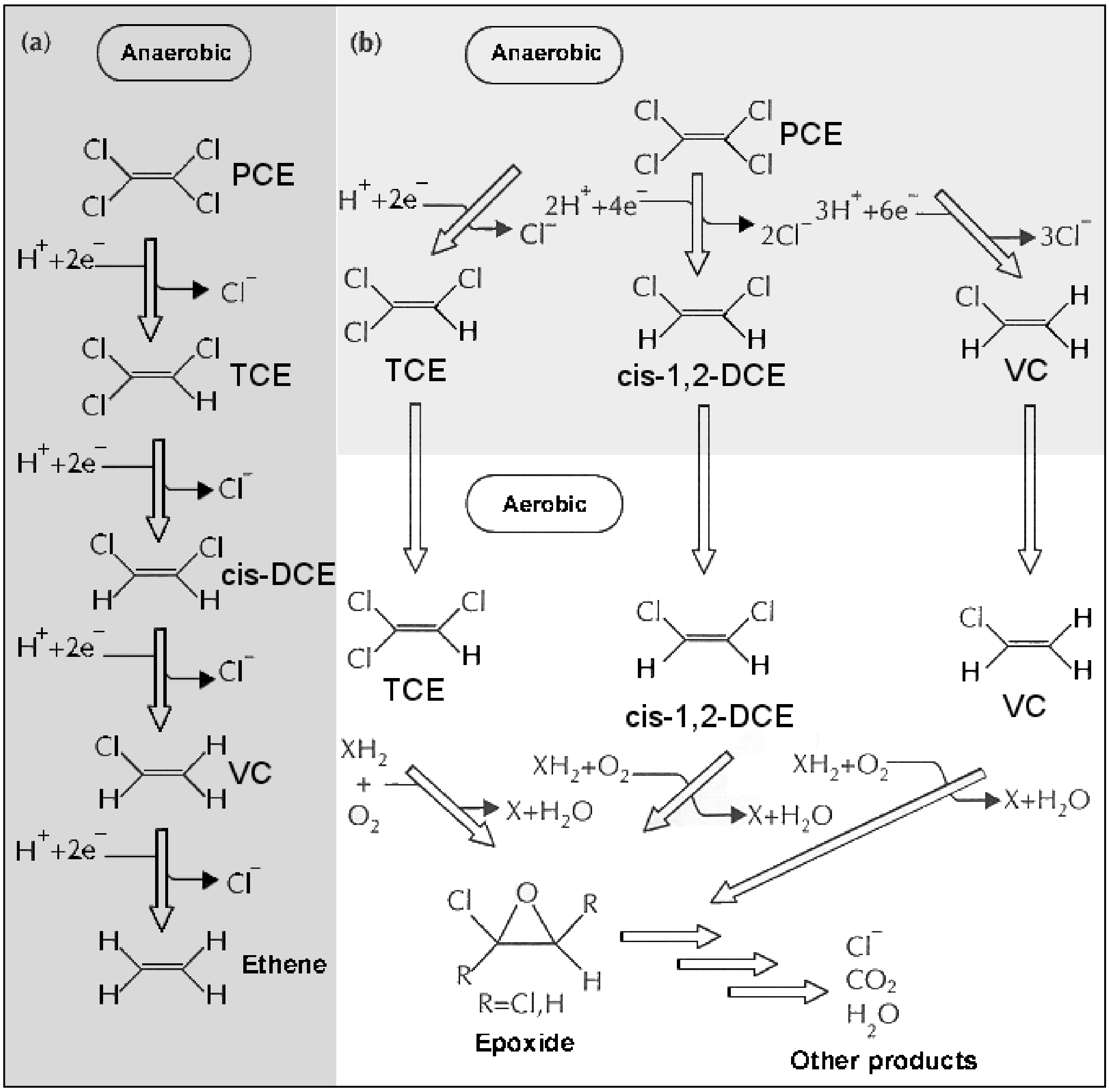

Figure 1. Two possible approaches for the biotreatment of PCE. (a) Anaerobic reductive dechlorination to ethene. (b) Anaerobic dechlorination to less-chlorinated ethenes, followed by aerobic cometabolic ar metabolic (e.g. via VC) oxidation to harmless products. (Holliger 1995)

2. Materials and methods

AOX was determined using ECS 1000 Euroglas BV-equipment. Nitrate was measured using nitrate specific electrode and reference electrode. Sulfate concentration was obtained by precipitating sulfate with $BaCl_2$ and determining Ba concentration with AAS. Ferrous-iron was determined using phenantroline-method 3500-Fe D and Shimadzu UV 1601 –spectrophotometer (Standard Methods 1992). DOC (Dissolved Organic Carbon) was analyzed using Shimadzu TOC-5000 analyzer. Calibrated WTW pH 96 –meter was used to determine pH in the groundwater.

Transformations of PCE were studied in anaerobic microcosms, which were constructed from samples of the contaminated site in Oitti. 10 grams of contaminated soil was added in every bottle. Bottles (120 ml) were fed with revised anaerobic mineral medium, PCE (aqueous concentration of approximately 5 mg/l) and either lactate, ethanol, glucose, H_2 or their mixture as the electron donors in two concentrations (100 or 200 mg COD/l). The control bottles were made without added electron donor or they were injected with NaN_3 as killed controls. Reducing conditions were maintained by the presence of Na_2S. Resazurin served as the redox indicator. The color of the indicator changed from blue to pink to colorless indicating anaerobic conditions in the bottles. The bottles were incubated at 8 and 25 °C. Methane was analyzed using gas chromatograph (Perkin-Elmer Sigma 300) equipped with a hot wire detector. PCE and TCE were measured on a gas chromatograph (HP 5890 series II) equipped with an electron capture detector. All chlorinated ethenes were analyzed at the end of the experiments on a gas chromatograph (HP 6890) equipped with a mass selective detector (HP 5972 A) using head space -method.

3. Results and discussion

3.1 Groundwater conditions

The aquifer was investigated for redox conditions. Concentrations of ferrous-iron were high indicating anaerobic groundwater. Nitrate and sulfate can serve as electron acceptors and in high concentrations inhibit the reductive dehalogenation of chloroethylenes (Doong and Wu 1992; Mohn and Tiedje 1992). Nitrate and sulfate concentrations varied between 3,5–5,8 mg/l and 19–26 mg/l, respectively. Nitrate and sulfate at these concentrations do not inhibit reductive dehalogenation. DOC (Dissolved Organic Carbon) demonstrates the presence of organic material in the groundwater. DOC may serve as an electron donor for the reductive dehalogenation (Stiber *et al*. 1999). DOC levels were in most cases lower than 1 mg/l indicating that the suitable electron donor for dehalogenation is not naturally available in the Oitti groundwater. pH-values varied between 6,4...6,6. Neutral pH favors biodegradation (Norris *et al*. 1994). Natural pH in Oitti is near neutral and does not inhibit biodegradation. AOX-level varied between the detection limit and 159 µg/l. In many sampling points of Oitti site the AOX-levels have not significantly decreased since the year 1992, when the monitoring was started (Öhberg 1997).

3.2 Dechlorination experiments

Microbial production of gas and methane was determined in order to indicate reductive conditions in the bottles. The theoretical production of gas was 2,3 ml for one bottle when 100 mg COD/l was added and 4,6 ml for the addition of 200 mg COD/l. The production of gas was low. The concentration of methane remained below the detection limit in all bottles at 8 °C and at 25 °C in the bottle supplemented with NaN_3. In all other bottles at 25 °C methane was formed indicating very reducing conditions.

At 25 °C the dehalogenation started in all bottles except for that supplemented with NaN_3 (killed controls) (Figure 2). These results show that the degradation of PCE occurred biologically. At 25 °C, it made very little difference what electron donor was added. PCE degraded even without any added electron donor.

At 8 °C, the rate of the dehalogenation was signicantly lower than at 25 °C. At 8 °C glucose and H_2 were the most efficient electron donors, but resulted in very slow dehalogenation (Figure 3).

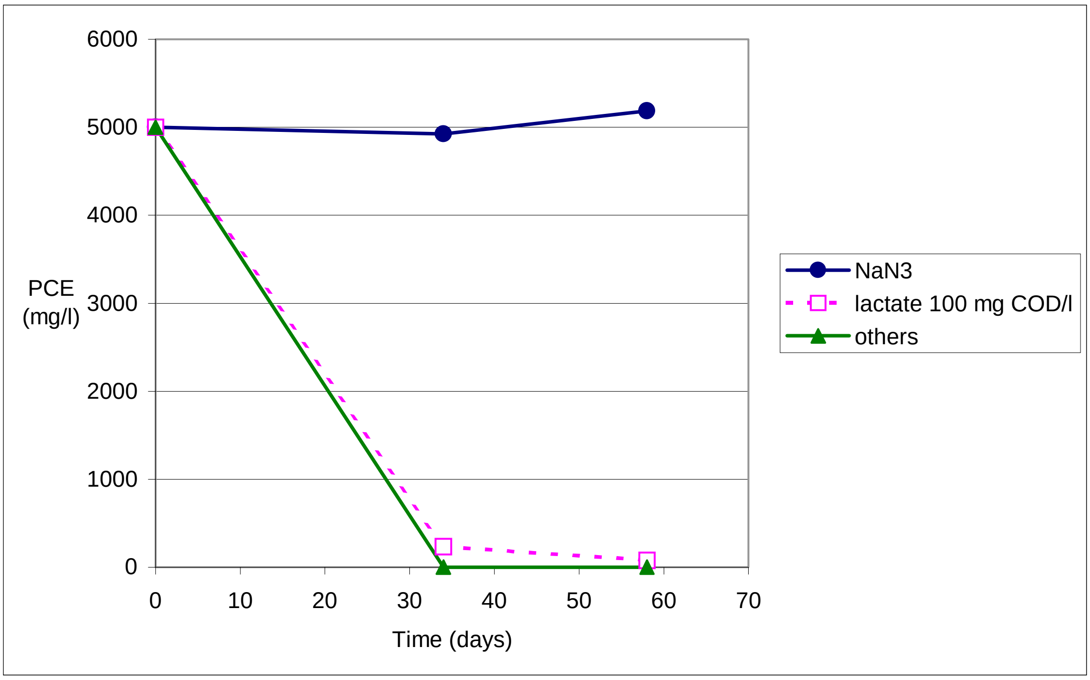

Figure 2. Anaerobic tetrachloroethylene biodegradation at 25 °C. Others(Δ)=no donor, glucose, ethanol, H2 and mixture 100 and 200 mg COD/l, lactate 200 mg COD/l.

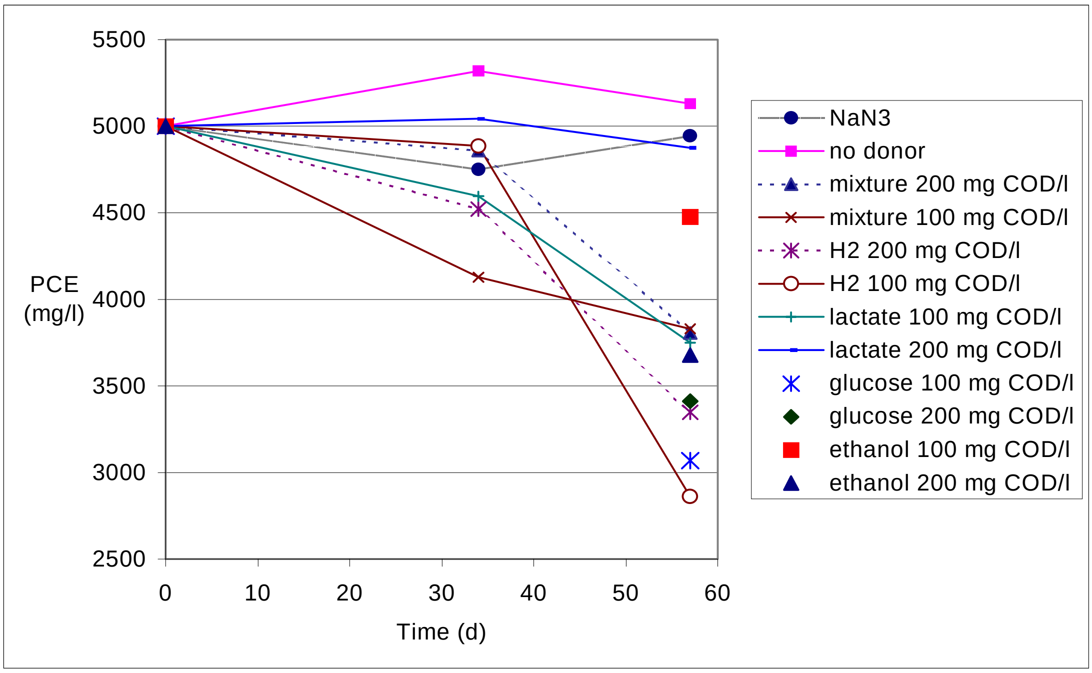

Figure 3. Effect of electron donor on tetrachloroethylene anaerobic biodegradation at 8°C.

At the end of the experiments (120…125 d) all the chlorinated ethylenes were qualitatively analyzed in selected bottles and the results are shown in Table 1.

Table 1. Chlorinated ethylenes in anaerobic microcosms after 120…125 days incubation time. (+) = detected, (-) = not detected, (±) = detected in one of the duplicates. Mixture = ethanol, glucose, H2 and lactate.

Compound	mg COD/l	T (°C)	PCE	TCE	DCE	VC
No donor	-	25	+	-	-	±
NaN_3	-	25	+	+	+	-
Ethanol	200	25	+	-	-	-
Glucose	100	25	+	-	±	-
Glucose	200	25	+	-	-	-
H_2	200	25	+	-	-	-
Lactate	200	25	+	-	±	-
Mixture	200	25	+	-	-	-
No donor	-	10	+	+	+	-
NaN_3	-	10	+	+	+	-
Ethanol	200	10	+	+	+	±
Glucose	200	10	+	+	+	±
H_2	200	10	+	+	+	-
Lactate	200	10	+	+	+	-
Mixture	200	10	+	+	+	-

VC was found only in some bottles indicating that VC does not accumulate. The degradation of VC is the rate limiting step in reductive dechlorination of chlorinated ethylenes (Ballapragada *et al*. 1997). VC is undesired end product since it is more toxic than the parent compounds.

4. Conclusion

The AOX-analyses of this and former studies suggest a DNAPL-source in the aquifer in Oitti. The DNAPL is a continuous source of groundwater contamination. The results suggest reductive dechlorination of chlorinated ethylenes in contaminated groundwater in Oitti if a suitable electron donor is provided. However, the complete dehalogenation of chlorinated ethylenes will take many years in a boreal groundwater aquifer. Pilot-scale experimentations are being started to study the design criteria of in situ bioremediation.

5. Acknowledgment

This work was funded by the Tampere University of Technology Foundation and the Land and Water Technology Foundation.

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Development of simplified procedures for sampling of contaminated soils

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ABSTRACT: Three simplified procedures for sampling of contaminated soils were developed. They are portable, easy to set and can be operated under space and time restrictions.
a) A sampling method without using a drilling mud: A sampler with a spiral cutter on its outside surface like a screw was developed. Compared with a conventional sampler not using a drilling mud, this sampler needs about half the time for boring.
b) A shallow depth boring machine: An electrical rotary type boring machine using the new developed screw-type sampler was developed for obtaining soil samples from a depth of about 10 to 15 m below the ground surface without using a drilling mud.
c) A simple method for surface soil sampling: A simple method for surface soil sampling was achieved by attaching a new developed screw-type sampler with a smaller size to a electric hand drill.
These new developed tools were successfully applied to investigate a TCE contaminated site together with leaching tests by using PID-gas chromatography.

1. Introduction

In Japan, countermeasures to improve the water quality of lakes, rivers and coastal areas have been in place for several decades; and they gradually bear fruit. However, the recognition for pollution of soil and groundwater had been low so far. Soil pollution has only recently become a serious social problem. At present, relating act has been improved at the sudden pitch. In addition, investigations and countermeasures of soil and ground water pollution promote trial and error in many municipalities and private enterprise.

Investigations are often carried out at sites that are still in operation and where space and time are restricted. In such cases, conventional sampling methods may cause problems due to noise and vibration during the operation, they also need considerable space. In order to overcome these disadvantages, three new sampling methods were developed as follows.

One basic problem related with sampling contaminated soil is to prevent contaminated material from spreading to surrounding non-contaminated areas. For that reason, a drilling mud usually applied in conventional sampling methods should not be used. A second problem consists in the generation of heat caused by the drilling. In the case of sampling soils contaminated by volatile organic compounds (VOCs), generation of heat should be kept to a minimum in order to prevent volatilization. This led to the development of a sampler with a spiral cutter on its outside surface like a screw. By this, the drilling ability was improved, and the generation of heat was decreased because the friction of the periphery surface of the sampler was decreased.

For contaminated areas, it is necessary to determine the distribution of contaminated zones with respect to depth. Soil samples have usually to be collected and analyzed up to a drilling depth of several ten meters below ground surface. In this case, a rotary-type boring machine (see Photo 1) is typically used. This method allows deep sampling in any kinds of soil, and all-core sampling is possible if an appropriate sampler, e.g. a triple tube sampler, is used. Soil samples obtained by this method have excellent quality showing neither disturbance nor shrinkage of the sample. However, since the main body of the boring machine is large and heavy, it cannot operate on narrow sites and the mobility of the machine is not good either. Moreover, required drilling time and costs per site are high. Therefore, percussion style boring methods like SCSC (Yamamoto, 1994) and Geoprobe (PB Reports, 1998) used in Europe and America for the investigation of contaminated soils have been introduced to Japan. However, because they are percussion style, problems of noise and vibration of hammer and compression of the soil samples have been reported (Suzuki, 1999). To encounter these problems, a simple electrical rotary type boring machine was developed for investigation of contaminated soils. Using the new developed screw-type sampler, soil samples from a depth of about 10 to 15 m below the ground surface can be obtained at an excellent quality without using a drilling mud.

Initial investigation of contaminated sites usually requires to specify the areas of contamination by taking a large number of soil samples at shallow depth of about 1 to 2 m below surface. It would therefore be convenient to have an easy and quick method for surface sampling. By attaching a new developed screw-type sampler with a smaller size to a electric hand drill, such a method for easy collecting was developed.

Finally, a case study of these new tools for a soil contaminated by VOCs (TCE) is reported, together with soil leaching tests and analysis using the photo ionization detector-gas chromatography(PID-GC) and gas detecting tubes.

2. Sampling method without using drilling mud

The drilling mud used for usual boring method has the function to prevent a collapse of the bored wall. Other functions are to remove and discharge the drilling chips, to reduce the friction resistance force, to cool of drilling bit etc.. However, drilling mud can't be used in the case of contaminated soils, so it is necessary that there is a substitution for the drilling mud. A casing pipe with an inner diameter larger than the sampler’s outer diameter may be installed in order to keep the stability of bored wall. In order to compensate for the other functions of the drilling mud, a spiral cutter was added to the surface of the soil sampler, as shown in Figure 1. With this spiral cutter, discharging and removing of the drilling chips become easy and the generation of heat is decreased. Moreover, the penetration ability to the ground is improved by converting rotary forces into axial forces like a screw nail.

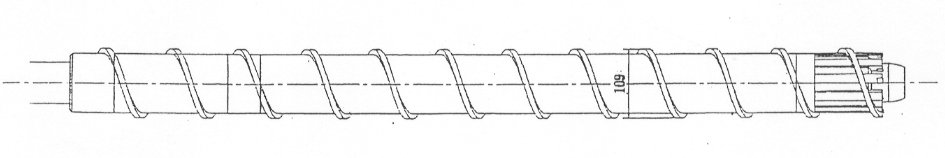

Figure 1. Sampler with a screw-like spiral cutter on its outside surface.

The difference between this new developed screw-type sampler without drilling mud was then tested as compared to a conventional sampler. The sampler was improved on the basis of a triple tube sampler system with 99mm outer diameter designed for general use. Because the height of the spiral cutter adds 5mm to either side, the outer diameter of the improved sampler is 109mm. The diameter of collected soil sample is 71mm. The boring machine used in this sampler test is an oil feed type used in usual boring investigation, and its 100m class of boring ability is a popular type. The test ground is composed of Kanto loam layer with a N-value of about 5 and Narita sand layer with a N-value of about 10, shown in Figure 2, which makes it a typical ground in the Greater Tokyo area. In the test, it was drilled to GL-10m. The situation of the test is shown in Photo 1.

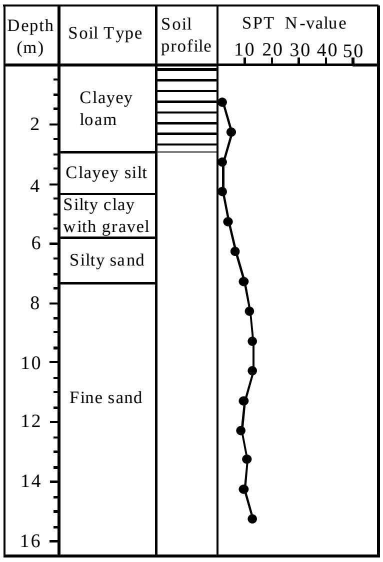

Figure 2. Soil profile of the drilling ability test site of the screw-type sampler.

Photo 1. Drilling ability test by using the screw-type sampler (Example of a rotary-type boring machine).

The length of sampled soil per process is basically 500mm, but lengths of 700mm and 900mm were also tested. 15 soil samples were collected in total. As the result of the test, times required for drilling only is 5 minutes in average for 500mm sampling length. In case of 700mm and 900mm sampling lengths, time almost doubled. The silty clay with gravel layer at GL-4.3m to GL-5.7m required about double time, but it was still possible to drill to GL-10m. However, below GL-8m the power of the boring machine proved insufficient for the casing pipe of 149.8mm outer diameter that was used to prevent the bored wall from collapsing. This indicates that the outer diameter of sampler and casing pipe should be reduced to make drilling more efficient. There was no temperature increase observed in freshly collected soil samples.

From previous boring investigation carried out near this test site using drilling mud, it was known that conventional boring using drilling mud requires about the same time for soil sampling as the screw-type sampler. Without drilling mud, it takes about the double time. It was further assumed that sampling lengths over 500mm would not work because of the friction resistance getting too large.

In order to assess disturbance and shrinkage of the soil samples, the ratio of the sampled soil length to drilling length was taken. In case of the 500mm sampling length , this sampling ratio remained 100% and hence showed no signs of shrinkage. Photo 2 shows the example of a collected soil sample. But, in case of the 700mm and 900mm sample lengths, the ratio varied between 93% and 100%. This smaller ratio is assumed to be caused by the inner tube rotating together with the outer tube. One reason may be that the drilling chips fill in the void between both tubes, causing a higher friction than with the usual drilling mud in the void. Also the drain hole in the sampler was disturbed by the drilling chips, this may have hampered the progress of the sampling tube. Now, this problem was solved by installing a sealing mechanism between the inner tube and the outer tube at the top of the sampler.

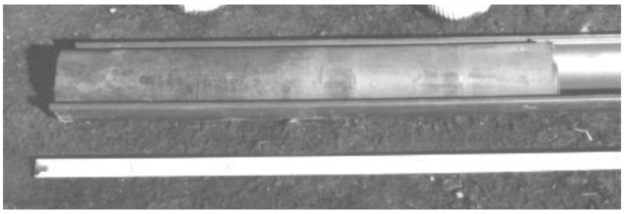

Photo 2. Example of the soil sample collected by the screw-type sampler.

Several soil tests were carried out using soil samples collected by screw-type sampler. For the clayey soil, uniaxial test, consolidation test, and physical test were carried out. In case of the sand, liquefaction test, dynamically deformation test and physical test were carried out. On the basis of these test results and the past tests data, it was confirmed that the soil samples collected by screw-type sampler were undisturbed. An example of the uniaxial compression test result is shown in Figures 3.

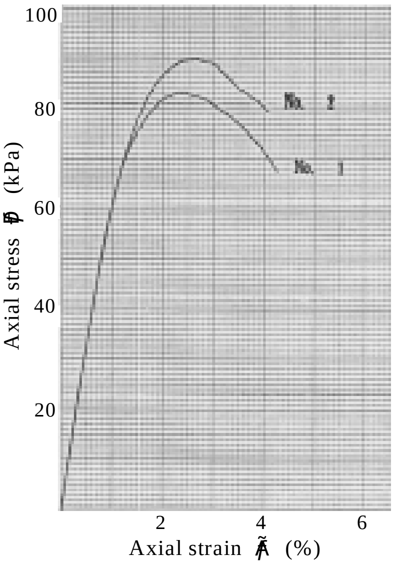

Figure 3. Example of the uniaxial compression test result for the soil sample collected by the screw-type sampler.

By installing the spiral cutter on the surface of the soil sampler it could be shown that boring without drilling mud, which is the optimum method for investigation of the contaminated soils, could be efficiently carried out. Even more, it was confirmed that no disturbance occurred; and that soil samples of excellent quality could be obtained. In addition, this sampler makes drilling more efficient and can also be employed in convential boring using drilling mud.

3. Shallow depth boring machine

For the purpose of investigating contaminated soils, a simplified rotary-type boring machine was developed that allows sampling at shallow depths but with excellent mobility. The drilling rod mounted on a metal table moves up and down along a frame as shown in Photo 3. For the trial, rotation of the rod as well as lifting of the table were powered by two electric motors of 1.0kW and 0.4kW, respectively. The inverter motor allows for smoothe regulation of rotational frequency and upward/downward velocity. Noise impact during drilling was very small, and there was absolutely no vibration either. The machine can be handled by one person due to the wheels attached to the frame. With the described features, the overall weight of the machine was about 160kg.

Photo 3. View of the shallow depth boring machine.

Drilling tests were carried out on the loam ground with a N-value between 3 and 5. The drilling depth was 4m. Instead of the drilling mud, the new developed screw-type sampler was used. Because of the small N-value of the ampling ground, there was no problem for drilling using only the dead weight of the boring machine. Soil samples at 600mm sampling length took about 3 minutes. Total time for drilling up to 4m depth required about 90 minutes.

However, once the ground became harder or the drilling bit hit small gravels, it became apparent that the counterweight of just the machine's dead weight was insufficient and the boring machine bounced up. Also, although the boring machine was equipped with wheels, the moving of boring machine was difficult on uneven grounds. To solve these problems, the boring machine was mounted on a compact caterpillar, as shown in Photo 4. This improvement prevented the machine from bouncing; and operating on uneven grounds became easy. The result of drilling test in this improved condition is shown in Table 1.

Photo 4. Shallow depth boring machine mounted on a mini caterpillar.

Table 1. Drilling test results by the Shallow Depth Boring Machine.

Sampling Depth (m)	Soil Type	N-Value (estimated)	Sampling Time (minutes)	Sampling Ratio (cm/cm)
0.0–0.7	Loam	5	4	65 / 70
0.7–1.4		5	2	65 / 70
1.4–1.8	Clay	5	1	40 / 40
1.8–2.1		5	1	30 / 30
2.1–2.8		5	2	70 / 70
2.8–3.5	Clayey sand	8	2	70 / 70
3.5–4.2		11	3	70 / 70
4.2–4.5		12	5	30 / 30
4.5–5.2		12	9	60 / 70
5.2–5.5		12	6	30 / 30
5.5–5.8		14	5	25 / 25
6.0–7.0		9	6	40 / 100
7.0–7.7		10	3	50 / 70
9.0–9.7		12	5	60 / 70
11.0–11.6		9	4	60 / 70
14.5–14.9		39	3	40 / 40

Note: sampling ratio = sampling length / boring length

The drilling mud was not used until a depth of about 6m was reached. Since there were gravels the depth from 6m to 7m, the drilling was changed to using drilling mud beyond this depth, but boring and sampling soils was possible up to about 15m depth even at N-values of over 10. As Table 1 shows, it took about 3 to 4 minutes collecting soil samples of 700mm length, and there was no shrinkage of the sample. Two persons were sufficient for handling drilling operation.

This confirmed that the new developed boring machine was suited for the purpose of the contaminated soil investigation.

4. A simple method for surface soil sampling

During initial investigation of contaminated sites, identifying the zones of contamination requires that rather large numbers of soil samples being taken at shallow depths of about 1 to 2 m below the ground surface. Hand augers for example have been in use for this purpose. However, drilling by manpower requires a long time per sampling point as well as considerable input of labor. To overcome this, a simple method for collecting soil samples was developed by making the diameter of the screw-type sampler small enough to be installed on an electric hand drill. The sampler for trial was the improved triple tube sampler, the outer diameter being 50mm and the diameter of the soil sample 23mm. Length of the soil sample was 400mm. This sampler was installed on a 100V electric hand drill, as shown in Photo 5. Drilling and soil sampling was possible as long as the ground was not hard. However, it was impossible to drill through small gravels, and handling beyond a depth of 1m demanded increased efforts. However, the sampler proved effective for collecting soil samples in the initial stage of investigation. Further improvement are planned to render this sampling method more convenient.

Photo 5. Surface soil sampling with electric hand drill.

5. Case study for TCE contaminated soils

An investigation of a ground contaminated by volatile organic compounds (TCE) was carried out as the flow chart shows in Figure 4. Since the scope of the contamination had been previously determined by other methods, this part deals with the detailed investigation of the site.

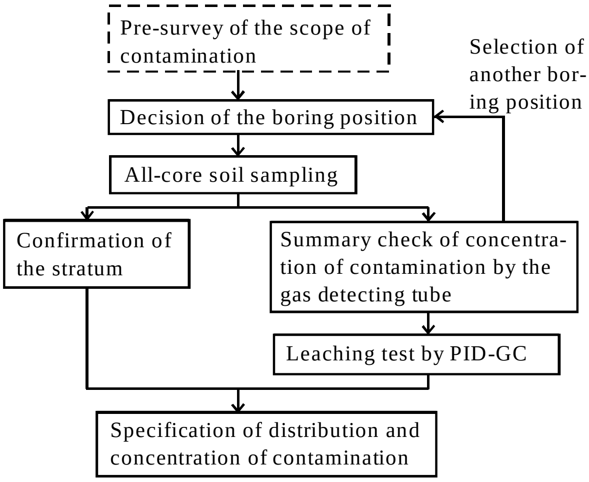

Figure 4. Flow chart of the investigation of the ground contaminated by TCE.

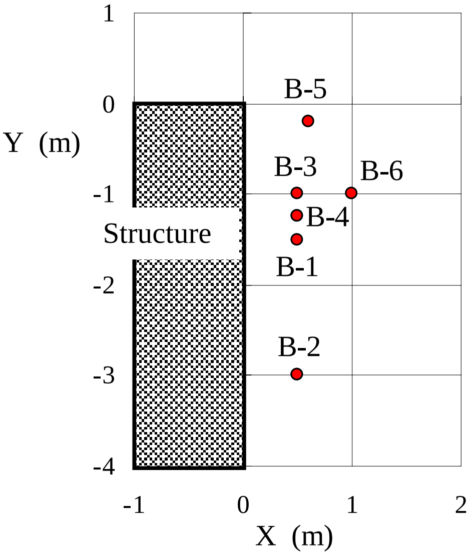

Figure 5. Position of boreholes at the investigated site.

Table 2. Leaching test results using Photo Ionization Detector-Gas Chromatography (PID-GC).

Boring Number	Sampling Depth (m)	TCE by PID-GC (mg/l)	TCE by Gas Detecting tube (ppm)
B-1	0.8	n.d.	n.d.
	1.3	0.002	n.d.
	1.7	0.358	10
B-2	0.7	n.d.	n.d.
	1.5	0.230	9
	1.8	0.170	7
	2.3	1.374	42
	3.0	0.129	7
	3.6	0.002	n.d.
B-3	1.2	0.007	n.d.
	1.8	0.052	2
B-4	1.3	0.733	23
B-5	1.5	0.240	14
B-6	1.4	0.333	18
	1.8	0.009	0.5

Note:n.d. - not detected

First, the stratum condition was determined from all-core samples using the above-mentioned boring machine and the screw-type sampler. Simultaneously, gas detecting tubes were used to check whether or not TCE was present in the soil samples. If soil samples were found to be contaminated, contaminated parts of the soil were picked up and subjected to leaching tests using PID-GC set up in a working hut near the site. Boring position are displayed in Figure 5 and the results of the leaching tests are shown in Table 2. It can be concluded that soil parts with higher concentrations found by the gas detecting tube also resulted in high values with the PID-GC analysis. At this site, the concentration of TCE exceeded the standard for environmental quality (0.03mg/l leachate or less from soils) in Japan. Because the boring machine was able to be moved easily from boring point to next point, this site investigation could be accomplished in just one day.

6. Conclusions

The three new developed methods for investigating contaminated soils reported here have proven to be very effective tools. Future improvements remain to apply these methods to various kinds of ground, e.g. sandy ground and more harder ground, and to further rationalize their handling.

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Remediation centre for contaminated soils

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ABSTRACT: A versatile remediation centre for contaminated soils has operated at Virkkala close to Helsinki since 1998. It is the first regional soil remediation centre in Finland and serves a large area in south-western Finland. Contaminated soils are collected from tens of small and large sites each year and transported to Virkkala for a very high class and environmentally safe treatment under controlled conditions. The centre consists of a 2 ha large hall for storage and treatment of the soils, a 1 ha outside bio-remediation field and a service & truck washing hall. Three treatment technologies are available at the centre: Stabilization/solidification, washing and bio-remediation. With these methods all the most common types of contamination can be treated: Heavy metals, oils, PAHs, creosotes and chlorophenols. Special care has been taken with prevention of environmental emissions, because the centre is located close to a housing area and on a lake-front. All the storage and treatment areas are covered with a double or triple bottom liner system and all environmental emissions are being monitored constantly. EU’s Life Environment –fund has supported the project.

1. Introduction

Remediation of contaminated soils was started at the early 90’s in Finland. In the national survey published in 1995 about 10 000 contaminated sites were identified, most of them in the south-western Finland. In the beginning the remediation was only done on-site with mobile equipment, but it was soon realised that several regional remediation centres are necessary for more effectively taking care of the problem. Lohja Envirotec started to plan the Virkkala soil remediation centre in 1994 and after a four-year long environmental permit process (one of the first mandatory Environmental Effects Assessment studies, EEA, was done as part of the process) the centre was opened in 1998 as the first regional soil remediation centre in Finland. The centre has been built in three phases, the last one of which was finished at the summer of 2000.

2. Virkkala soil remediation centre

The centre is located 65 km west of Helsinki in the middle of the triangle formed by the three largest Finnish cities and with a third of the country’s population living in the area. Contaminated soils are normally being transported from an up to 200 km’s distance, but in some cases even from a 500 km’s distance. The centre utilises the premises and facilities of a former cement factory, which was closed in 1993. This has given a splendid opportunity to utilise the available equipment, buildings and infrastructure with much lower costs than in the case of a green-field operation.

The main facility of the Centre is the 20 000 m2 large and 15 m high concrete hall (former limestone homogenisation hall), inside which most of the storage and treatment of the soils takes place. Truck washing, service works, social facilities and office facilities are located in the adjacent former truck service hall. A 10 000 m2 large bio-remediation area and the rain-water collection system are located outside the hall.

In the environmental permit the maximum allowed treatment capacity is limited to 80 000 tons/a, but in the beginning the volumes are 20–30 000 tons/a. The permit allows treatment of soils contaminated with heavy metals, oils, PAHs, creosotes and chlorophenols.

The construction and operation of the centre have also served as a demonstration project in the European Union’s Life Environment programme, which has also considerably funded the project.

3. Treatment methods

The founding idea of the centre has been to combine several of the best available treatment methods into the same place. The treatment methods have been chosen so that all the most common types of soil pollution can be treated (figure 1): Solidification/stabilisation method can be used for heavy metals, soil washing method for organic substances and heavy metals and bio-remediation for organic substances. The availability of all the three methods also allows for effective treatment combinations, so called “treatment trains”, for example washing+solidification or washing+bio-remediation.

3.1 Solidification/stabilisation

In Finland there are plenty of sites contaminated with heavy metals originating from wood preservation chemicals, many of which contain heavy metals such as arsenic, chrome and copper. Also lead is a common contaminant. These heavy metals are difficult to treat, because they cannot be destroyed. The only way is to immobilise them by binding them into insoluble form, with chemicals and binders, such as cement. The method is also called eco-concreting, because the soil is actually turned into concrete. This end product, eco-concrete, is normally utilised as a valuable earth construction material as the base layer in fields or roads. After hardening the leaching of harmful substances becomes so low that the material fulfils the strict Dutch limit values.

At the Virkkala centre eco-concreting is done with mobile high-capacity mixers, which are taken into the hall twice a year. These Australian continuously operating Aran mixers can treat 1000 m3 of soil per day.

3.2 Soil washing

Soil washing is a method consisting of a long process where the contaminated soil is being separated into several grain sizes. The idea is that, because the contaminants are bound into the finest particles, to separate in each step the finer and finer materials from the coarser materials, which are practically free of contaminants. The washing plants normally consist of several (10–30 pieces) components, including sieves, scrubbers, floating, spirals, etc. The process produces clean material, which is normally 70–90% of the original volume and the end slurry, which is normally 10–30% of the original volume and contains practically all the contaminants. This end slurry must then be treated by solidification or bio-remediation depending on the type of the contaminants.

At the Virkkala centre there is a Swedish washing plant, which can treat 5–10 tons/h. The method is suitable for treating sandy soils contaminated with organic or inorganic contaminants.

The plant is located inside the hall where it can also operate under mild winter conditions.

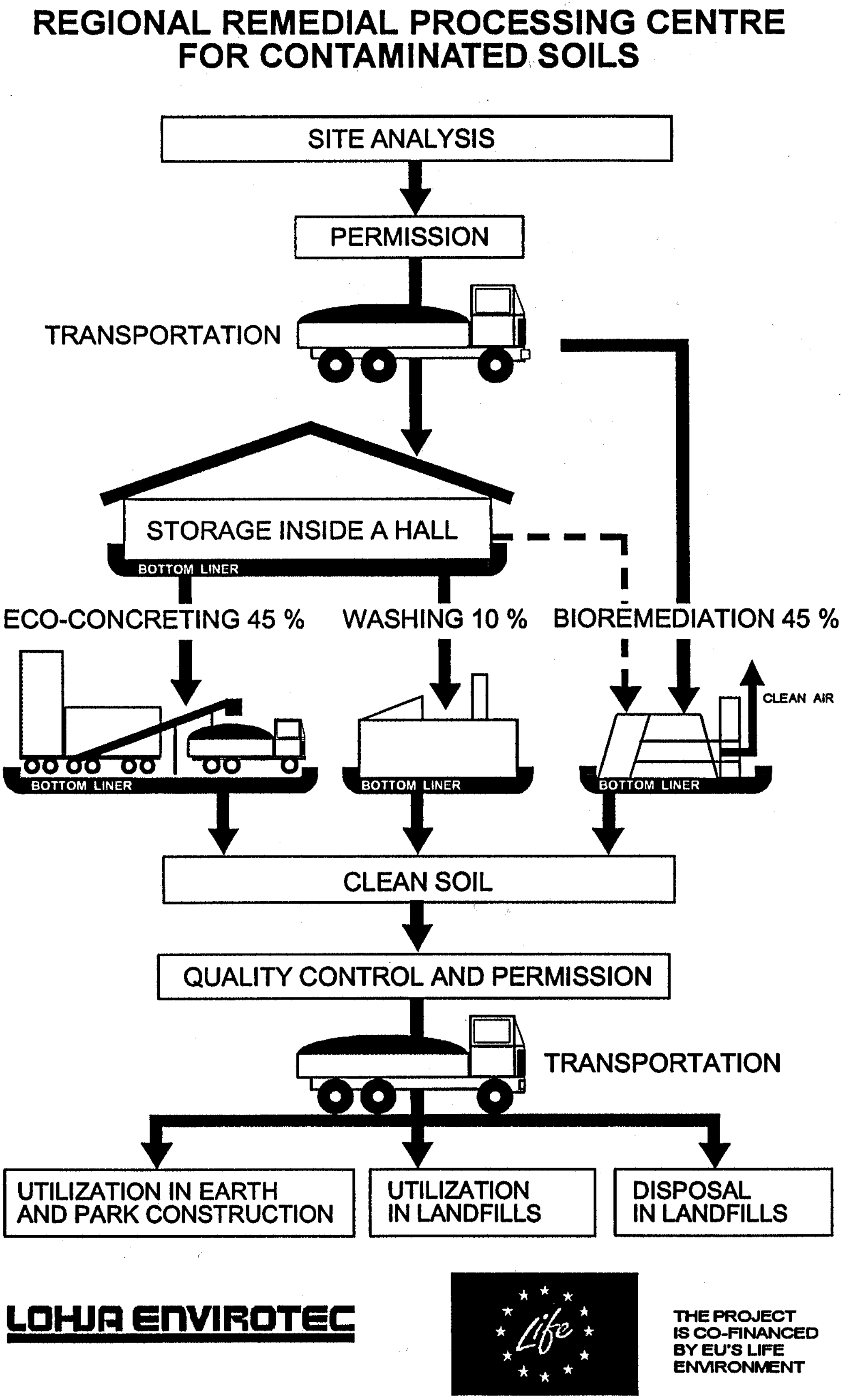


Figure 1. Treatment process of the Virkkala soil remediation centre.

3.3 Bio-remediation

Bio-remediation is a very common method used for treatment of organic contaminants, for example in the case of gas station remediation projects. In this method the soil's own bacteria "eat" the contaminants, if the right conditions (air, temperature) are provided inside the soil heaps. So far in Finland bio-remediation has been used only as the traditional method, where the uncovered soil beds are being turned now and then. However, this traditional method is not environmentally sound, because the contaminants are mostly being evaporated into the air and only a small share of them is being "eaten" by the bacteria.

At the Virkkala centre, a so-called bio-pile method is being used for the first time in Finland. In this method the soil beds are covered by plastic sheets and air is being pumped through a set of pipes into the soil and then sucked out through another set of pipes. The sucked air is then being cleaned either by active coal or by catalytic burning or by biological methods, before returning into the bed again. If necessary, the air is being heated under winter conditions. The bio-pile method is more effective and environmentally safe than the traditional one. The bio-remediation process is being operated by the largest Danish bio-remediation contractor Bioteknisk Jordrens Soilrem A/S.

4. End-placement of the treated soils

After remediation has been successfully done and controlled, all the soils are taken out of the Virkkala centre, because there is no end-placement capacity there. So far all the end-placement has been provided by the regional waste management company Rosk'n Roll, owned by the 12 communities and some industrial enterprises in the region. At Rosk'n Roll's two landfill sites the treated materials have been 100% utilised as earth construction materials in the construction of new roads and fields, and also as the daily covering material. In the future, utilisation will be considered also in other earth construction structures outside the landfill sites.

5. Environmental protection at the centre

Since the start of the planning of the Virkkala centre, environmental protection of the centre's site and the surroundings has been one of the major issues, because it is located only 100–200 m from the nearest houses and on the lake-front. In the very thorough EEA process it was found out that with certain environmental protection measures the centre can be located on the planned site. The major environmental protection actions were prevention of leaching of contaminated water into the ground and prevention of dusting. One of the important actions against emissions was the decision to locate most of the activities inside the hall under controlled conditions and protected from rain and wind. On top of this, the following special actions have been taken:

5.1 Bottom liner system

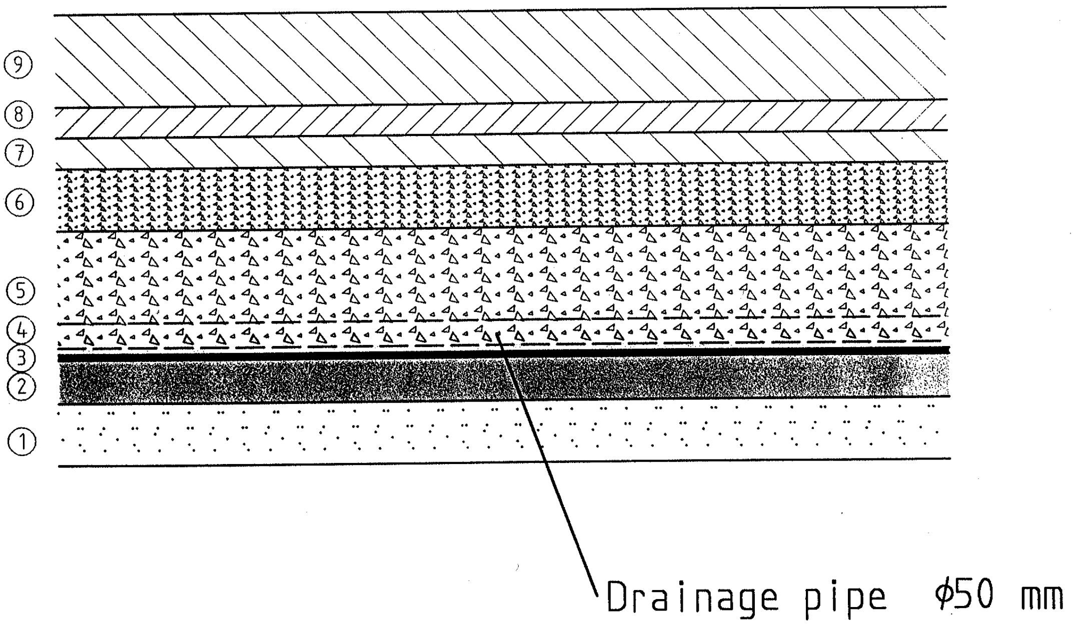
During construction of the Virkkala centre all the storage and treatment areas for contaminated soils were covered with a special watertight liner system, which was developed and greatly improved during the construction time. In 1998 under the 1st phase of the construction the bottom liner construction consisted of a sand bentonite mineral liner and two layers of a special, at that time considered as watertight, asphalt (so-called "Lemdense"). However, soon after the first soil parties were received, it was found out that the Lemdense asphalt was leaking. This was noticed because there is a drainage system between the asphalt layers and the sand bentonite layer. Actually this structure has acted as a giant lysimeter providing valuable information of the effectiveness of asphalt liners. The real water-tightness (k-value) of the asphalt liner was found out to be about 100 times higher (worse) than the design value given by the asphalt producer and required by the structure designer. These experiences from the Virkkala centre have also lead to changes in the design of landfill liners: If asphalt liners type “Lemdense” are being used instead of the plastic liner, there should be a layer of rubber-bitumen asphalt (so-called “Lemproof”) on top in order to reach the required water-tightness. A more detailed description of this case is given in Kari Ruohonen’s presentation in this same Ecogeo 2000 congress.

Based on these experiences, a greatly improved bottom liner system was used in the construction of the 2nd phase in 1999 (figure 2). This was a triple liner system with a polymer modified sand bentonite mineral liner (Trisoplast), a 2 mm HDPE plastic liner and two layers of the special asphalt. The polymer modified sand bentonite (Trisoplast) is a Dutch product, which has several greatly improved properties compared to normal sand bentonite. It is more watertight, flexible, resistant to chemicals, etc. Due to these properties the thickness of the mineral layer can be diminished by more than 80% compared to normal sand bentonite without compromising in any of the required properties. This results in considerable savings in landfills and all other types of liner constructions. More information of Trisoplast can be found in Pasi Virtanen's poster presentation in this same Ecogeo 2000 congress. The HDPE liner was added into the structure, because the asphalt layers could not be considered as a second liner.

5.2 Emission control system

A special environmental emissions control program was taken into use already before the construction of the Virkkala centre was begun. Ground water quality is being monitored from several wells inside the centre area, soil samples are analysed both from the centre area and from the nearby housing area, air emissions are being monitored inside the hall, outside in the centre area and in the nearby housing areas. A special “odour team” with representatives from the neighbourhood was nominated and all the people living in the neighbourhood have been given a chance to keep “odour diaries”. An annual environmental report is given to the authorities and a shorter version to the inhabitants. No meaningful emissions have been detected so far.

One issue to be considered was the possibility of contaminated dust spreading into the vicinity by truck tyres. To prevent this a special truck washing line has been built and the driveway leading from the hall to the washing line has also been covered with a liner and water collection system.



⑨ Eco-concrete (when necessary)	150 mm
⑧ Asphalt sealing layer	50 mm
⑦ Asphalt sealing layer	50 mm
⑥ Drainage layer (Crushed stone #0-16)	100 mm
⑤ Drainage layer (Crushed stone #2-32)	200 mm
④ Geotextile, ≥1000g/m^2	2 mm
③ Plastic sealing layer (HDPE)	2 mm
② Mineral sealing layer (Trisoplast)	70 mm
① Levelled base	

Figure 2. The improved bottom liner system of the Virkkala soil remediation centre.

Probabilistic risk assessment of a contaminated site

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ABSTRACT: The results of deterministic and probabilistic risk assessment at a contaminated site were compared. The deterministic point estimates of the incremental lifetime cancer risk following exposure to dioxin/furan and PCB contaminated recreational site were 1×10^{-4} for dioxins/furans and 3×10^{-5} for PCBs. The point estimates located at the 99,8 and 97,3 percentiles in the probabilistic range of risk. The distribution means were 4×10^{-6} for dioxins/furans and 4×10^{-6} for PCBs, respectively. The point estimates highly overestimated the risk, whereas, the probabilistic approach resulted valuable information regarding the possible distribution of risk. Clean-up levels corresponding risk level of 10^{-6} were also calculated. The point estimates were 5,5 ng TCDD-equivalents/kg soil and 0,5 mg PCBs/kg soil. The 5th percentile values, which are protective for 95% of the population, were 11,6 ng TCDD-equivalents/kg soil and 0,4 mg PCBs/kg soil. The sensitivity analysis revealed that the soil concentration data is the dominating parameter when it comes to the uncertainty in this assessment.

1. Introduction

The traditional way of doing risk assessment is to use single value best estimates for each parameter in risk calculation. This deterministic approach rarely represents the real life situation. Most of the parameters are variable in nature, for example, exposed people weight different amounts. Furthermore, many of the exposure assumptions are unknown. The major shortcoming in deterministic approach is the ignorance of the elementary features of exposure parameters, which are the variability and uncertainty.

Because of the variability and uncertainty, most of the input values are really random variables, which can take any value in range of values, with a certain probability of occurrence. This probabilistic nature of parameters is taken into account in probabilistic risk assessment. (Burmaster 1995)

This paper presents the use of probabilistic risk assessment in a case of contaminated site. Results of the probabilistic approach are compared to the results of the traditional deterministic approach. Carcinogenic risk and risk-based cleanup levels are calculated.

The most commonly used probabilistic method in health risk assessment is the Monte Carlo simulation. In Monte Carlo simulation, numbers for parameters are generated according to their distributions and risk equation is solved repetitively.

2. Methods

The point estimates for the risk where calculated using a deterministic approach recommended by the U.S.EPA (U.S.EPA 1989). Probabilistic risk assessment was done by Monte Carlo Simulation with Latin Hypercube Sampling using Crystal Ball® 4.0 spreadsheet program (Decisioneering). Exposure parameters were approximated by probability density functions (PDFs) found from the literature. PDFs for contaminant concentration data was evaluated using Kolmogorov-Smirnov goodness-of-fit test and Maximum Likelihood Estimation in Crystal Ball program.

Sensitivity analysis was done calculating a contribution to variance for each exposure parameter. Contribution to variance is received by squaring the rank correlation coefficient and normalizing then to 100% (Decisioneering)

3. Exposure assessment

The contaminated area is a part of a recreational area planned to serve the inhabitants of nearby residential areas. Wide variety of industrial and commercial activities has taken place in the area. The current contamination is mainly due to dumping of fly ash from waste incinerator. The major contaminants in fly ash are polychlorinated dibenzodioxins and –furans (PCDD/PCDF), polychlorinated phenols (PCBs), lead (Pb), zinc (Zn), and copper (Cu). Cancer risk following exposure to PCDDs/PCDFs and PCBs is assessed in this case study.

Probability density functions for soil concentration data were approximated from the site data. Soil concentration data from earlier years were used (Insinööritoimisto Paavo Ristola 1988, 1997). A lognormal distribution was chosen to represent concentration data based on goodness-of-fit data and personal judgement. The 95th percentile concentrations were selected as the point estimates. Distribution parameters for soil concentrations are given in table 1.

Table 1. Point estimates and distribution parameters for soil concentrations.

Chemical	Units	Point estimate	Distribution type and distribution parameters [a]
PCDD/PCDF as TCDD-equivalents	(ng/kg)	643	Lognormal (μ = 174 σ = 392 95% = 643)
PCB	(mg/kg)	12	Lognormal (μ = 3,69 σ = 42,2 95% = 12,16)

[a] Distribution parameters of underlying normal distribution $X = \ln [\underline{X}]$.

The contaminated fly ash is covered with clean sand and gravel. The goal of this paper is to evaluate the usefulness of probabilistic risk assessment compared to the traditional deterministic approach. Therefore, in order to simplify the exposure assessment the risk was assessed as if no clean cover exists.

Ingestion of soil, dermal contact, and ingestion of mother's milk where chosen as possible exposure pathways. Inhalation and ingestion of particles in air contributed less than 1% to the total exposure, and where therefore not included here. The lifetime average daily doses for each pathway was calculated using equations 1, 2 and 3, adapted and modified from the U.S.EPA guidelines (U.S.EPA 1989). The equation for the exposure via mother's milk was adapted from CalTox (CalTox 1993a)

$$DI = \left[\left(\sum_{i=m}^{n} \left(\frac{IR_i}{BW_i} \times \frac{t_i}{10} \right) \times EF_c \times U \times ED_c \right) + \left(\frac{IR_a}{BW_a} \times EF_a \times ED \right) \right] \times CS \times CFS \times \frac{1}{AT} \tag{1}$$

$$\begin{aligned} DD = & \left[\left(\sum_{i=m}^{n} \left(SA_i \times \frac{t_i}{10} \times FSA_i \right) \times EF_c \times ED_c \times RT \right) + \left(SA_a \times FSA_a \times EF_a \times ED_a \right) \right] \\ & \times CS \times CF \times AF \times FC \times \frac{1}{AT} \end{aligned} \tag{2}$$

$$DM = C_{bmilk} \times \left[\frac{IR_{bm}}{BW} \right] \times \frac{EF \times ED}{AT} \qquad C_{bmilk} = I_{mo} \times BW_{mo} \times B_{bmk} \tag{3}$$

Where

DI = lifetime average daily dose following ingestion of soil (mg/kg-day)
DD = lifetime average daily dose following dermal contact with soil (mg/kg-day)
DM = lifetime average daily dose following ingestion of mother’s milk (mg/kg-day)
IR = the soil ingestion rate (mg/day)
BW = the body weight (kg)
ED = the exposure duration (years)
U = the amount of days when the soil is unfrozen (days/year)
CS = the contaminant concentration in the soil (mg/kg)
EF = the exposure frequency (days/year)
CFS = the conversion factor (10^{-12} kg/ng)
AT = the averaging time (days)
SA = the skin are as a function of body weight (cm^2/kg)
FSA = the fraction of skin area exposed
AF = the soil adherence factor (mg/cm^2)
FC = the fraction of soil that is contaminated
C_{bmilk} = the chemical concentration in mother’s milk (mg/l)
IR_{bm} = the amount of mother’s milk ingested (l/d)
I_{mo} = the mother’s total exposure (mg/kg-d)
B_{bmk} = the ratio of chemical in milk and mother’s exposure (d/kg-milk)

Subscript *c* denotes a child, and *a* denotes an adult. Input parameters are shown in Table 2.

The results of exposure assessment are shown in the table 3. Only the pathways contributing more than 1% to the overall exposure are shown.

Table 2. Variables and constant used in exposure assessment.

Parameter	Point estimate	Distribution parameters and type		Reference
IR (mg/d)				
< 6 years	179	μ = 179 95% 208	LN	U.S.EPA 1996
Adult	480	-	-	U.S.EPA 1996
BW (kg)			LN	Burmaster & Crouch 1997
1-2 years	11,8	μ = 11,8 σ = 1,9		
7-8 years	25,1	μ = 25,1 σ = 3,9		
35-44 years	80,9	μ = 80,9 σ = 13,4		
U (d/year)	273	min = 204 max = 355 likeliest = 273	TR	Huttunen & Soveri 1993
EF_c (d/year)	1	min = 0,2 max = 1,0	U	Personal judgement
EF_a (d/year)	40	min = 20 max = 60	U	Personal judgement
ED_c (years)	10	μ = 11,36 σ = 13,76 truncated at 10 years	LN	Israeli & Nelson 1992
ED_a (years)	10	μ = 11,36 σ = 13,76	LN	Israeli & Nelson 1992
AT (years)	75	min = 73 max = 79,5	U	U.S.EPA 1996
SA (cm^2/kg-d)			LN	Burmaster 1998
1–2 years	5,77	μ = 5,77 σ = 1,30		
7–8 years	14,84	μ = 14,84 σ = 2,26		
35–44 years	52,90	μ = 52,90 σ = 9,14		
AF (mg/cm^2)	0,52	μ = 0,52 σ = 0,9	LN	Finley et al. 1994c
FC	1	-	-	-
FSA	0,19		U	U.S.EPA 1996
1–2 years		min = 0,057 max = 0,48		
6–7 years		min = 0,047 max = 0,52		
adult		min = 0,052 max = 0,56		
IR_{bm} (kg/kg-d)	0,11	0,11 CV 0,2	LN	CalTox 1993b
EF (d/a)	365	365	-	-
ED (year)	1	-	-	-
BW_{mo} (kg)	64,2	μ = 64,2 σ = 15	LN	Burmaster & Crouch 1997
B_{bmk} (d/kg-milk)				
(PCB)	0,52	μ = 0,52 CV=10	N	CalTox 1993b
(TCDD)	0,92	μ = 0,92 CV=10	N	

μ, mean; σ, standard deviation of underlying normal distribution X = ln [X]; CV, correlation coefficient; LN, lognormal; W, weibull; U,uniform; TR, triangular

Table 3. Exposure to TCDD-equivalents and PCBs through different pathways. Lifetime average daily dose following DI = ingestion of soil, DD = dermal contact with soil, and DM = ingestion of mother's milk (mg/kg-day).

	TCDD-equivalents		PCB		
	DI (mg/kg-day)	*DM* (mg/kg-day)	*DI* (mg/kg-day)	*DD* (mg/kg-day)	*DM* (mg/kg-day)
Deterministic					
Point estimate	$6{,}68 \times 10^{-10}$	$5{,}91 \times 10^{-11}$	$1{,}25 \times 10^{-5}$	$2{,}35 \times 10^{-6}$	$6{,}23 \times 10^{-7}$
% of total exposure	91,9	8,1	80,7	15,2	4,0
Percentile [a]	98,73	93,19	98,1	93,4	87,8
Probabilistic					
Mean	$6{,}77 \times 10^{-11}$	$1{,}36 \times 10^{-11}$	$1{,}40 \times 10^{-6}$	$5{,}97 \times 10^{-7}$	$6{,}73 \times 10^{-7}$
Standard deviation	$1{,}97 \times 10^{-10}$	$7{,}01 \times 10^{-11}$	$1{,}02 \times 10^{-5}$	$5{,}68 \times 10^{-6}$	$1{,}05 \times 10^{-5}$

[a] The location of point estimate at the probabilistic range of exposure.

4. Risk characterization

The risk is characterized by considering the exposure, bioavailability and cancer slope factor. The conservative estimate of oral TCDD bioavailability is 100%. 0,5 – 50% of TCDD is found to be absorbed in experimental animals (Copeland 1993). For PCBs the oral absorption is assumed to be 90% (RAIS 1999). The dermal bioavailabilities are 0,1–3% for TCDD and 0,6–6% for PCBs, respectively (U.S.EPA 1992). Bioavailabilities were assumed to be uniformly distributed.

Carcinogenic slope factors (CSFs) were entered as point values, so their effect on variability in the risk estimate was not estimated. Used CSFs were 160 000 kg-day/mg (oral) (U.S. EPA 1997), 300 000 kg-day/mg (dermal) (RAIS 1999) for TCDD-equivalents and 2 kg-day/mg for PCBs (IRIS 1999).

Incremental lifetime cancer risks (ILCRs) were calculated using equation 4. Results are introduced in the table 4.

$$ILCR = \left[CSF_0 \times \left(B_o \times (DI + DM)\right)\right] + \left[CSF_d \times B_d \times DD\right] \qquad (4)$$

Where

CSF = the cancer slope factor (kg-day/mg)
B = the bioavailability
DI = lifetime average daily dose following ingestion of soil (mg/kg-day)
DD = lifetime average daily dose following dermal contact with soil (mg/kg-day)
DM = lifetime average daily dose following ingestion of mother’s milk (mg/kg-day)

Subscript *o* denotes oral and *d* denotes dermal

Table 4. Risk estimates for TCDD-equivalents and PCBs.

	TCDD-equivalents	PCBs
Deterministic		
Point estimate	$1,16 \times 10^{-4}$	$2,65 \times 10^{-5}$
Percentile [a]	99,82	97,33
95th percentile	$1,33 \times 10^{-5}$	$1,28 \times 10^{-5}$
Probabilistic		
Mean (μ)	$3,51 \times 10^{-6}$	$4,19 \times 10^{-6}$
Median	$8,82 \times 10^{-7}$	$2,58 \times 10^{-7}$
Standard deviation (σ)	$1,28 \times 10^{-5}$	$3,83 \times 10^{-5}$
Coefficient of variability	3,66	9,14
Range minimum	$6,02 \times 10^{-10}$	$2,72 \times 10^{-11}$
Range maximum	$6,86 \times 10^{-4}$	$2,49 \times 10^{-3}$
Range width	$6,86 \times 10^{-4}$	$2,49 \times 10^{-3}$

[a] The location of point estimate at the probabilistic range of risk.

Point estimates located at the high end of probability distribution and were therefore conservative and overprotective. Mean and median estimates of risk were smaller than the generally acceptable risk 10^{-6}. The probability distributions of estimated risks were found to be lognormally distributed. Lognormal distribution is positively skewed distribution, that is most of the values are the low risk end of the distribution.

5. Risk-based cleanup levels

Risk-based cleanup levels corresponding risk level of 10^{-6} were calculated. One in a million risk is generally though to be acceptable risk. Soil concentration parameter was solved from combined risk and exposure equations. Results are presented in table 5.

Table 5. Risk-based cleanup levels corresponding 10^{-6} risk.

	TCDD-equivalents (ng/kg)	PCB (mg/kg)
Deterministic		
Point estimate	5,53	0,45
Percentile [a]	0,03	7,56
5th percentile	11,64	0,38
Probabilistic		
Mean (μ)	129,22	1,47
Median	54,56	1,10
Standard deviation (σ)	294,75	1,31
Coefficient of variability	2,28	0,89
Range minimum	2,91	0,12
Range maximum	10 583,30	35,77
Range width	10 580,39	35,77

[a] The location of point estimate at the probabilistic range of risk.

The deterministic estimate of TCDD-equivalent cleanup level is located at 0,03 percentile, meaning that for only 0,03% of the exposed population the risk will be higher than the acceptable risk 10^{-6}. The range minimums gives the conservative estimate of soil concentration were the risk is smaller than 10^{-6} in all cases.

6. Sensitivity analysis

Sensitivity analysis was done calculating the contribution to variance for each exposure parameter. Contributions to variance in dioxin/furan risk assessment are shown in figure 1. The most important parameter in PCB risk assessment was also chemical concentration in the soil (contribution 90,7%). Less important parameters in PCB risk assessment were exposure duration in childhood and adulthood (contributions 4,0 and 1,3%).

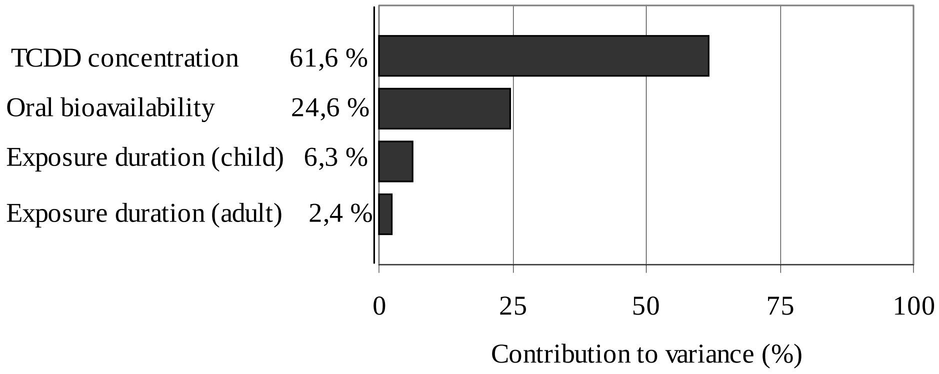

Figure 1. Contributions to variance in dioxin/furan risk assessment. Parameters contributing more than 1% are shown.

7. Conclusions

Relatively high deterministic estimates of risk were achieved. However, the probabilistic assessment revealed that these estimates were conservative. The 95th percentiles (for 95% of the exposed population, the risk is smaller than this value) for both TCDD-equivalent and PCB exposure were 10^{-5}. The medians (50% of the population experience higher risk) were two orders of magnitude smaller (10^{-7}).

Due to the lognormal shape of risk distribution, majority of the exposed population experience low risk and only few persons are at higher risk. The small high-risk minority will be protected if management decisions are made based on the deterministic assessment. This comes questionable in case where resources are scarce but will stay acceptable approach if resources are not the limiting factor.

8. Acknowledgements

The support of Helsinki University Development Services Ltd, Environmental Projects is kindly acknowledged.

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Geostatistical methods in characterization of contaminated soils

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ABSTRACT: Geostatistical estimations and simulations are based on the modelling of the spatial correlation. The aim of the present paper is to demonstrate geostatistical methods using data from Oitti and Sipoo spill sites in southern Finland. At both locations, the soils have been contaminated by dense nonaqueous phase liquids (DNAPLs). Subsurface structures, soil contamination and groundwater quality were visualized and described by using geostatistical estimations and simulations.

1. Introduction

The main goal of geostatistics is to estimate the unknown variable values in space.
The unknown value is either estimated or simulated by using the variogram model and the values at the nearby sample points. Variogram model tells how well and how far the variable values are correlated - often, the nearby values are more similar than the faraway samples. Geostatistical analysis has usually following components:

(1) description of the data set by using summary statistics and histograms,
(2) correlation of different variables,
(3) separation of different populations,
(4) spatial description of data (e.g. variograms), and
(5) geostatistical estimation (kriging) or simulation.

The main difference from the classical statistics is the use of spatial information of the earth science data sets. The choice between estimation and simulation depends on the final goal of the study. The geostatistical estimation like kriging-interpolation (e.g., Journel and Huijbrechts, 1978) is used when the local accuracy is important, for example, in ore evaluation. Kriging is defined as a collection of generalized linear regression techniques for minimizing an estimation variance defined a prior model for a covariance (variogram) that may or may not have constraints to eliminate bias (Olea, 1991). In kriging the sample histogram should be normal. Kriging interpolation often underestimates high values and overestimates the low ones. When the reproduction of the original data variability is needed, as in the environmental studies, the geostatistical simulation is preferred.

Geostatistical simulation produces for a given set of drill logs several realizations of the subsurface. Each interpretation honors exactly the “hard” well log data, but each realization is different from each other. Based on the available data, one is not better than another, and all should be evaluated. When several realizations are produced, the summary statistics can be used to present the uncertainty that the variable value is below or above a certain critical threshold. In addition, if the same spatial pattern occurs on most of the realizations it can be kept rather certain, if the original model is correct. The achieved uncertainties are model dependent and, thus, subjective. However, the geostatistical simulation gives more than just one alternative based on the same model.

Many variables within environmental studies have unsymmetric distributions with a long tail of high values. A very typical example of such data is water quality analyses for polluted materials. Some kind of transformation is needed. Nonlinear transformations are not very good because they bring very different values near to each other in interpolation. Hence, the back transformed values are very uncertain. A better alternative is the indicator kriging (Journel, 1983). The indicator transform gets a value of 1 when the variable value is less than a critical threshold and 0 else. Indicator kriging gives instead of estimated values the estimated probabilities of variable value being below or above a certain threshold.

At the present paper the Oitti and Söderkulla spill sites will be studied (Figure 1). At both sites soil and groundwater have been contaminated by dense nonaqueous phase liquids (DNAPLs). In soils, these solvents evaporate partly in the air and move rapidly downwards or dissolve to groundwater. Solvents migrate to impermeable boundaries such as clay layers and bedrock surface; or they migrate as a dissolution in groundwater. The migration directions are not necessary the same in these two cases. The coarse soil layers do not bind these solvents. In contrast, the fine silt or clay layers bind solvents effectively. In soil layers, the solvents do decompose slowly, but in ground water, they remain intact. For these reasons, it is important to know the subsurface structure. In the present paper I apply geostatistical methods in visualization and description of subsurface structures and soil and groundwater contamination within Oitti and Söderkulla spill sites.

Figure 1. The approximate locations of the Oitti and Söderkulla spill sites in southern Finland.

2. Oitti spill site

Oitti is situated on the Salpausselkä moraines that form two parallel ridges in which cross-bedded sands and gravels coarsen upwards. The soils around Oitti are very heterogeneous. In the 1950's and 1960's about 10,000 litres of dry cleaning solvent from a dry cleaning establishment near the municipal centre at Oitti, southern Finland was disposed of in a well and in pits. The groundwater was found contaminated in 1992 when a regional groundwater quality survey was done in the region. Although the major part of the total amount of solvent was deposited in a condensed form into a landfill, the storage sites at the dry cleaning establishment became injection wells by default because of the permeable nature of the underlying strata (porous sand and gravel, typical of the glacial formations overlying the area). The solvent consists mainly of trichloroethylene and tetrachloroethylene which are dense nonaqueous phase liquids (DNAPLs). Subsurface structures and DNAPL migration were visualized using the data from a year 1996 (Varis: a personal communication). The groundwater samples used in this study were collected approximately at the same time from different locations.

The ground penetrating survey was done in small area around the cleaning establishment (Peltoniemi et al., 1996) (Fig. 2A and B). There is a conducting clay layer below sandy layers (Laine and Peltoniemi, 1997). Below this layer no information was obtained. Clay layers are fragmented or gently folded according to interpreted depths. Because the depths to clay layers have a rather symmetric distribution the Gaussian simulation (Deutsch and Journel, 1998) was applied. The variogram model shows a short range of 20 metres (Fig. 2C) that represents mostly the direction across the ridge. Because of the lack of data along the ridge it was assumed that the range is larger, about 50 metres in this direction. The nodes were simulated along a random path and ordinary kriging was applied by using in addition to known data values previously simulated nodes in the search neighbourhood. Fifty simulations were summarized by calculating their mean at every node (Fig. 2D). The result map shows the implemented anisotropy and that clay layers are highest in the centre of the ridge. If the clay layers are fragmented, they should be simulated as objects.

The second known barrier is the bedrock surface. The data consisted of refraction seismic profiles (Figures 2A and 3A) and the depths picked from the map of Quaternary deposits of the area (Geological Survey of Finland). The studied area is larger than in the case of the ground penetrating survey. Bedrock topography was simulated as the depths to the clay layers. There seem to be bedrock valleys across the ridge (Fig. 3B). As a comparison, the kriged elevation model (Fig. 3C) shows the form of the ridge.

Organic halogens (AOX) were analysed from the groundwater samples (Varis; a personal communication). A map of AOX contents in groundwater (Fig. 3D), modelled by applying the sequential indicator simulation (Deutsch and Journel, 1998) to the water-well analyses, support these results.The DNAPLs migrate with the groundwater to the north and west according to the 50 simulations of groundwater quality. These directions correspond the direction of the ridge and the slope toward the valley in the west and parallel with the possible east western fractures.

Based on the previous data analysis and subsurface realizations, the solvents may have trapped on the clay layers or bedrock valleys and, thus, in future, they may form a new source for groundwater contamination.

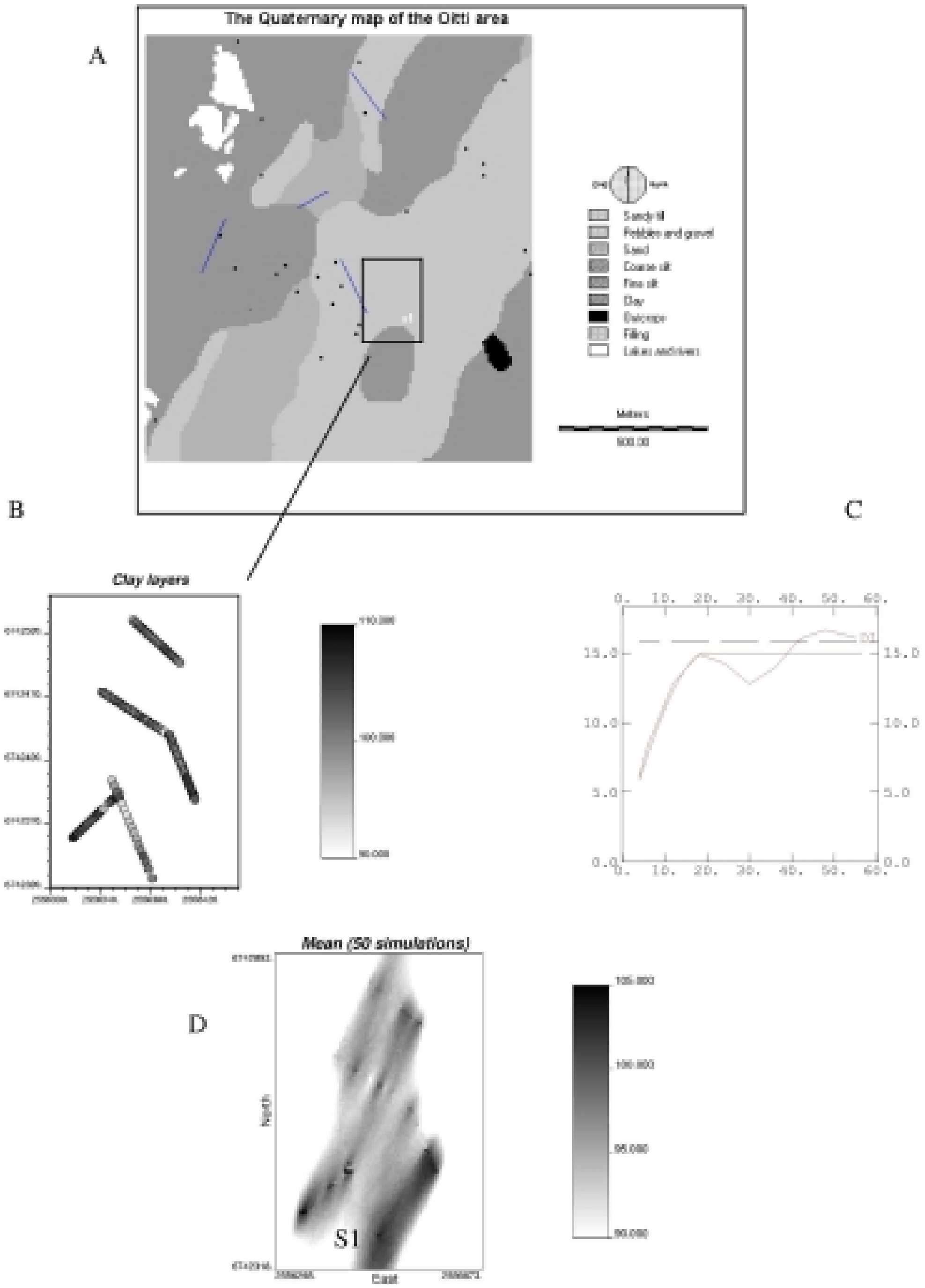

Figure 2. A) Locations of groundwater samples (black points) and refraction seismic profiles on the Map of Quaternary deposits of the Oitti area (Geological Survey of Finland); B) locations of ground penetrating survey profiles; C) an experimental semivariogram calculated from the depths to the clay layer; D) a summary map of 50 Gaussian simulations. S1 - the former cleaning establishment.

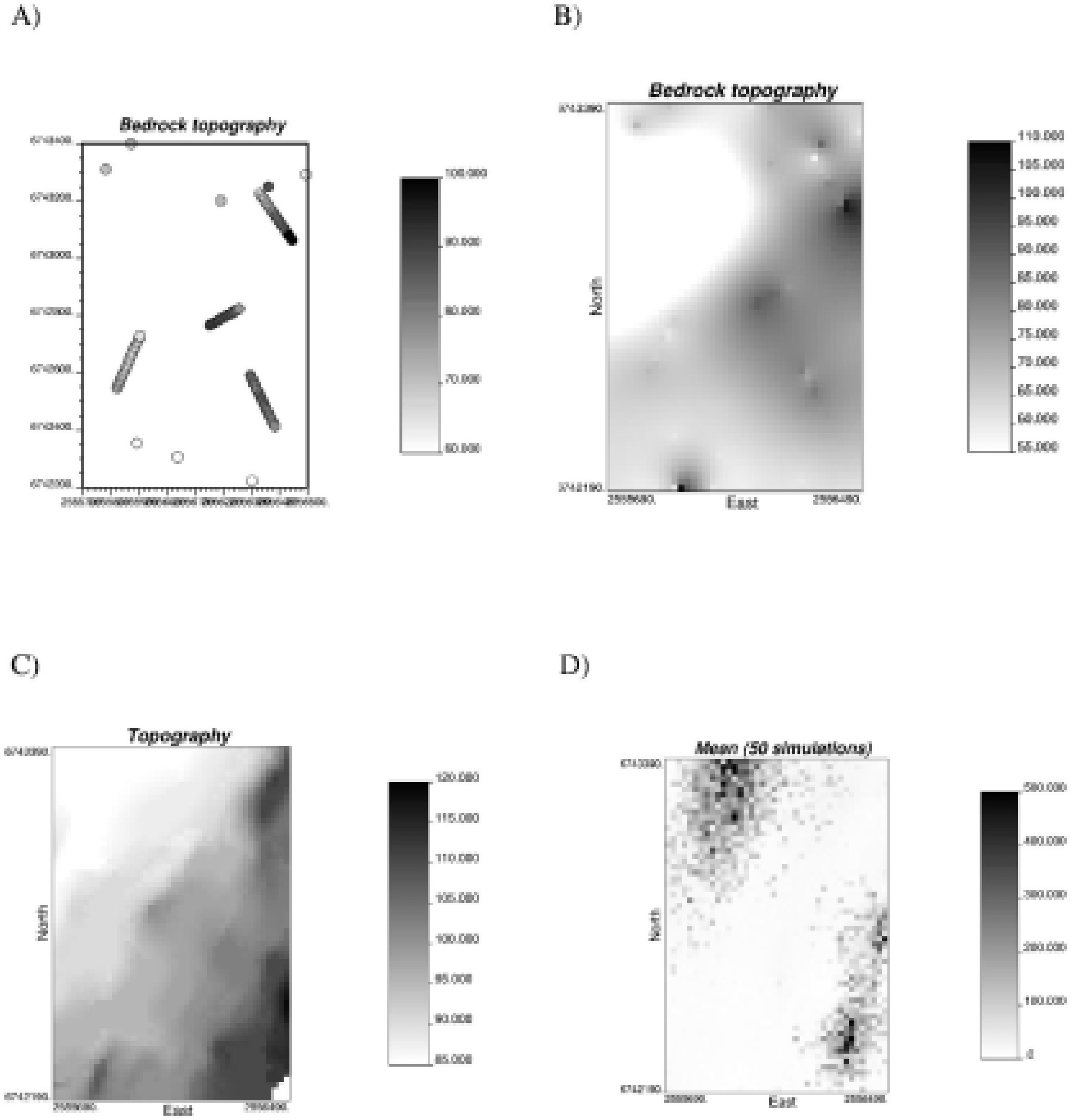

Figure 3. A) Depths to the bedrock surface; B) a summary map of 50 Gaussian simulation of bedrock topography; C) the kriged elevation model based on the elevation counter data from National Land Survey of Finland; D) a summary map of 50 indicator simulations of AOX content of groundwater. S1 - the former cleaning establishment.

3. Söderkulla spill site

The Söderkulla spill site is situated in Sipoo, to the east of Helsinki. In this case, subsurface structures consist of horizontal sand and clay layers. Soil and groundwater have been contaminated by DNAPLs, mainly by trichloroethene. The probable source for heavy liquids is the establishment which worked with metal products.

The subsurface consists of nearly horizontal sand and clay layers. Soil type distribution was simulated by truncated Gaussian simulation (e.g., Roth et al. 1998) conditioned on the soil proportions per depth and the drill hole data (Fig. 4). The realization shows one possible subsurface structure based on the known data.

The soil samples have been analyzed by gas chromatography (Uusimaa Regional Environment Center). The solvents consist of trichloroethene, vinyl chloride, dichloroethene and xylene. The main component is trichloroethene. In addition, soil contamination has been measured by using the photo-ionization method (Uusimaa Regional Environment Center). The high trichloroethene contents seem to correspond high photo ionization value but the reverse is not true (Fig. 5) because the photo ionization method measurements correlate with the total content of several organic compounds. In addition, the photo ionization measurements were done in situ, and the analyses from the samples in the laboratory. Photo ionization measurements have a skewed distribution (Fig. 6A). In addition, there is almost no spatial correlation (Fig. 6B): the range is below 10 metres. Probabilities that the photo ionization measurements give a value greater than 77.8 (a threshold above which there are 20% of measurements) is visualized by indicator kriging (Fig. 6C and D). It was assumed that 77.8 ppm is a threshold for the presence of solvents in soil. Accordingly, on the top of the formation soil contamination forms one compact area. At a level of 12 metres there are two separate areas of contamination.

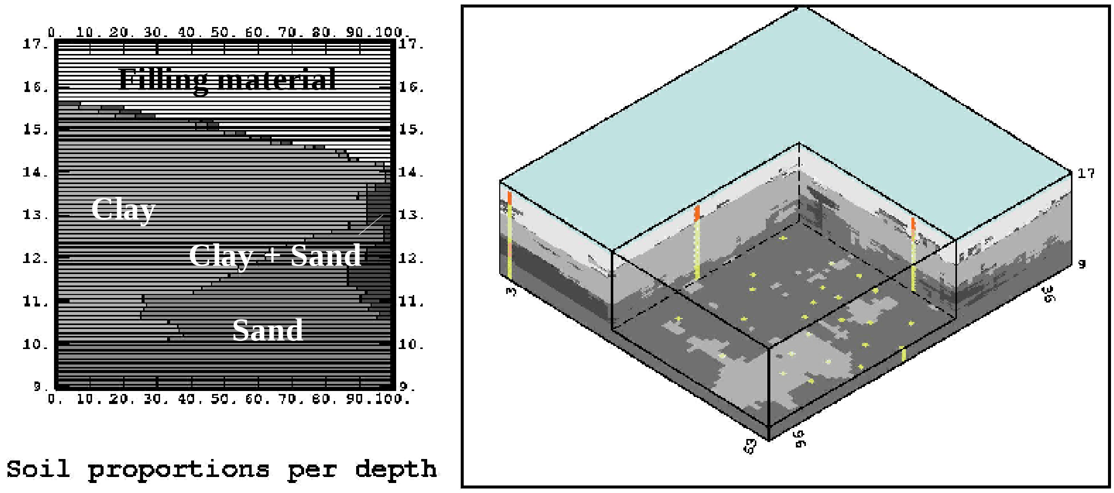

Figure 4. Subsurface structure at the Söderkulla spill site.

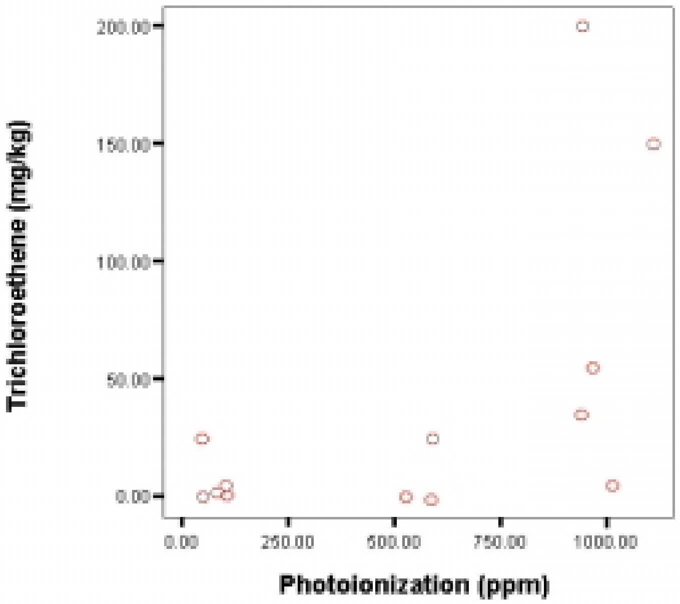

Figure 5. Trichloroethene contents versus photo ionization measurements.

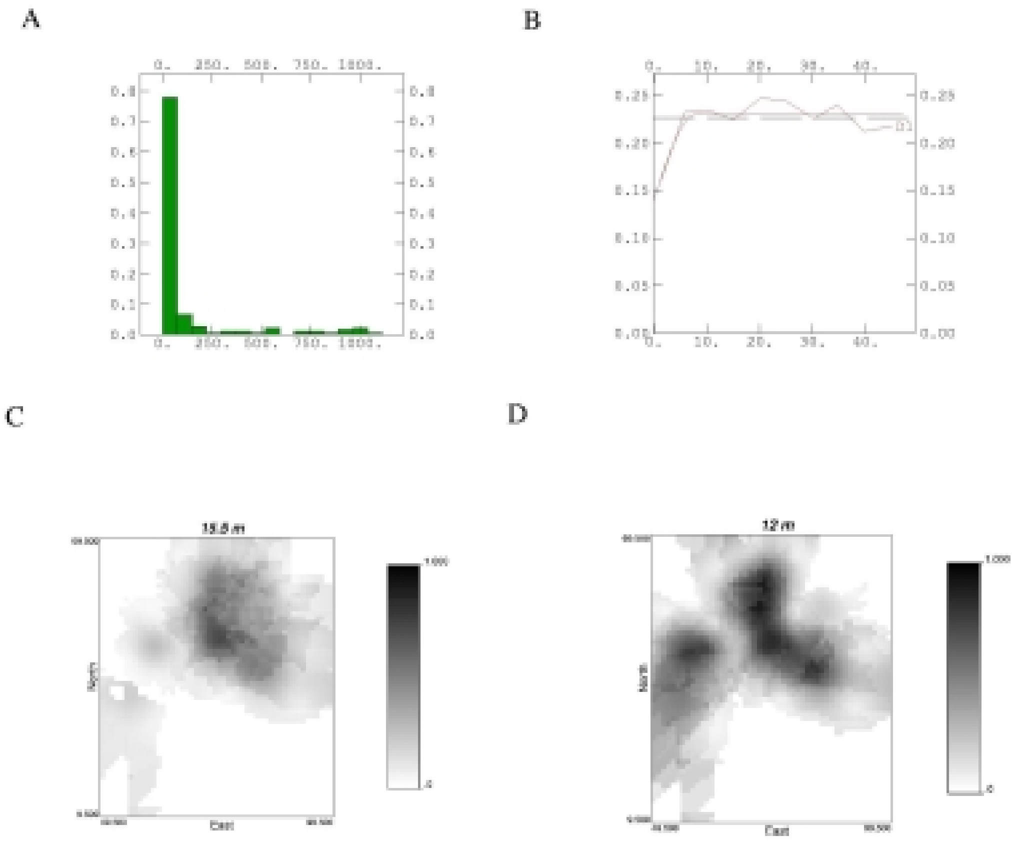

Figure 6. A) A histogram of photo ionization measurements; B) an experimental variogram calculated from the photo ionization measurements; the probability that the photo ionization measurement gives a value above 77.8 at a level of C) 15.5 m and D) 12 m.

4. Conclusions

Geostatistical methods can be used in characterization of contaminated soils, such as,

(1) Visualization the possible subsurface by simulating realizations that honor known data and geological models,
(2) interpolation of important surfaces such as groundwater level and bedrock topography,
(3) mapping the subsurface contamination by kriging or simulation,
(4) evaluating probabilities that a variable value exceeds a critical threshold at a certain location, and
(5) evaluation of the spatial uncertainty of simulated spatial patterns.

The results are based on subjective models, and thus obtained probabilities and uncertainties are model dependent. The main advantage of geostatics is the use of the spatial correlation structure often present in earth science data sets. Geostatistical simulation is especially applicable in environmental studies because of the reproduction of the original data variability.

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Implications of Finnish groundwater conditions on aerobic *in situ* bioremediation of chlorophenol-contaminated aquifers

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ABSTRACT: In this work, implications of ferrous iron and humic substances on aerobic biodegradation under *in situ* conditions have been studied. In Finland, high concentrations of ferrous iron and humic substances in groundwater are common and can cause process failures during aerobic *in situ* remediation. For this study chlorophenol-contaminated aquifer in Kärkölä, Southern Finland, was selected. Chemical and biological oxidation of ferrous iron was studied in batch experiments at ambient groundwater temperature, different oxygen partial pressure and/or pH. Chemical iron oxidation in synthetic groundwater followed well-established kinetics. Chlorophenols and humic substances did not significantly affect the chemical iron oxidation. Combined biological iron oxidation and trichlorophenol biodegradation experiments were carried out to reveal the competition-kinetic for available oxygen. An enrichment culture of ferrous iron oxidizing and chlorophenol-degrading microorganisms was obtained from the on-site operating bioreactor and was used in the combined biological oxidation experiments. Trichlorophenol biodegradation did not depend on the concentration of dissolved oxygen or ferrous iron. Depending on the enrichment procedure are trichlorophenol-degrading bacteria capable to outcompete iron-oxidizing bacteria for dissolved oxygen.

1. Introduction

Groundwater contamination by various anthropogenic compounds such as chlorophenols (CPs) is a wide spread problem in industrialized countries. *In situ* remediation processes are often more efficient and economical than pump-and-treat systems (for review, see Langwaldt & Puhakka 2000). Most organic contaminants are *in situ* biodegradable under aerobic, anoxic or anaerobic conditions. Aerobic *in situ* bioremediation processes require the addition of oxygen to the groundwater.

In Finland, groundwater typically contain high concentrations of ferrous iron and humic substances (HS). In this respect, chemical and biological oxidation of ferrous iron or HS are undesirable reactions which compete for available oxygen. They may result in process failure through precipitate formation.

For this study, an aquifer was chosen which has CP-contaminated groundwater and an on-site operating full-scale fluidized-bed bioreactor (FBR) in Kärkölä, Southern Finland. The aquifer harbours a diverse microbial community with a widely spread ability to degrade CPs. (Männistö *et al.* 1999). Previous studies have shown the capability of the microbial community for biodegradation of CPs under in situ conditions (Langwaldt & Puhakka 1999).

The objective of this work was to reveal the impact of ferrous iron oxidation on *in situ* bioremediation and to optimize *in situ* process performance by minimizing the undesired iron oxidation.

2. Materials and methods

Ferrous iron oxidation and CP-biodegradation experiments were performed in batch experimental vessels at 7.5–9.5 °C in the dark (Figure 1).

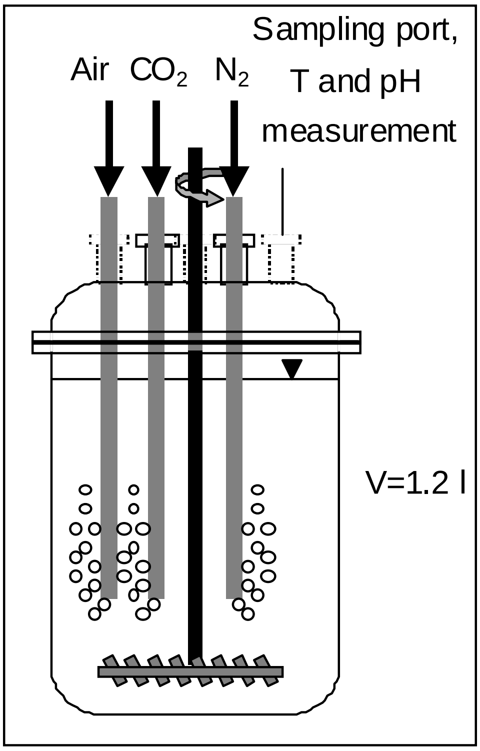

Figure 1. Vessel for ferrous iron oxidation and trichlorophenol oxidation experiments.

Dissolved oxygen (DO) concentration and pH were altered by changing the flow ratio of the gases, nitrogen, carbon dioxide and air. During experiments DO and pH were kept constant in a range of ± 0.1 and 0.25 units, respectively. CPs and DOC were analysed as described by Langwaldt et al. 1998. Samples (3 ml) were analysed for ferrous iron by a modified standard method (APHA, 1992). Three different media were used to exclude potential effects of HS and CPs, present in the contaminated groundwater. Chemical and physical properties of the media were as shown in Table 1.

Table 1. Chemical and physical properties of used media.

Medium	Alkalinity at 20 °C (mmol/L)	Conductivity at 20 °C (µs/cm)	DOC (mg/L)	CPs (mg/L)
Synthetic groundwater	1.85–1.98	255–259	1.52–2.35	non
FBR-effluent	n.a.	260–285	5.15–7.09	< 0.005
Contaminated groundwater	1.90–2.14	263–295	7.78	5.0–6.2

n.a. not analyzed.

For experiments on chemical iron oxidation, synthetic groundwater was prepared by dissolving 50 mg NaCl/L and 168 mg $NaHCO_3$ /L in water. Hereby potential effects of CPs and HS were excluded. Furthermore, biologically cleaned groundwater (FBR-effluent) and contaminated groundwater were used for chemical iron oxidation experiments. The contaminated groundwater contained 2,4,6-tri- (TCP), 2,3,4,6-tetra- (TeCP) and pentachlorophenol (PCP). FBR-effluent and CP-contaminated groundwater were autoclaved prior to use. Biological oxidation experiments were performed with autoclaved FBR-effluent. For biological iron-oxidation and CP-degradation experiments the enrichment culture was obtained from the on-site bioremediation system. Carrier-sand from the fluidized bed of the FBR was used as enrichment of ferrous iron oxidizing and CP-degrading bacteria. Sand was stored in the FBR-effluent at 7.5–9.5 °C in the dark. Biomass attached onto the FBR-carrier sand was measured as volatile solids (APHA, 1992) and by enumeration of cells. Average biomass on the FBR-carrier was 51.1 mg VS/(g wet sand). Onto FBR-carrier sand 1.2–3.2 x 10^9 cells/(g wet sand) were attached. The mass of sand added to the vessel 1 and 2 is shown in Table 2. Ferrous iron, $(NH_4)_2Fe(SO_4)_2*6H_2O$), and/or synthetic TCP were supplemented to the vessels.

In vessel 1, the initial TCP concentration was held constant and the initial iron concentration was increased to study the effect of iron on TCP-degradation. In vessel 2, the initial ferrous iron concentration was kept constant and the initial The TCP-concentration was stepwise increased to study its inhibitory effect.

Table 2. Set-up for batch biological iron and CP-oxidation experiments.

Experimental conditions	*microaerobic*		*aerobic, saturated*	
	Vessel 1	Vessel 2	Vessel 1	Vessel 2
Oxygen concentration (mg/L)	1.3 ± 0.5	1.3 ± 0.5	11.5±0.5	11.5±0.5
Initial TCP	constant	varied	constant	varied
Initial iron	varied	constant	varied	constant
Sand (g)	9.1	9.4	9.3	8.3

3. Results and discussion

Chemical iron oxidation rates with synthetic groundwater were measured and the results are presented in Figure 2. The oxidation rates followed the equation (1) established by Stumm & Lee (1961) with an average K-value of $2.18*10^{13}$ $M^{-2}atm^{-1}min^{-1}$ (arithmetical) or $1.89*10^{13}$ $M^{-2}atm^{-1}min^{-1}$ (graphical). The measured temperature dependence of the chemical oxidation rates agrees with earlier results by Stumm & Lee (1961).

$$- d [Fe(II)] / d[t] = k_1 [Fe(II)] pO_2 [OH^-]^2 \qquad (1)$$

The measured chemical iron oxidation rates in the three different media are shown as pseudo first order constants in Figure 3. The majority of the measured rate constants are in the 95% confidence interval for the synthetic groundwater, showing that HS and CPs did not significantly affect the chemical iron oxidation.

The results of the combined biological iron oxidation and TCP-degradation experiments under microaerophilic conditions are shown in the Figures 4 left and right and for condition of oxygen saturation in the Figures 5 left and right. Measured oxidation rates were converted into oxygen depletion rates based on the following stoichiometries to allow comparison between the two oxygen consuming reactions.

Mineralization of TCP: $\mathrm{TCP} + \mathbf{5.5}\ \mathrm{O_2} \Rightarrow 6\ \mathrm{CO_2} + 3\ \mathrm{HCl}$

Ferrous iron oxidation: $\mathrm{Fe^{2+}} + \mathbf{0.25}\ \mathrm{O_2} + 2.5\ \mathrm{H_2O} \Rightarrow \mathrm{Fe(OH)_3} + 2\ \mathrm{H^+}$

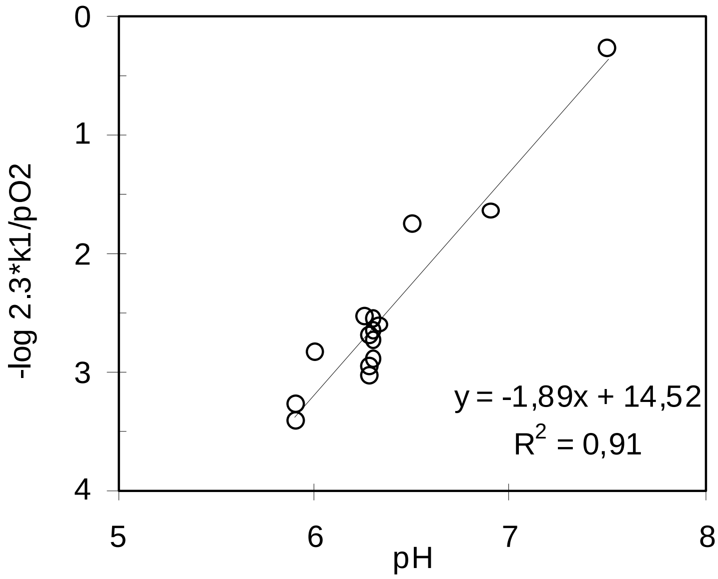

Figure 2. Chemical iron oxidation in synthetic groundwater.
k1 pseudo first order constant, DO from 0.9 to 11 mg/L, o = Synthetic groundwater, the linear regression line is shown.

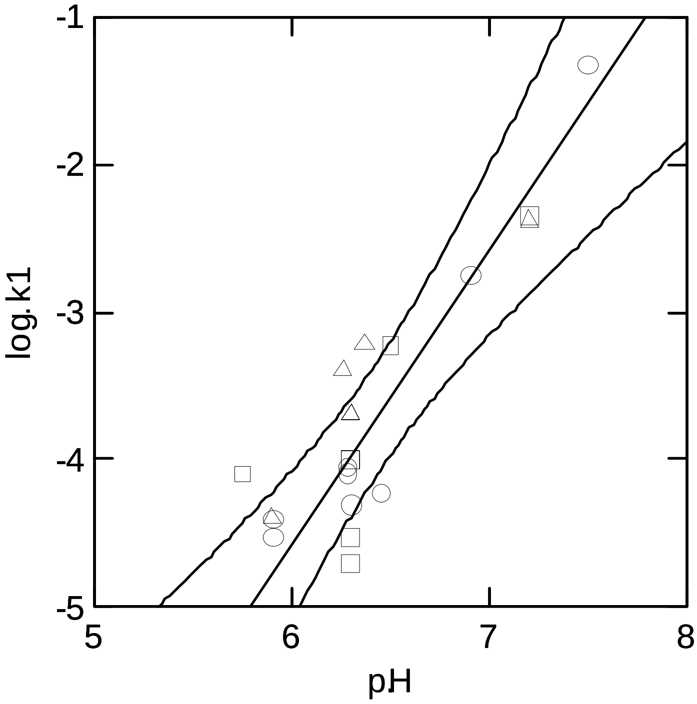

Figure 3. Chemical iron oxidation in different media.
k1 is the pseudo first order constant, DO = 10.0 ± 0.5 mg/L, o *= Synthetic groundwater (no HS, no CPs),* Δ *= FBR-effluent (HS, no CPs), = contaminated groundwater (HS and CPs).*

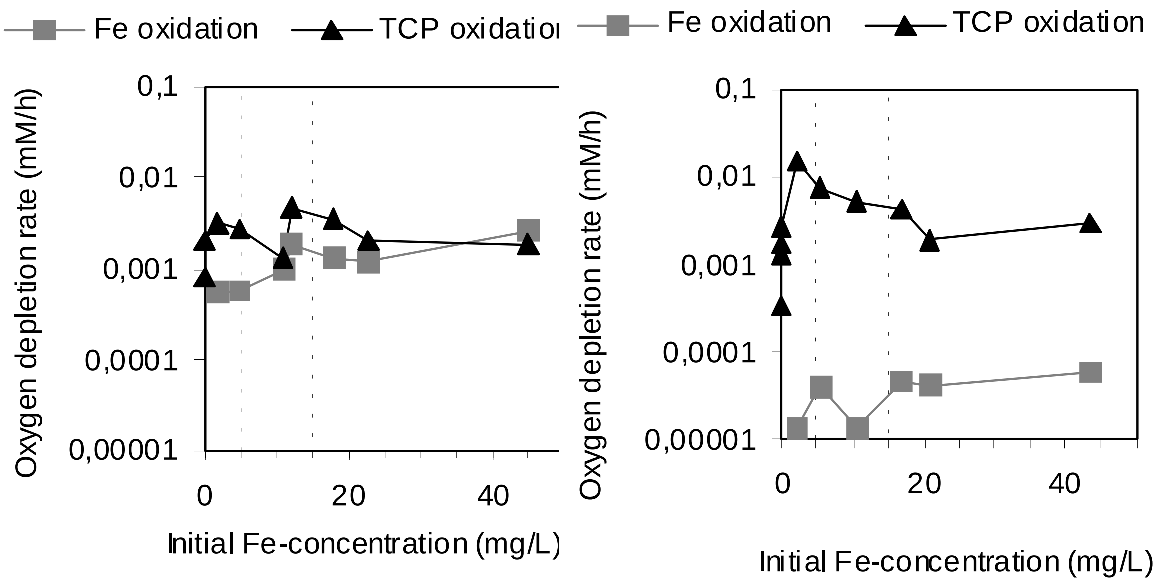

Figure 4 left and right. Experiments in vessel 1 at ambient pH of 6.3. Average initial TCP-concentration was 3.55 mg/L. Initial iron concentration increased from 0.0 to 44.9 mg/L. Broken lines indicate the range of Fe-concentrations in the contaminated groundwater. Figure 4 left. Experiments at microaerophilic conditions, DO = 1.3 ± 0.5 mg/L Figure 4 right Experiments at aerobic conditions, DO = 11.5 ± 0.5 mg/L.

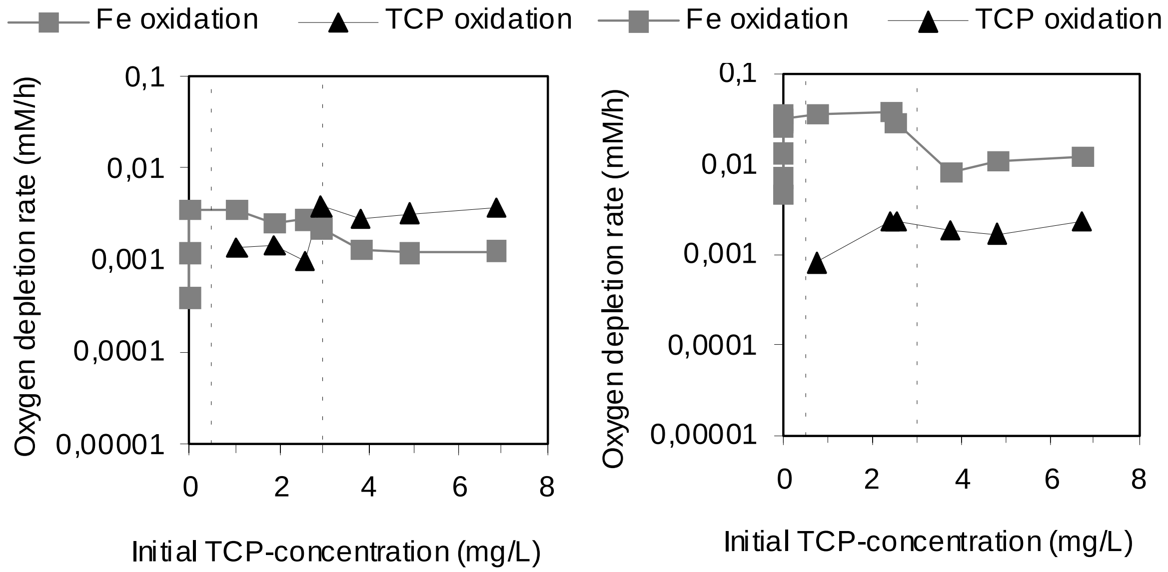

Figure 5 left and right. Experiments in vessel 2 at ambient pH of 6.3 Average initial Fe-concentration of 5,87 mg/L. Initial TCP-concentration increased from 0.0 to 6.9 mg/L. Broken lines indicate the range of TCP-concentrations in the contaminated groundwater. Figure 5 left. Experiments at microaerophilic conditions, DO = 1.3 ± 0.5 mg/L Figure 5 right Experiments at aerobic conditions, DO = 11.5 ± 0.5 mg/L.

At low DO concentration were the biological oxidation rates of iron and TCP at the same order of magnitude. Biological oxidation of ferrous iron showed no inhibition by TCP up to 6.9 mg/L. Whereas, in a previous study the biological iron oxidation was completely inhibited by PCP at 6.1 mg/L and the rate of iron oxidation was decreased to that of the chemical oxidation (Langwaldt *et al*. 2000).

4. Conclusions

Our previous studies have shown that HS have no effect on in-situ CP-biodegradation. Ferrous iron oxidation, however, may interfere with *in situ* bioremediation by reducing the hydraulic conductivity. At ambient *in situ* conditions is the biological ferrous iron oxidation inhibited by PCP. This study shows that CPs and HS do not significantly affect the chemical iron oxidation at the groundwater conditions of the Kärkölä site. TCP-biodegradation is not significantly affected by neither ferrous iron or dissolved oxygen concentration. Ferrous iron oxidation rates depend on enrichment procedure and presence of TCP. In summary, ferrous iron oxidation has to be accounted for in the design of the *in situ* remedial process.

Acknowledgements

The research was funded by the Academy of Finland.

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Clean-up criteria for contaminated land management – How to achieve a cost effective balance

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ABSTRACT: It has become quite clear that even in the rich industrialized world there are not enough resources to clean contaminated soils to the desired levels. Furthermore, even if the resource were to be available, the technologies are inadequate to achieve these aims. This has necessitated the development of alternative cost effective contaminated land management strategies. These are based around the twin concepts of Risk Analysis and Cost Benefit Analysis. This paper explores the methodology and some of its' consequences.

1. Introduction

The contaminated land problem was brought into focus in the late seventies by the incidents at Love Canal in the United States and Lekkerkerk in the Netherlands. Other contaminated sites in the entire world were quickly identified and it soon became apparent that contaminated land was a frequent rather than a rare phenomenon. It also triggered a public response that demanded both clean-up and prevention of future incidents. This in turn prompted politicians and their servants to promulgate rigorous soil quality criteria backed up by some of the most draconian legal sanctions hitherto found in the environmental field. The Dutch, for example, developed the multi-functionality principle that required all soils to be of such a quality that they could be used for all functions, from agriculture to supporting waste sites. It was embedded in the criminal code of Dutch law. The United States addressed the clean-up problem directly through the Super Fund that was based directly on the two pillars of clean-up and that the Polluter Pays.

Unfortunately the costs both in financial terms and in disruption to society terms have proven to be beyond the bearing capacity of even the richest nations. This has lead to a general retreat from the initial position of land quality restoration to one of a more economically feasible contaminated land management philosophy. In fact it has taken to May of this year, that is 20 years, for the Dutch to abandon in principle the Multi-functionality objective.

Whilst this readjustment of our collective expectations from the land quality restoration programs has been going on there has been a second related development that is emerging as a key driver in contaminated land problems. This is the, often only perceived, impact of the land quality parameters on the value of the land in a financial transaction. This development has brought a whole new spectrum of considerations to the fore and is forcing a reappraisal of the meaning and use of land quality standards.

It is against this rapidly changing backcloth that the search for new and more robust assessment methodologies and criteria has to be seen. There are several possible starting points for developing novel procedures for the examination of contaminated land and the design of response strategies. These include the application of the Observational Method and the formulation of Generic Characteristic Values for identified site archetypes.

In recent years the methodologies and technologies of quantitative risk analysis have been applied to the problem. Whilst they can give rational answers to the soil quality problem they in fact push the debate back to the community that then has to agree on what is an acceptable risk from soil pollution. None the less these methodologies are the most promising to date and will be looked at further in what follows. It should be noted that the United Kingdom has based her recent contaminated land legislation entirely on the risk analysis principle.

2. Risk analysis

Risk Analysis provides a context for the whole analysis and management of the contaminated site. It provides a common, if sometimes difficult, forum for communication of the problem to all concerned and it can be coupled with cost-benefit techniques to provide a very powerful management tool. Equally the techniques can be used in the field of pollution prevention design to balance of the need for pre-investment in measures to avoid possible problems. In what follows a description of this approach and its' application will be presented. The methodology has several major disadvantages or issues and these will also be presented.

2.1 Risks and risk based methodologies

The key distinguishing factor between risk based design methodologies and other more conventional ones is that they are based on a recognition that soil contamination is only relevant because it has the potential to cause harm. Or put another way, the chemical characteristics of the contaminated soil itself are of no importance in themselves as such. This approach is in marked contrast with earlier ones that sought to reduce the contaminant level at the site to a prescribed, and often legislated, value. It is this paradigm shift from site contaminant parameters to receptor (or target) impact values that brings with it the many advantages of the new methodology.

A second important consequence of this approach is that it is no longer possible to use design procedures that are based on prescribing management techniques or the properties

The harm or risk involved can be of several types. These include;

- Risk to Human Health either in the long or short term.
- Risk to Flora and Fauna including uptake in food chains.
- Risk to the Eco-system as a whole including diversity.
- Risk to the Asset Value of the Site even though realization is not necessarily planned.
- Risk to the Use Value of the Site restricting its economic value.
- Risk of incurring Liabilities to others by cross boundary migration.
- Risk of Legislative non-compliance leading to fines or imprisonment.
- Risk to the Reputation of the owner or user of the site.
- Risk to Ground Resources such as groundwater.

There is a notional risk to the bearing capacity of ground in its' support function but this has been only rarely documented. Often these risks can be concurrently experienced and many of the categories overlap strongly. It is clear from this list that the span of any suite of Risk Analysis techniques will have to be quite wide for them to be effective.

This simple picture is complicated by the fact that no one person appreciates and deals with risk in an entirely ration manner. A distinction has to be made between risk as such and perceived risks. It has to be recognized that perceived risk is the real driving force behind many calls for remediation. The methodologies can be extended to include risk perception elements but there has been little or no documented study of this.

2.2 The Source-Path-Target methodology

Soil contamination problems give rise to four basic questions:

1. What contamination is present? - The site investigation problem.
2. Where are the contaminants going to? - The migration problem.
3. If the contaminants get there, will there be a problem? - The impact problem.
4. If the impact is significant, what can be done about it? - The remediation problem.

The first three problems can be integrated in the "Source-Path-Target" methodology, a viable subset of risk analysis techniques. The last is concerned with remediation technologies themselves rather than the design methodologies and will not be considered further here.

The methodology starts with identifying three elements of the contamination management problem, the Source, the Path and the Receptor (or Target). The objective of the analysis is to relate events, such an emission of toxic substances from a contaminated site, to its effect at some sensitive point, or "target" in the environment. This relationship is a chain of sub-events, such as leaching followed by transport by groundwater and subsequent abstraction as drinking water, and is referred to as the "Path" connecting the Source of risk to the Target where its' impact will be felt. In the general methodology the path can refer to effect transfer functions more abstract than the physical flow of toxic substances.

The Source is characterized by the nature and emission strength of the chemicals in the site. The Path is the chain of pollutant migration events as described above and is a vector. In general there are multiple pathways between source and target and the further removed these two are from each other, and the more members in the chain of events forming the path that have to be considered, the more difficult the analysis.

The target is defined by its sensitivity and its’ position in the environment. This is expressed as a maximum allowable impact value and is target specific. In theory the sensitivity of the target could be defined in toxicological terms if the detailed nature of the chemicals arriving at the target from the site contaminants and the required dose-effect relationships were to be known. However this is not always possible as the data are either not available or because the pollutants reaching the target often form a complicated cocktail of individual substances whose cumulative impact is only poorly understood. None the less there has been rapid progress in this area for hydrocarbons and several simple risk analysis models such as RBCA from the ASTM or Risk Human from the van Hall Institute have quite extensive data bases associated with them. These allow very viable estimates of the impact at target to be made.

Many countries have approached this problem of poor toxicology by setting chemical concentration standards rather than impact values. These are the maximum allowable concentration of MAC based standards of which the Dutch A, B, and C values or the new target and intervention levels have received wide application. This can result in a drastic simplification of the problem but sacrifices some of the advantages of the impact analysis route.

The practical problem of using the methodology however turns not only on what the MAC, or impact values are, but where along the impact pathways are they to be applied. The conceptual position around the site where the MAC values are to be applied is called the "target envelope". Changing the position of this envelope can have profound influence on the range of remedial countermeasures available and the costs involved.

For the risks other than those to health a different set of maximum allowable impact values have to be set. These can be financial or less quantifiable and can reflect elements of perceived risk as well as real risk.

The pathways connect the source with the receptor and are vectors characterized by direction and speed. They may be simple as in convection and dispersion through the groundwater system or complex and multi-membered such as a food chain pathway. Although physical pathways can be easily visualized, some of the risk areas mentioned above require abstract pathway notions that are very difficult to work with. The physical pathways

can dilute, delay and disperse toxic material emitting from the site, can provide opportunities for biodegradation or chemical stabilization or conversely can result in re-concentration of toxins by bio-accumulation or adsorption.
For a typical site at least the following pathways have to be considered,

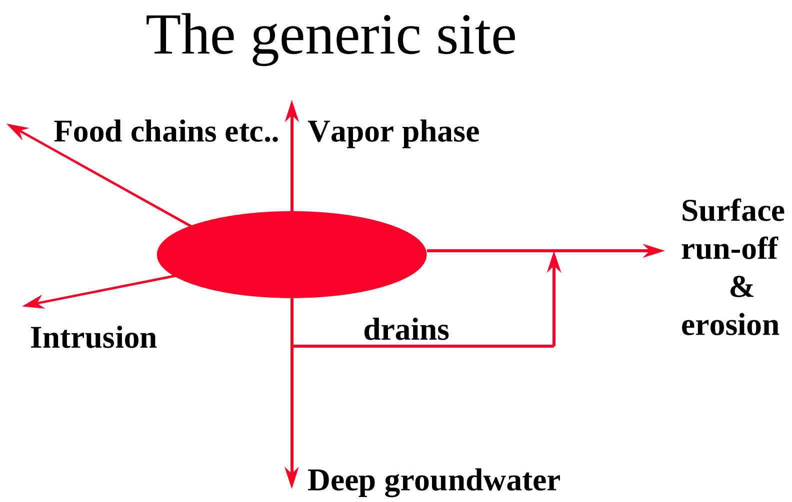

Figure 1.The generic site.

- Leachate through the shallow groundwater system and local drains.
- Leachate to the deeper groundwater system especially where this is an important aquifer.
- Surface run-off of toxic inventory either by erosion or leaching Vapor phase dispersion into surroundings.
- Dust (particulate) dispersion into the surroundings.
- Uptake in the food chains.
- Intrusion into the site and physical displacement.

All these pathways can be operative at some point in the history of the site, from initial contamination, through the remedial actions to the long-term inevitable loss of institutional control on the site.

Again the pathways by which the fact of contamination at a site can reach a target and impact it for risks other than health risks requires careful study and delineation.

The source is characterized by its' nature and emission as a function of time. This is given by the sort of chemicals in the site, their mobility and their concentration. The concentration alone says little of the emission strength, for example 500 ppm of cadmium in a site as sulfide is a very different risk than 5 ppm of the same cadmium present as a highly mobile chloride. This is of particular importance as most sites contain a cocktail of pollutants whose behavior furthermore changes in time. This is especially the case as remediation technologies are applied and conditions deliberately changed. A common example is where the lowering the groundwater table prior to excavation can result in a major re-mobilization of heavy metals as they are re-oxidized up into soluble species and their subsequent migration along the convection pathways caused by the dewatering operation. The mobility of a pollutant in a site is also influenced by physical factors such as temperature and pressure.

The source is the point where the risk perception of people involved focuses. This is often one of imagined emission and potential danger on the site itself. The language used to describe the site is telling. Words such as “chemical time bomb” and “disaster waiting to happen” are well known. It is however these notional emission factors that have to be used in the risk analysis.

The three elements of Source, Path and Target are put together to form the so-called "linkage". One way of expressing this is in the following diagram

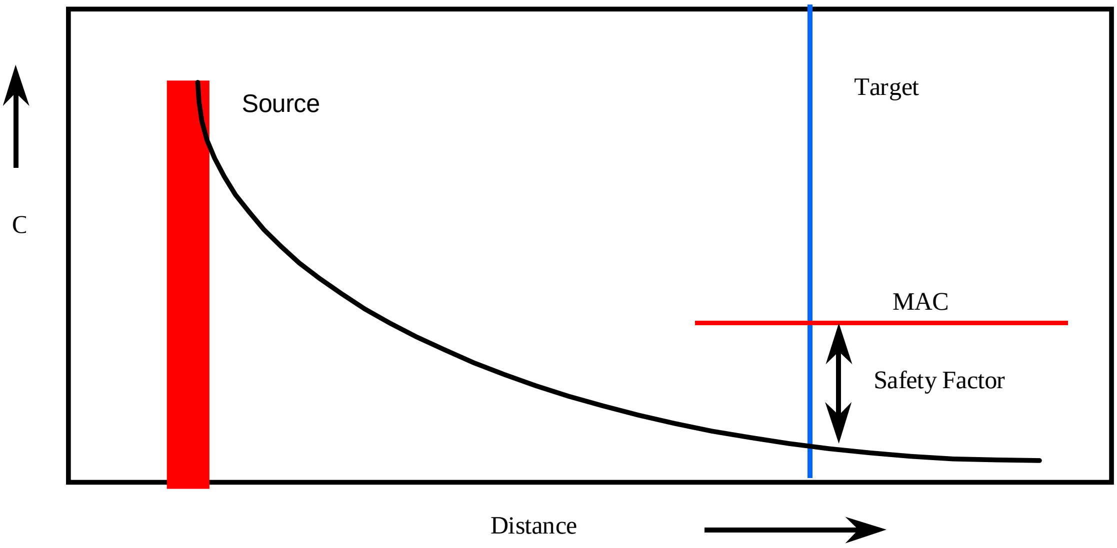

Figure 2. The linkage.

Here the drop in concentration with distance away from the emitting source is shown. Somewhere on the pathway is found the target. If the concentration is below a maximum allowable level then there is, in principle at least, no problem. It is above a remedial management strategy, which might or might not involve clean-up, is called for. The difference between the concentration at the target and the maximum allowable concentration can be expressed as a safety factor. Traditionally these safety factors are huge reflecting our fear of contamination and our uncertainty of understanding the system involved.

2.3 Implementation and consequences

Systematic and quantitative application of the source-path-target methodology makes it possible to translate the environmental problem at the target to an emission characteristic at the source. In turn this makes it possible to approach the soil remediation problem in terms of manipulating the emission characteristics at the source to achieve a desired risk level at the target.

In order to do this, the following steps are necessary;

1. List all the possible source-path-target combinations including the irrational and non-quantifiable ones.
2. Construct a data-set based on available information, common sense, similar sites and incidents or just plain guesswork.
3. Use the data set and an appropriate risk analysis model to assess the impact of the source at the target. At this point many if not most of the potential source– path–target linkages will be eliminated leaving only realistic combinations over.
4. Conduct a sensitivity analysis on the remaining linkages to identify those where the evaluation is sensitive to parameters that are poorly known. (the “phase 1 sensitivity analysis”)
5. Carry out a cost-benefit analysis between the consequences of not knowing a parameter to a higher level of certainty against the cost of re-evaluating the parameter. (“Need to know” principle).

6. Determine the “need to know” parameters and repeat the steps to this point until there is sufficient confidence in the parameter database.
7. Evaluate the source emission characteristics that will just reduce the impact at the target to below those maximally allowed.
8. Design and cost a remedial management scheme that will achieve such an emission characteristic.
9. Evaluate the sensitivity of the impact at target to errors or failures in the design and/or implementation of the management scheme. (the “phase 2 sensitivity analysis”)
10. If there is a significant chance of unacceptable failure, go on to perform a cost benefit analysis on reducing that chance. (The “discrimination analysis”).
11. Converge, by more than one cycle if necessary, to the final optimum management strategy.
12. It is very advantageous to formalize the above process so that it can be easily integrated into a modern IT based environment and an adequate quality system.

It is important to address the correct problem with the methodology. Many sites contain multiple sources and it is worthwhile considering whether these should be treated together or separately in the analysis.

3. Issues associated with a risk based methodology

Unfortunately every methodology has its’ own limitations and failings. For this methodology there are several issues involved and they can be usefully divided into three categories.

The first category relates to the technology of Risk Analysis itself. There are three major issues

- There is the issue of methodology. Is the methodology secure? What risks are being taken as important? What levels of risk are acceptable, and who determines this and how?
- The second issue has already been touched upon and is related to the inadequacy of the relevant databases. Toxicology is notoriously weak, especially for chemical cocktails. Models of the future characteristics of the emission curve, the failure mechanisms and the migration along the multiple pathways are all open to question and few if any have been verified for the time-scales involved. An especially difficult area is the incorporation of these uncertainties into a statistical assessment of the design performance. Failure to cater for this adequately can lead to massive over-design of the management strategy as large safety factors are built in.
- A third set of technology issues is thrown up by the difficulties caused by the uncertainties in each of the elements that go to make up the problem.

These issues will become clearer as more applications are based on the methodology but at this point in time great care and skill is required to avoid discrediting it. The effect of this can be seen by the massive safety factors that have to be used to meet most stringent legislation such as the old Dutch A, B, C values.

The second category relates to the perception of the rest of the public to such a design proposal, or indeed to contaminated site management in general (as distinct from total contaminant removal).

- The most serious issue here is the generally very poor credibility standing enjoyed by engineers and scientists proposing these measures.
- A difficult issue is the lack of experience of many in the community in dealing with the concepts and jargon of risk analysis. This is compounded by the fact that there are rarely clear-cut black and white answers to simple questions such as “is it safe?”. In fact the problem may be deeper and the very fact of having to confront risk may trigger irrational responses throughout the community.

These issues can only be dealt with by clear and often bespoke communication procedures to ensure that everybody knows what is really going on and can satisfy themselves that their concerns are being treated seriously and adequately. In fact the application of this methodology almost always goes ahead in parallel to a carefully crafted communication program.

A final category involves that of the engineers themselves.

- The first issue here is one of professional skill. Moving away from traditional "look it up in the standard" approaches to a Risk Based approach puts a heavy burden on the skill base of the engineer responsible for the design. This is especially so given the wide range of diverse disciplines involved in the essential core of the process.
- The second issue follows on from the first. When is such an engineer "qualified" and by whom? This is also related to a whole range of professional concerns such as, what is professional liability position of the engineer at the moment if such methodologies were to be applied and who exactly is taking the risk?

These issues require addressing adequately in order to gain the very considerable advantages associated with this methodology. These advantages are a very significant cost reduction for the site management compared to a conventional approach.

4. The Advantages of using the risk analysis methodology

Notwithstanding the difficulties to be faced in applying the methodology it has already proved successful. The main successes have come from avoiding the prohibitively expensive need for excavation and removal of contaminated soils. On the one hand the costs are much reduced for the same local risk mitigation but it is also often the case that the risks associated with the removal of the contaminated soil and its disposal elsewhere are in fact greater on aggregate that leaving it in place.

A second advantage of the risk-based methodologies is that it makes explicit the residual risks in a contaminated land management strategy. This helps a little way to rationalising the risk perception aspects of the problem that can dominate the public debate on any strategy.

A third advantage is that of the possibility of innovative remedial action designs specifically tailored to controlled emission release based on risk assessments of that release. As an example, recent work at GeoDelft has been considering the relative costs of achieving a satisfactory risk level using new and older techniques. The results show that the new techniques of partial containment behind chemically active barriers with controlled but safe emission levels cost only 2% of the cost of restoring the site to multi-functionality and but 4% of the excavation strategy.

5. Risk based contaminant management strategies – The future

There are several obstacles to be overcome before the risk-based methodology is proven and accepted. None the less the obvious economic advantages of the results of using the methodology make it inevitable that this will take place.

These advantages are gained by only managing the risks that are significant and relevant, by developing site specific criteria for action rather than generic ones and by providing the tools for accurate and credible communication to the problems' stakeholders.

The future will see a move towards standardisation of methodologies and tools, a drastic reduction in the cost of the analysis process itself, a certification of the consultants working in that area and a recognition by all concerned of the need for a robust quality standard based on transparent and agreed protocols.

Air injection wells – Just another pump and treat method or a cost effective, innovative tool for *in situ* remediation?

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ABSTRACT: The remediation of groundwater has been one of the most urgent tasks regarding environmentalism for several years. Experience has shown, that heterogeneous aquifer structures and sorption on to soil material are the reasons for long decontamination times. An Air Injection Well (AIW) is a simple and low cost method for the remediation of dissolved volatile organic compounds and for the enhancement of natural attenuation, e.g. the support of biodegradation by generating an aerobic environment in or by adding nutrition to the saturated zone. The possibilities for the application of an AIW are illustrated by means of two large scale experiments and one field application. The Advantages and disadvantages of the AIW are discussed.

1. Introduction

The remediation of the groundwater, i.e. the decontamination, has been is an aim that has turned out to be very cost and time intensive. After numerous discussions two groups were formed with different points of view regarding the whole problem, on the one hand with complete decontamination and the restoration of the environment as the one and only aim. On the other hand there was a proposal to leave contaminated sites as they are and trust in natural (and cheap) degradation processes to solve the problem in the coming future.

The combination of these two objectives seems to be the only solution accepted by a majority. But this will only succeed, if low cost and effective techniques can be found for the remediation. Experiences has shown, that an AIW seems to meet these different requirements for certain contaminants (volatile DNAPLs and aerob biodegradable compounds).

2. AIW principles and circulation flow

An AIW is a combination of two common constructional or remediational techniques. This is an air lift pump on the one hand and a strip reactor on the other hand. With an air lift pump, water can be pumped upwards in a vertical tube using pressurised air as the energy supply. The air is injected at the base of the tube. Due to the buoyancy the air moves upwards and transports water in the same direction. In the case of an AIW the well tubing is screened below the groundwater table. It is not the aim to pump the water out of the aquifer but to create a groundwater circulation area in the aquifer (Figure 1). The driving force of the groundwater flow is the difference in hydraulic head between the AIW and the surrounding aquifer. It is induced by the air injection.

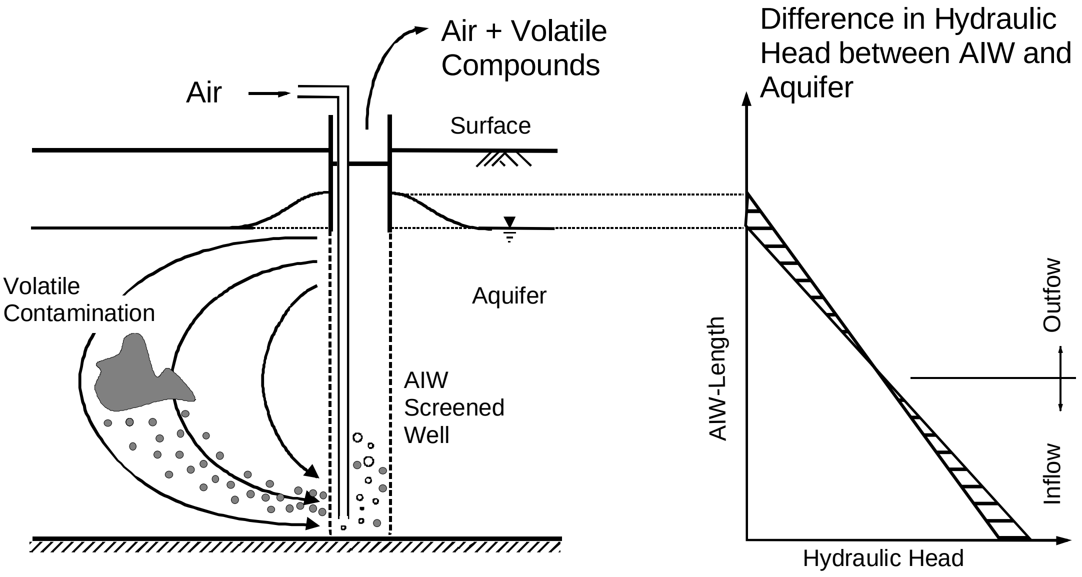

Figure 1. AIW and differences in hydraulic head between the well and the surrounding aquifer due to air injection.

The second technique, stripping, is a common method used for removing volatile compounds from water. The contaminated water is aerated and due to the difference in equilibrium concentrations the volatile compound is transferred to a certain amount into the air.

For these reasons the injected air is not only the driving force for the groundwater circulation but also a stripping medium.

3. AIW components

The main part of an AIW plant is the well itself. It normally consists of a screened metal tube with a diameter of 2”. Assuming there are suitable underground conditions, this diameter can be driven into the soil whereas larger wells always have to be drilled. This means there is the advantage of simple, cost-effective installation of the AIW or - if necessary - of several AIW, if the efficiency has to be increased. This should be the preferred strategy instead of using one AIW with a larger diameter.

The upper part of the AIW consists of a normal tube in order to avoid the loss of possibly contaminated air into the vadose zone.

At the upper end of the AIW, the air injection pipe passes through the well tube and is laid down to the lower end of the AIW, where the air injection takes place.

A compressor is necessary to produce of the pressurised air. Additional periphery components are: water a separator, activated carbon filters or other cleaning devices and a flow meter. During recent years theoretical and experimental work has been done to investigate the functional principles and to determine design rules regarding the hydraulic and the required air injection rate. They can be found in Luber (1999).

4. Large scale experiments

The first full scale application of AIW took place in two remediation experiments under controlled conditions at the so called VEGAS-facility in Stuttgart, Germany. Two aquifer models each with a different subsoil structure were installed in vessels there. The used aquifer materials in both experiments were coarse to medium sands with a hydraulic conductivity between 3.2 to $34 \cdot 10^{-4}$ m/s (see Figure 2).

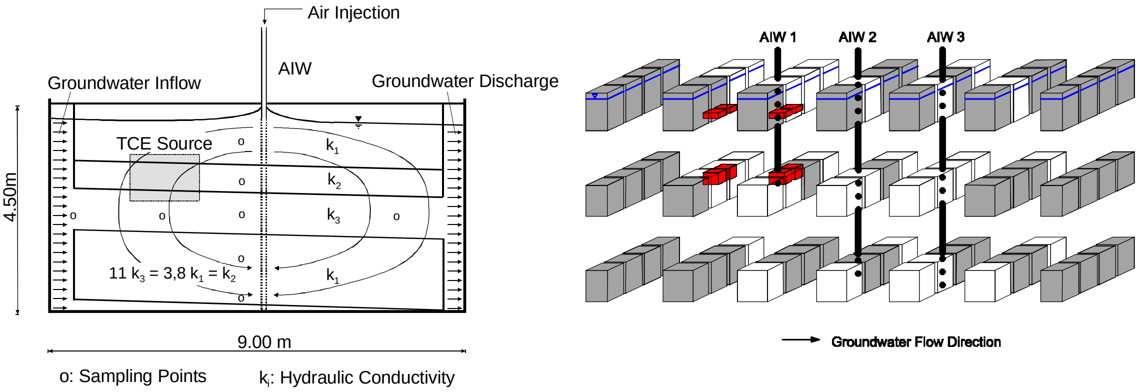

Figure 2. Set-up of the artificial aquifers at the VEGAS-facility.
Left: Vertical cross section of the layer-model, k3 = 3.2 · 10–4 m/s
Right: For better visualisation open composition of the block-model; approx. volume of each block: ~ 2.8 m³; grey coloured blocks: k = 12 · 10–4 m/s; others: k = 34 · 10–4 m/s

In each of the models with a size of 4,5 m · 6 m · 9 m (H · W · L) two remediation experiments with a duration of several months were carried out. In both cases the aquifers were contaminated with around 30 kg Trichlorethylene (TRI). The volatile organic compound was placed in residual saturation in a soil volume of approximately 1,6 m³. The unavoidable loss of TCE during the contamination was measured and taken into account in later considerations.

Through edgeways placed vertical distribution layers the aquifers could be fed with groundwater (Q-controlled). On the other side of the vessels the water flowed through a similar layer into a water treatment plant. The remediation experiments were carried out with different groundwater flow rates (Table 1).

Table 1. Average groundwater velocities at different times after the beginning of the experiments.

Layer Model		Block Model	
Time (d)	Velocity* (m/d)	Time (d)	Velocity* (m/d)
0 – 24	0,55	0–8	1,20
24 – 62	0,10	8–66	0,30
62 – 145	0,45	60–70	0
		70–111	0,30

*: Averaged Darcy velocity of the inflow cross section

The relatively high groundwater velocities were necessary in order to avoid any influence of the vessel walls on the hydraulics of the AIW. The lower velocities were chosen for the examination of the AIW capability in different groundwater flow situations.

The main difference between the two experiments was the number of AIW used for the remediation process (besides the different aquifer structures). In the first experiment, that was carried out on the layer model, the focus was on the determination of the efficiency of one AIW only. The second experiment on the block model, should evaluate the benefit of the use of more than one AIW.

Immediately after the groundwater flow was started, the remediation activities began. The TCE-concentrations of the AIW discharge (air) and of the groundwater discharge were measured continually in order to balance the mass removal through from the aquifers. The results of these determinations are shown in Figure 3.

In both cases a significant amount of TCE was lost through the groundwater discharge. But this loss occurred only at times of relatively high groundwater velocities (high gradients of the groundwater flow). Regarding those periods of time, where the groundwater velocities where low almost all the TCE mass was removed from the aquifer by the AIW. In addition the efficiency of the 3 AIW on the block model was much higher even though the groundwater flow all together was higher in the block model than in the layer model.

Increasing the groundwater flow again after 62 days in the layer model resulted in a short term TCE mass removal only. This was probably due to the dissolved TCE mass during the lower groundwater flow. Since the AIW still removes TCE at significant rates during times with low groundwater flow rates, whereas the mass loss through the groundwater outflow is very low, one can see the comparatively higher remediation capability of the AIW at lower groundwater flow rates. Not until the groundwater flow is increased again, does the contaminant removal by the AIW drop close to nothing. A total TCE mass of 23,0 kg was removed from the layer model. Sampling the aquifer material after the experiment gives reason for the assumption, that all of the TCE input was removed in the one or other way from the aquifer. That connotes a loss in the mass balance of 4,4kg (16,4%) TCE, which is a very good result taking the scale of the experiment and the compound characteristics into account.

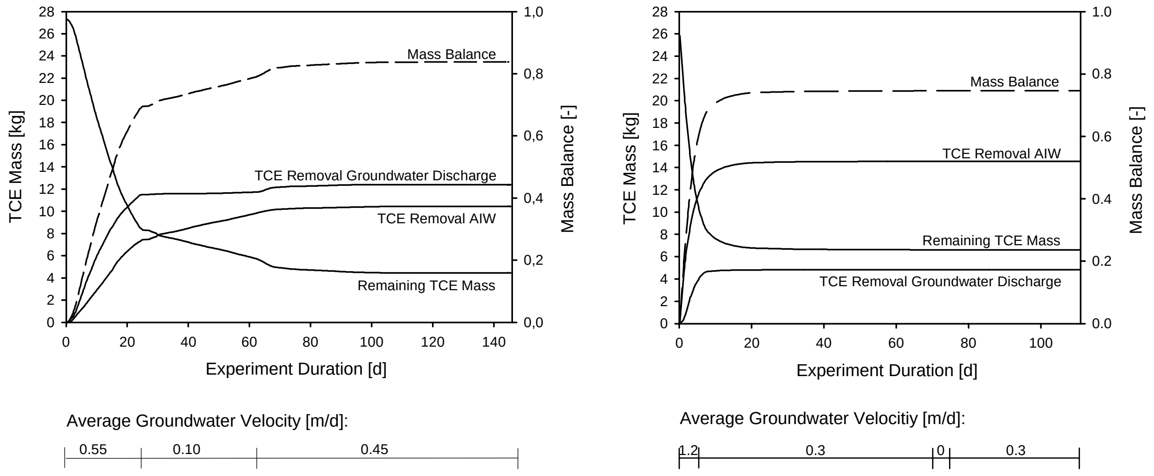

Figure 3. TCE removal and mass balance from the layer model (left) and the block model (right).

The increase of the groundwater velocity or the shut down of the experiment at times in the block model did not show any effect on the TCE removal at all since most probably no more TCE was in the aquifer at this time. Due to the higher hydraulic conductivity the total TCE mass removal took place comparatively quickly. After 66 days no significant amount of TCE was removed from the aquifer via the AIW or the groundwater discharge. The mass balance in the block model resulted in a mass loss of 25,4%, which still is a fairly good result.

5. Field application

At the large scale experiments at the VEGAS facility the emphasise of the AIW application was on the stripping of the volatile contaminant. But in this case the aim is to distribute a compound – namely oxygen – in the aquifer, in order to supply the microbiological degradation of the contaminants in the subsoil.

On site, organic lead compounds (Tetraethyllead, TEL) had been produced in the past. The TEL was accidentally infiltrated into the vadose zone together with hydrocarbons, that were used in the production processes. According to the density of the mixture the phase liquid spread on the groundwater surface. Due to the evaporation of the volatile compounds of the hydrocarbons, the mixture became more and more viscous and was distributed during long terms with the natural movement of the groundwater table in a layer with a thickness of 2 to 3 m. Since the groundwater table has risen during recent years, the contaminants are more or less below the groundwater table nowadays.

The TEL is transformed to mineral lead in the presence of oxygen via several steps (Tri-, Diethyllead). This was proofed with small scale laboratory tests by Mulroy & Ou (1998). Until now it is not clear whether the organic lead is degraded microbiologically or if it is transformed by hydrolysis.

Due to the low concentrations of the organic lead compounds the hazardous influence on the environment is removed as soon as the organic lead is transformed into mineral lead, which is immobile.

The subsoil at the site is formed by fluvial deposits, mostly sand with a hydraulic conductivity of $3{,}5 \cdot 10^{-4}$ m/s. The natural gradient of the groundwater flow is comparatively low with i = 1‰. The whole aquifer thickness is about 50 m, but as already mentioned, contamination is found a little below the groundwater table which is located at a depth of 3 to 4 m.

In order to saturate the groundwater in the relevant zone, 4 AIW with a screened length of 4 m below the groundwater table were installed on the site at a highly contaminated spot. The distances between the AIW were 5 m. A ground plan with the AIW and monitoring wells is given in Figure 4.

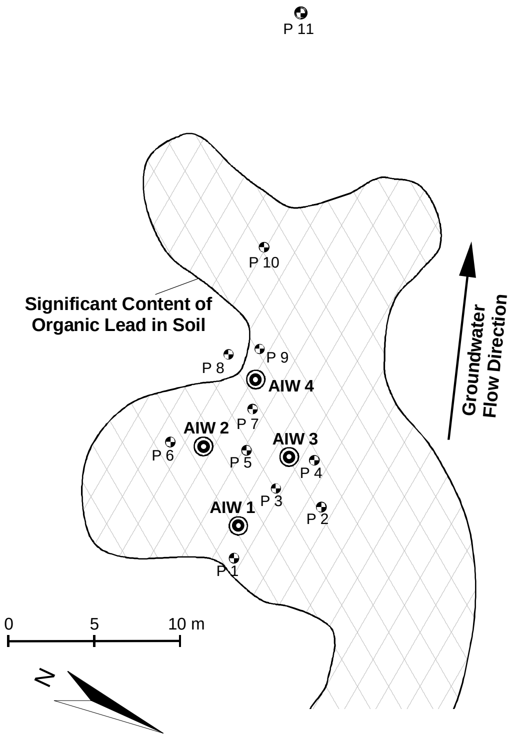

Figure 4. Ground plan of the site with: AIW, monitoring wells and distribution of the organic lead contamination.

Even though TEL is a volatile organic compound the emphasis of the AIW application in this case was not so much on the stripping of the contaminants but on in the supply of the relevant soil volume with oxygen. The oxygen concentrations in the groundwater at different times after start up are presented in Figure 5.

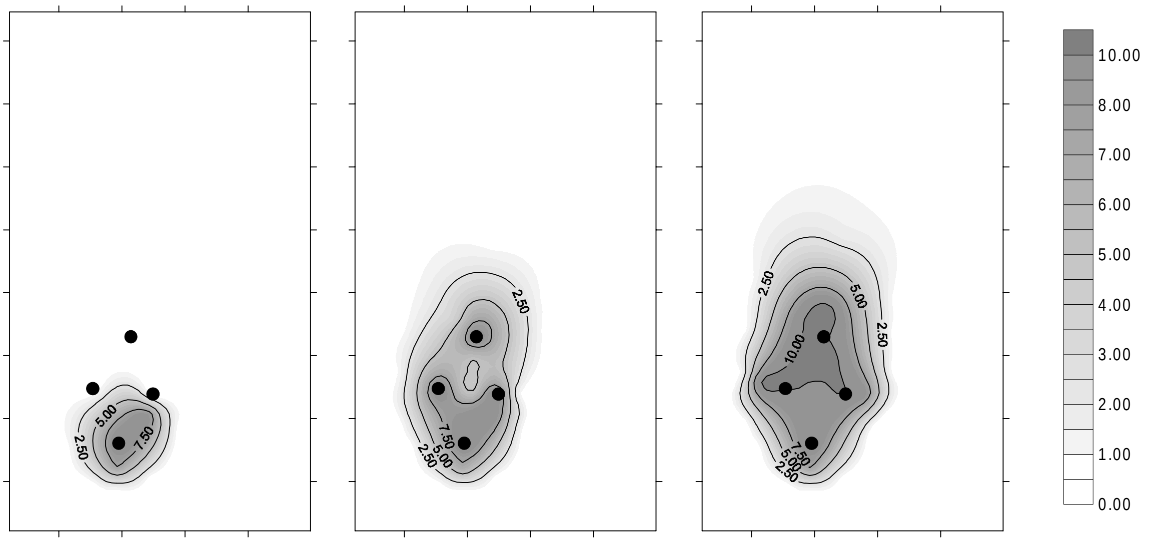

Figure 5. Oxygen concentration [mg/l] in the groundwater adjacent to the AIW at three different times (left: 27 days, one AIW only; middle: 63 days, operation of all four AIW for 36 days; right: 272 days, four AIW for 245 days; distance between two ticks: 5 m).

In the first four weeks only one AIW was operated in order to monitor its influence. Then the oxygen concentrations increased approximately by one order of magnitude starting from values around 0.4 mg/l. The range of influence seemed to be about 4 m (radius) showing that the number of monitoring wells was too small for an exact determination. With regard to the results of the oxygen measurements after 63 and 272 days respectively, the oxygen concentrations increased continually, even though a certain amount should have been consumed for the degradation of the organic lead compounds.

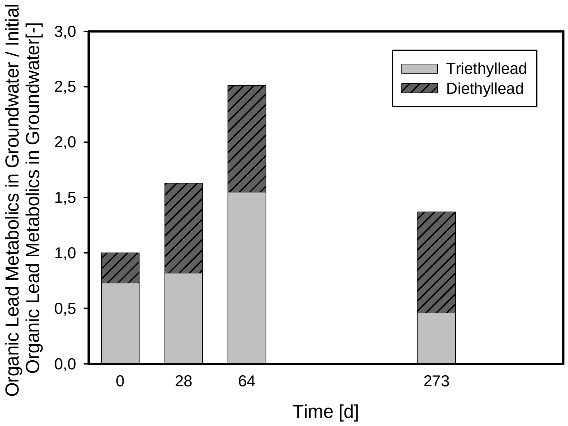

Figure 6. Concentration of organic lead metabolics in groundwater at monitoring well P 5.

The degradation of the TEL started shortly after the beginning of the AIW operation. Whereas the low soluble TEL had appropriate low and more or less constant concentrations before and after the operation of the AIW, the content of the better soluble metabolic compounds increased significantly due to the changed flow situation around the AIW and the degradation process (Figure 6 and 7). Most probably formerly dead end pores now release some quantity of stored organic lead, that is degraded during the further progress of the AIW operation. This results in higher concentrations of Tri- and Diethyllead initially. All compounds are decreased by the ongoing oxygen supply. Taking P 5, which is positioned in the centre of the four AIW, as an example, this phenomena can be followed up in Figure 6.

The other monitoring wells showed similar reactions. The development of the total organic lead (that consists of Tri- and Diethyllead and a negligible amount of Tetra- and Monoethyllead) in the groundwater in three monitoring wells is shown Figure 7. After the increase of the concentration in the first 100 days, the concentrations dropped to a certain level which is a little higher than originally – besides an increase during the last but one measurement, which cannot be explained at the moment. Maybe higher rain fall caused an infiltration of organic lead from the vadose zone. The more or less constant concentrations of the organic lead in water indicate a constant degradation process from the TEL (low soluble) via the Tri- and Diethyllead. A further reduction of the concentrations can be expected at the time as the supply from TEL decreases, i.e. the main part of the low soluble TEL, that acts as a storage for the metabolic compounds, is degraded.

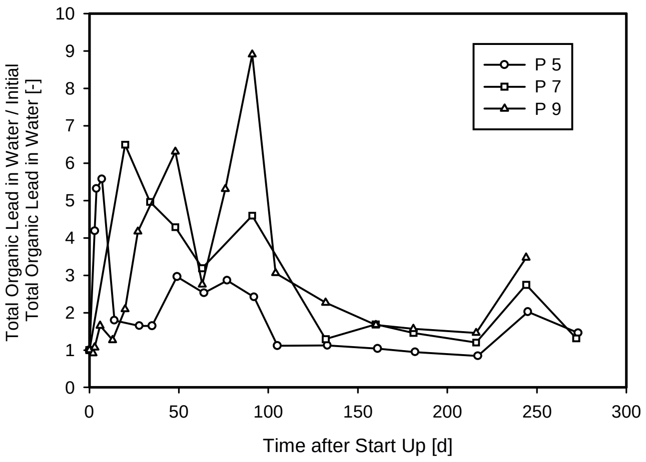

Figure 7. Total organic lead concentrations in the groundwater versus time.

The organic lead concentrations downstream of the natural groundwater flow direction (monitoring wells P 10 and P 11, see Figure 4) show no significant reaction, although the flow time between the AIW and the wells had long been completed, which was demonstrated by a tracer test. So far this circumstance is the most definite indication for the degradation of the organic lead, since other parameters (germ population, CO_2 evolution) did not change in a significant way. Due to a huge heterogeneity of TEL concentrations in the soil at short distances, this data cannot be interpreted at moment.

For the enhancement of the degradation process two steps will be taken in the future: a supply with nutrients is being considered and further AIW will be installed.

6. Pros and cons

The remediation experiment at the VEGAS facility in Stuttgart with the AIW was the first application under controlled conditions on a true scale. The AIW showed good results in removing TCE from the aquifer regarding the low groundwater flow situation. If the groundwater flow increases, a considerable amount of TCE mass is „lost“. A possible solution for this problem could be the installation of further AIW in order to increase the removal capability.

The application of the AIW in the field showed very good results with regard to the oxygen supply of the groundwater. It can be predicted that the distribution of liquid substances in the groundwater zone close to an AIW would work in a similarly satisfactory manner. Some factors point towards the ongoing degradation of the organic lead.

Summarising the advantages and disadvantages of the AIW on the basis of:

- the large scale experiments carried out at the VEGAS facility, Stuttgart, where the stripping effect for volatile compounds was in the foreground
- the field application emphasising the capability of the AIW to support a degradation process (natural attenuation) one ends up with the following points:

+ The AIW are produced with conventional parts, and due to their simple construction the investment is exceptional low. The installation of the four AIW in the field application cost 14 000,- Euro including the compressor and the drilling.
+ Operation costs are low too because of the use of the injected air as a stripping medium as well as a driving force for the induced circulation flow.
+ Regarding the "tempered" hydraulic behaviour of the AIW the costs for the investigation of the site can be reduced significantly.
+ Due to the low costs and the simple installation it is easy to install several AIW according to the actual extent of the site and the subsequent progress of the remediation process.
+ The application of the AIW is not limited to volatile organic compounds, it can also be applied for the support of biodegradation too.
+ The distribution of compounds into the aquifer (oxygen, liquid nutrients) works very good. It is carried out in a controlled predictable manner.
+ The removal capacity of the AIW is good regarding low concentrations, low groundwater flow gradients and shallow aquifers.
– However the AIW cannot be recommended for deep aquifers, high concentrations or high gradients of the natural groundwater flow (regarding the stripping of volatile contaminants).
– Remediation of compounds takes a relatively long time due to the gentle hydraulic activity of the AIW.
– High concentrations of iron in the groundwater afford the use of nitrogen instead of air as a process gas. This increases the costs.
– The hydraulic conductivity of the aquifer should be higher than 10^{-6} m/s.

Taking these points into consideration the method can be regarded as innovative, simple and applicable for a variety of different cases. However, like every other method, the application of the AIW cannot be recommended in all cases. The presence of high natural groundwater gradients seems to be the most important restriction, whereas - on the other hand – the low costs for operation and installation are probably the biggest advantage.

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Recycling of contaminated soil with asphalt technology

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Soils contaminated with different kind of pollutants

The handling of soils contaminated with different kind of pollutants such as oil, heavy metals etc. is a major world-wide problem. It is estimated that in Finland alone there are 20 – 30.000 sites with contaminated soil. These sites include old gasoline stations, car service stations, landfills, old sawmills and wood impregnation plants. Most of these sites are rather small. It is estimated that over the next ten years some 0,7 million m^3 of heavily contaminated and nearly 10 million m^3 of less severely contaminated soil will have to be treated in Finland. Finland is known to be a very “clean” country and one of the few countries still using natural ground water as a source of drinking water. The preservation of Finland`s unspoilt environment is an important goal.

The use of bitumen in contaminated soil remediation

Bitumen is known to be a durable, flexible, adhesive, inert binder with good water resistance and isolation/capsulation properties. Bitumen has been used commonly as binder in asphalt mixtures for road pavements. The technology is well defined and known. The normal way to produce an asphalt material is to mix heated (150 – 170°C) stone material with hot bitumen and then lay and compact the material when it is still warm. Asphalt mixes can also be produced at ambient temperatures using cold stone material and either bitumen emulsions or foamed bitumen as binder.

In the USA, petroleum-contaminated soil has been used as an ingredient of hot asphalt technology since 1985. The asphalt methods used are recycling, immobilisation and encapsulation. In the recycling process the contaminated soil (stone material) is processed by asphalt technology adding some virgin stone material and a bituminous binder. The product is then reused for example, in base layers in road constructions. In the immobilisation process the contaminated soil is encapsulated in bitumen or asphalt and then dumped in a landfill. In the encapsulation process the contaminated soil is isolated by impermeable asphalt layers using bottom, top and vertical isolation.

Water is the main pollutant dispersal medium as it acts as a carrier. For this reason it is important to stabilise the contaminated soil and to prevent water from penetrating into it.

Encapsulation of contaminated soil with bitumen in the cold asphalt process

The idea in the asphalt technology developed by Lemminkäinen and Fortum is to encapsulate the contaminated soil with bitumen in a cold process. Both bitumen emulsion and foam bitumen can be used. This material can then be reused for example in the ground-layer of a road construction. The development project was supported by Tekes, the National Technology Agency of Finland. The project began four years ago and is now at the final stage.

The normal hot asphalt technology would cause problems especially with contaminated soil containing volatile components, so the main effort has been devoted to the development of cold technology. The environmental friendly cold asphalt technology (Ekostab) developed within the project is relatively new in Finland. Soil treated by this method can be recycled instead of being dumped in a landfill. In foam bitumen technology a small amount of water is spread into the hot bitumen, making the bitumen foam so that, the mixing of the material is improved. In emulsion technology contaminated soil is mixed with bitumen emulsion. The bitumen emulsion is tailored specifically to the material in question. Prior to placement, the product is cured by allowing water to evaporate from the water-based emulsion or from the foam bitumen. Both processes are used on site at ambient temperature with cold stone material. The cold process ensures that the emission of volatile hydrocarbons is minimised.

The cold technology asphalt plant that has been used in the Ekostab cases in Finland is called the VEM 300. It is a rather simple plant with a feeder, which is divided into three sections, and a two- axle mixer. Both foam bitumen and bitumen emulsion (also lime and cement) can be used as the binder. The capacity is approximately 200 t/h. The mix can be stored in a silo before laying.

The Ekostab-process – laboratory tests

The Ekostab - process starts by taking samples from the site for analysis in the laboratory. The amount of different contaminates in the soil are determined by chemical analysis. The stone material is tested by structural analysis. The grading curve shows whether the material is suitable for a bituminous mix. If it seems that the material is suitable, a mix design that satisfies both environmental criteria and construction industry specification is formulated. Different mix designs are prepared in a laboratory mixer, and samples are compacted using a laboratory compaction device. The density, strength, stability and water resistance properties of the samples are tested by the Split cylinder test.

The permeability rate (k-value) is measured in a special “Concell”- flexible wall permeameter. In this device the sample is placed in a rubber membrane with porous stone attached to the bottom and top of the sample. The sample is exposed to water pressure and the amount of water passing through is measured and is expressed as the speed of the water. This permeability meter is shown in Figure 1.

Figure 1.Water permeability is measured by the Concell-meter.

The environmental effectiveness of Ekostab technology is measured in terms of leachability. The test used in Finland is the Dutch leachability test (NEN 7345-4). The samples are exposed to a leachant (water of a certain pH). The samples are then stored for 64 days and the water is changed after 0.25, 1, 2.25, 4, 9, 16, 36 and 64 days. The water is filtered and the concentration of contaminant released into the leachate or extract is determined by analytical methods. The results are expressed as the cumulative diffusion from the samples in mg/m^2.

EKOSTAB CASES IN FINLAND

Oil-contaminated soil from the site of an old gasoline station

In 1996 about 1500 tonnes of soil was excavated from the site of an old gasoline station. The soil was contaminated with petroleum hydrocarbons. The total petroleum hydrocarbon concentration ranged from 1000 mg/kg to 4000 mg/kg. The soils were characterised as silt, sand and gravel. Before the project many laboratory tests were made in order to determine the right formulation and mix design.

The mix design formulated for this case consisted of 50% affected soil and 50% aggregate and water based bitumen emulsion. The bitumen emulsion was added as much as all of the contaminants had been encapsulated. Ekostab-samples were taken and tested for density, stability, permeability and leachability. The Ekostab- mix was produced with a mobile cold asphalt plant.

Approximately 1500 tonnes of Ekostab were produced. The encapsulated material was used as a base-course for the road. For the wearing course it was spread normal asphalt layer.

Environmental control was organised by building four lysimeter basins near the Ekostab-road construction. The four lysimeter-basins, collected the leachate through a) contaminated soil, b) Ekostab, c) Ekostab + conventional asphalt and d) clean material layer. Amounts of contaminants were measured from the collection well. The lysimeters were monitored over the next two years. The main trends in the behaviour of these four layers are shown in Figure 2. All of the contaminants were encapsulated in the Ekostab product.

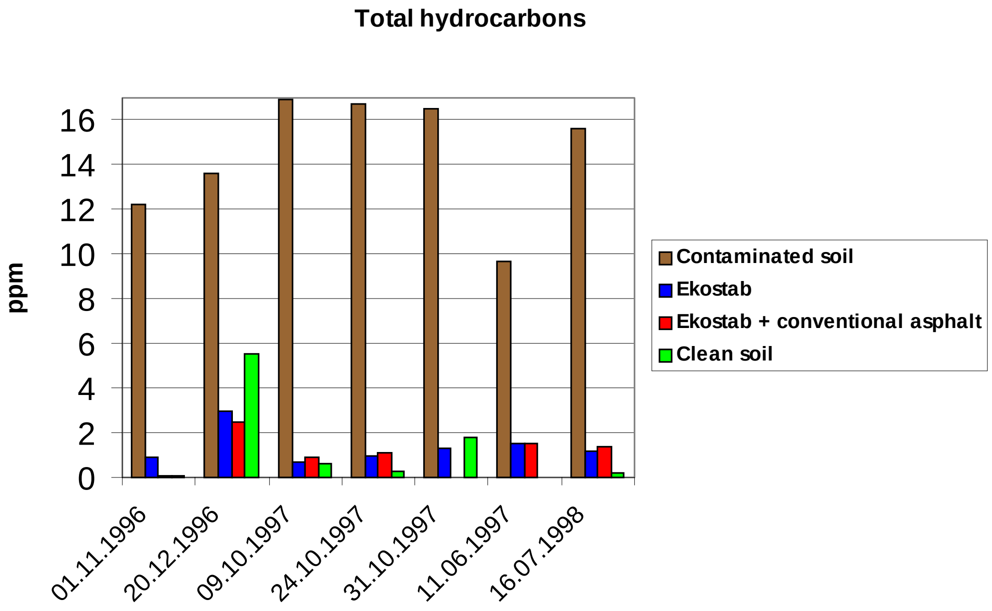

Figure 2. Environmental follow -up by means of four lysimeter basins showing the oil concentration in leachate (ppm).

The permeability rate (k- value) for a product sample, cored from the road construction, was measured by the Concell permeability meter. The measured k-value was 9.7 x 10 $^{-9}$ m/s.

Figure 3. Two Ekostab-core samples taken from the road.

After three years the road is in a perfect condition.

Oil–contaminated soil from – the site of an oil spill

In 1999 about 11000 tonnes of gravel and macadam were removed in the aftermath of an oil spill in a railway yard. The soils were contaminated with crude oil (50% volatile hydrocarbons and 50% heavy petroleum hydrocarbons).

The contaminated soil was processed in three different stages. Firstly, the finest part of the soil was transported to a landfill for composting. Then all of the volatile organic compounds were burned catalytically. After these treatments the soil was ready for processing by asphalt technology.

The mix designs and the amount of foam bitumen were formulated in the laboratory. In this particular case the contaminated material was fairly suitable for utilisation in road construction. The macadam was first crushed (0–32 mm) stone material. The foam bitumen was mixed in the same mobile cold asphalt plant.

Samples of the Ekostab-product were tested for particle size distribution, bitumen content, density, moisture content, stability, permeability and leachability. The result of the leachability test from the quality control stage is presented in Figure 4. The finished product used by the client as pavement base material in the railway yard and container field.

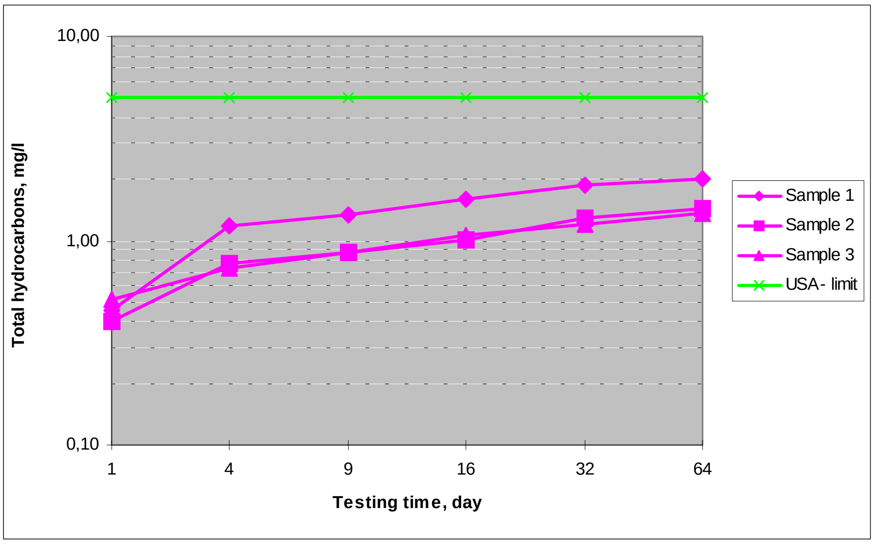

Figure 4. Graph showing the leachability of total petroleum hydrocarbons from the quality control stage.

According to these test results, bitumen encapsulation effectively encapsulated the oil-contaminants. The results of the leachability tests are compared with the concentration of oil in the original material and in Figure 4 with USA-limit -5 ppm (100 x drinking water standard 0.05 ppm).

/Federal Register VOL 55 61 rules, regulations, hazardous waste management system; identification listing of hazardous wastes: toxicity caracteristics revisions p. 11798–11822/

Figure 5. The finished Ekostab-product was used by the client as a pavement base material.

Testing of soils contaminated with heavy metals

The applicability of bitumen to the encapsulation of soils contaminated with heavy metals has been studied in some depth at Lemminkäinen´s Central laboratory. It is evident that bitumen can be used successfully to encapsulate heavy metals like lead, copper, zinc and chromium. Some typical results of laboratory diffusion tests, i.e. the Dutch leachability test (NEN 7345-4), are shown in Figures 6–7. The regulatory levels A and B which the cumulative emissions must not reach are included in the Dutch leachability test when heavy metals are measured. Level A indicates utilisation place which is permanently wet and level B indicates utilisation place which is contemporarily wet.

The results of the leachability tests are compared with the concentration of heavy metals in the original material and with the regulatory levels. Usually in the laboratory cases it has been possible to find the formulation so that the cumulative emissions stay under these levels. The Dutch leachability test is the most commonly used test method in Finland and in Europe. It is designed to determine the leaching of inorganic constituents and heavy metals from solid materials. The leachability test addresses long-term-stability of leaching behaviour.

In 1999 Lemminkäinen treated some 650 tonnes Pb-contaminated soil by the Ekostab-method. Lemminkäinen entered this new remediation technique in a technology competition organised by the National Technology Agency of Finland.

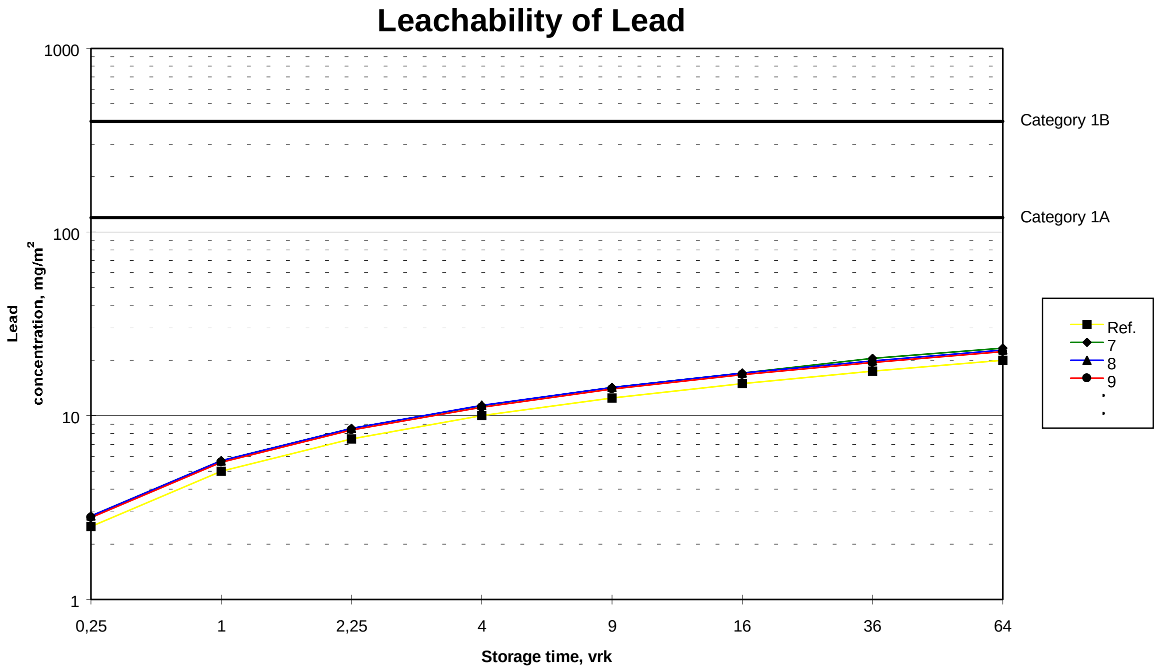

Figure 6. The leachability of Lead i.e. the Dutch leachability test.

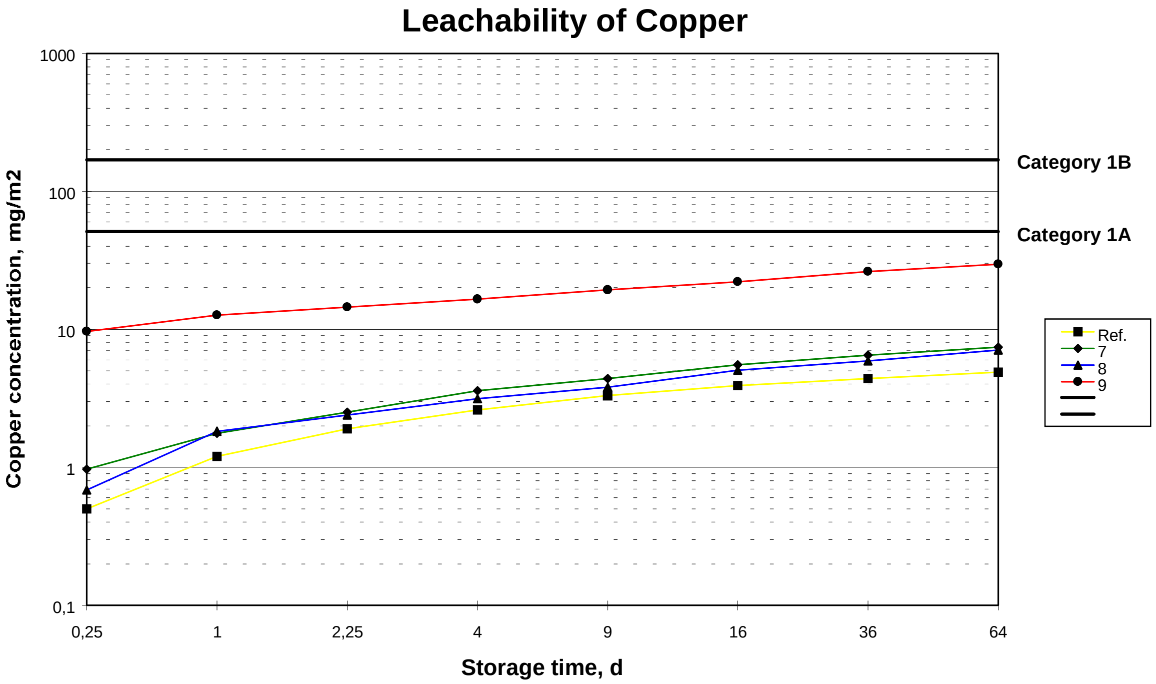

Figure 7. The leachability of Copper i.e. the Dutch leachability test.

Conclusions

In these environmental projects it is very important to pre-test the soil material and to find a suitable mix design and recipe. These projects need to be planned and carried out in collaboration with authorities, environmental consulting companies and site owners or customers.

A lot of research work has been done to determine the range of contaminants and soil material for which cold asphalt technology would be applicable.

This method can be recommended especially for the remediation of oil- contaminated soil. As bitumens are products of the same refining process, they are miscible with other petroleum products.

It is evident that cold asphalt technology is also suitable for encapsulating many heavy metals like lead, zinc, chromium and copper.

Ekostab is fast to produce and the VEM 300 plant is highly mobile. The produced material is environmentally safe and it is possible to utilise as a construction material.

Lemminkäinen and Fortum have been further developing this new cold asphalt remediation technology, and the experiences to date have been promising.

Mass stabilisation of contaminated dredging mud in Sörnäinen, Helsinki

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ABSTRACT: The coastal neighbourhood of Sörnäinen in Helsinki is an old city sector of industrial and harbour area. Nowadays these previous activities are, however, moving further away from the central parts of the city. They are replaced by residential building and other city activities with the need of the new coastal construction following them. Many of the coastal constructions have conventionally been carried out by dredging mud from the sea bottom and replacing it with frictional materials: natural gravel or blasted rock, for example.

Dredged mud is traditionally considered to be unsuitable for any kind of construction purposes. It is thus been transported to relocation areas. In the case of the city park of Sörnäinen it was, however, not allowed to relocate dredging mud to a relocation area due to the contamination of it. Therefore, it was decided to relocate the contaminated dredging mud into the coastal structure of the new shoreline of the coast of Sörnäinen.

For two main reasons it was necessary to treat the mud some way. Bearing capacity of it had to be improved for avoiding stability problems and settlements. On the other hand, the reinfection due to the contamination had to be avoided in the future, too. Mass stabilisation was chosen to be used for soil improvement and remediation method.

Keywords: mass stabilisation, soil remediation, soil improvement, coastal construction

1. Introduction

In the most usual cases so far, mass stabilisation has been carried out primarily to improve the geotechnical properties of soft soils. In this paper a case is presented, however, where the secondary idea of using the mass stabilisation method is carried out, too. That is a purpose to remediate contaminated sediments in situ, without relocating them to any other place, causing maybe in that case environmental problems somewhere else.

In addition to the stabilisation effect the solidification of contaminated masses is an important and desired effect of mass stabilisation nowadays. Especially, for the reason that the amount of the contaminated masses is keeping on rising due to the development of environmental knowledge. Treatment of dredging mud and contaminated soils are both relatively recent applications of the mass stabilisation technology. Both of them are good examples of applications where the method can be utilised in very bad soil conditions.

In the coast of Sörnäinen, Helsinki, a new park area is being constructed by filling sea in area about 30 m wide and 150 m long. The filling was initially planned to be made by dredging mud and clay away and replacing them with a blasted stone filling. The dredged mud and clay were planned to be transported to Taulukari relocation area in sea outside Helsinki. However, it was later found out that about 1,5 m thick top layer of the mud was contaminated by heavy metals, PCB and oil. Due to the contamination it was not allowed to relocate the top layer of the mud to Taulukari area anymore. It was relocated to a basin between the new edge embankment and the previous shore line. Mass stabilisation method was then used as both soil improvement and soil remediation procedure.

2. Mass stabilisation method

2.1 Principles of mass stabilisation

Mass stabilisation is a relatively new soil improvement method where stabiliser is mixed into peat, mud or soft clay. Procedure is carried out by a mixing tool, which so far has been installed on an excavator machine as shown in Figure 1. Mixing is done both in horizontal and vertical direction so that a homogeneous reinforced soil slab is formed due to the effect of the stabiliser. The mixing tool has been innovated by YIT-Construction Ltd in Finland.

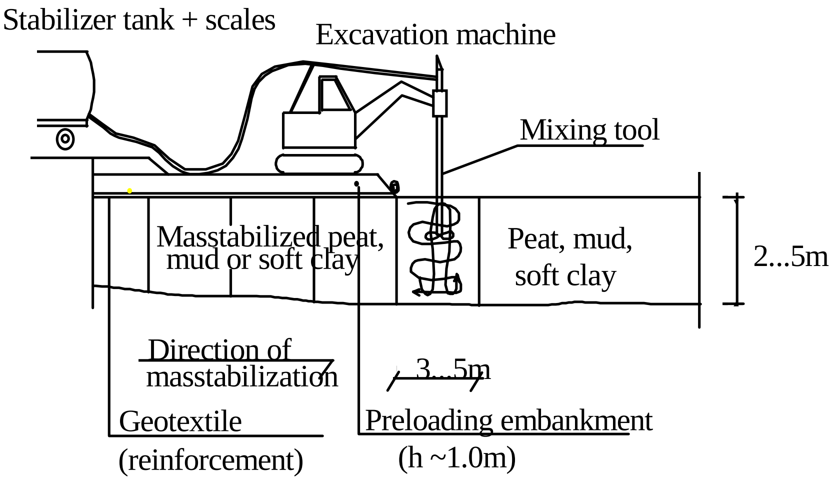

Figure 1. Mass stabilisation method in principle.

The technology was initially developed for stabilisation of soft peat layers. As the mass stabilisation technology has developed new fields of application has been innovated, treatment of dredging mud and contaminated soils, for example. Mass stabilisation can be implemented also by mixing stabiliser agents to soils that have been excavated or dredged and lifted to the ground or basins constructed by edge embankments, for example. Especially dredged mud is usually extremely soft and it is practically impossible to build anything on it. Usually such masses are transported to relocation areas. Mass stabilisation improves, however, the properties of the excavated or dredged masses of poor quality so that instead of transporting this material to landfill or relocation area, it can be used to other construction purposes: such as road structures, filling, noise barriers, coast banks etc.

Mass stabilisation can in many cases replace the conventional soil replacement method in which the soft soil layers are replaced with frictional materials like gravel or blasted rock. By using this environmentally friendly technology the need for natural stone- or crushed soil materials can significantly be decreased. Furthermore, the amount of surplus masses is minimized. This means that valuable gravel ridges and rock areas can be saved and also that the load on soil dumps is reduced. In addition, traffic- and pollution problems from transportation of filling materials and soak surplus masses from excavations can be avoided [1].

2.2 Laboratory and field testing

Geotechnical properties of stabilised soil depend on the physical and chemical properties of the natural soil deposit and on the properties of the stabiliser. The most important geotechnical properties of organic soils that have effect on stabilisation are natural water content, humification grade and pH [1].

To assure the safety and the quality of the final stabilised product, a number of stabilisation tests must be carried out beforehand in laboratory to find out the most suitable stabilisers, to optimise the stabiliser amount and to determine strength-deformation properties of the stabilised soil for the actual case. Also the permeability of the stabilised mass should be measured in laboratory, in case of mass stabilisation being used for solidification of contaminated soils.

It is also necessary to make the quality control tests afterwards, when the stabilisation work is finished, in order to ensure the improvement of the shear strength and to supervise the mixing work being done in due form. Supervising should always be carried out also during the construction phase by monitoring the mixing work and the feeding of the binder. Because the mixing work achieved in the field is so far less than that is done in the laboratory, the ability of the binder to dissipate homogeneously is of great importance. After the preload embankment has been constructed, the settlements should be followed up in order to monitore when the preload embankment may be removed.

3. Construction of the city park of Sörnäinen

3.1 Dredging and building of the edge embankment

After it was found out that the top layer of the mud was so badly contaminated that it was not allowed to relocate to Taulukari area, the construction plans were changed in a way that only an edge embankment was built with the replacement method. The contaminated mud was then relocated to the basin formed by this embankment and the previous shoreline. The width of the basin was about 17 m, length about 80 m and depth 4–5 m. A two meters thick layer of crushed rock was designed on the top of the dredged mud layer.

Because of a short construction time (only about 7 months) there was no time to wait for the natural hardening and consolidation of the mud. There was a need to find out a solution to avoid the contaminants to spread into the vicinity in the future, too. For these reasons the whole dredged mud layer was chosen to be mass stabilised. The cross section of the coast structure in principle with the preload embankment is shown in Figure 2.

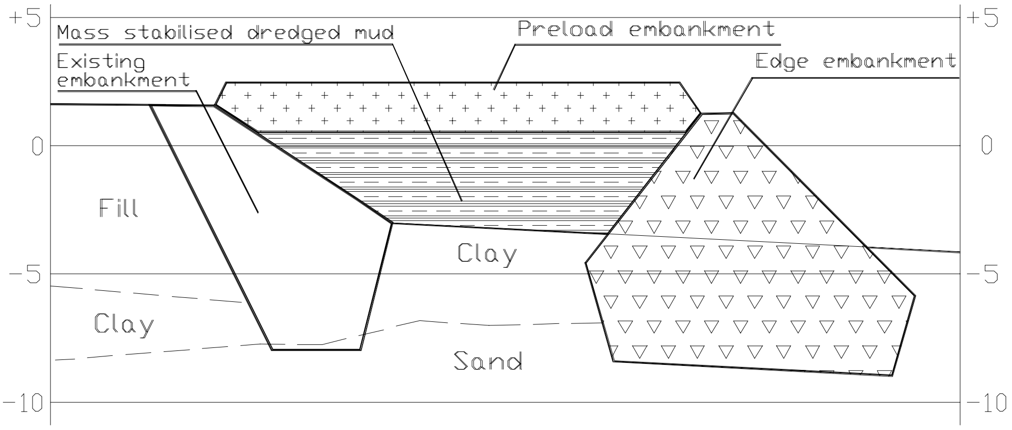

Figure 2. Cross section of the coast structure in principle in Sörnäinen, Helsinki.

Dredging was carried out in two phases. At first, was the contaminated top layer of the mud, situating in a place of the edge embankment, dredged and stored into two barges. In a second phase, was the deeper, not contaminated clay dredged and the edge embankment constructed at the same time. The not contaminated underclay was transported to the relocation area of Taulukari. The boundary surface of these two layers was monitored by number of laboratory tests beforehand. Laboratory tests was carried out from the clay being transported to Taulukari during the construction phase, too. Later on, as the edge embankment had been advanced for a while, was the contaminated dredging mud lifted into the basin to the top of the underlying contaminated sediments. Floating mobile protective mat was used during the whole dredging phase to avoid contaminants spreading into the nearby sea area.

Figure 3. Dredging and building of the edge embankment in Sörnäinen, Helsinki.

3.2 Mass stabilisation

The stabiliser agent was chosen by a comprehensive laboratory testing programme. Three different binders were tested using three different amounts of stabiliser. The tested binders were Rapid cement, Finnstabi FTC and Ekomix 2, Tested amounts of them were 50, 80 and 110 kg/m^3. Results from unconfined compression tests made after 14 days are presented in Table 1. For two samples also the permeability test was made after two months. In this case rapid cement was chosen as the binder, using an amount of 110 kg/m^3.

Table 1. Unconfined compression strength q, strain at failure ε and permeability k of stabilisation tests of contaminated top layer sediment of coast of Sörnäinen, Helsinki.

Binder	amount	q	ε	k
	(kg/m^3)	(kPa)	(%)	(m/s)
Rapid cement	50	<10	n.d	
Rapid cement	80	39	3	22,0*10^{-9}
Rapid cement	110	93	1,8	
Finnstabi FTC	50	<10	n.d	
Finnstabi FTC	80	19	4,5	
Finnstabi FTC	110	20	7,5	
Ekomix 2	50	<10	n.d	
Ekomix 2	80	33	4	9,6*10^{-9}
Ekomix 2	110	60	3,6	

Note: n.d. – not detected

The stabilisation work proceeded in sections from the shore line side edge of the basin. Directly after the stabilisation work, an one meter thick compact layer was constructed on the top of the stabilised section, see Figure 4. After one month, when the stabilised mud had been hardened and field tests had been made, the embankment was raised. Then about one meter thick preload embankment was placed on the top of the compact layer.

Figure 4. Mass stabilisation work and construction of the compact layer in Sörnäinen, Helsinki.

The quality control tests were made after one month. The bearing capacity of the mass stabilised mud was measured using soundings in 9 points. Total number of the tests was 15. Vane auger was used in 5 tests and deep stabilisation penetration test was carried out 10 times. Desired value of the shear strength was 30 kPa. However, the soundings showed that the average strength of the stabilised layer is above 120 kPa and the minimum value ever measured 40 kPa.

After the tests had been done, was the preload embankment constructed for a four months settlement time, see Figure 5. The material of the embankments were chosen in a such way that it can be utilized in the final structure.

Figure 5. Preload embankment on the mass stabilised mud in Sörnäinen, Helsinki.

4. Conclusions

The measured shear strength was about four times higher than the aimed. It might have, for that reason, been able to have been reduced the amount of the binder. On the other hand, the stabilisation tests did not encourage to do so. One reason for those unexceptably good bearing capacities measured is probably that it had to be mixed some clay from the deeper layer among the dredged mud to get the surface of the mud rising over sea water level enough. It did not be the quite same soil any more as tested in laboratory.

In this case rapid cement was used as a binder due to the results of stabilisation tests. New stabiliser agents, mainly cement and mixtures of cement industrial by-products are often more cost effective than traditionally used lime and lime-cement mixtures. These new binders have also made it possible to stabilise organic soils, too. Active research in developing both even more effective stabilisers and mixing tools creates new applications and improves the competitiveness of this environmentally friendly technology.

The treatment of dredging mud is a good example of new areas of application where mass stabilisation can be utilised in both improving the properties of poor soil masses and to bind contaminated agents in these masses, which previously had to be replaced. Because of the huge lack of the relocation areas and soil dumps nowadays it seems that the future of mass stabilisation method looks quite encouraging.

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Preliminary evaluation of the results of *in situ* respiration tests from four Finnish sites

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1. Introduction

In situ bioventing is a fairly new and upcoming technology for cleanup of hydrocarbon contaminated sites. Since the second half of 1980's large amount of articles have been published on the subject. First bioventing projects were started in Finland in the first half of 1990's. It is generally believed that in situ bioventing is a costeffective method compared to other cleanup methods which makes in situ bioventing a very attractive cleanup method (Hart 1996).

However, in situ bioremediation is not applicable to all hydrocarbon-contaminated sites and site specific confirmation of the feasibility is usually needed. This is also required by the environmental regulators prior a bioventing project is started. Both laboratory and in situ procedures have been suggested for evaluation of the site-specific feasibility of in situ bioventing (Madsen 1991). In situ respiration test is one of the procedures that is commonly recommended for the evaluation of the feasibility of in situ bioremediation of hydrocarbon contaminated subsurface (EPA 1995 a and b, Davies et al. 1998).

2. In situ biodegradiation and respiration tests

All in situ bioremediation methods, including bioventing, are based on the assumption that microbes can degrade hydrocarbons and that these microbes are present in the subsurface almost without exception. Thus in situ aerobic biodegradiation of hydrocarbons occurs naturally in the subsurface. However, there are several important factors that control the rate of the in situ biodegradiation in the subsurface. The most important of these factors are concentrations of oxygen and in the soilgas, soil temperature and amount of moisture in the subsurface. (Alexander 1985, Madsen 1991, Zhou & Crawford 1995)

As a result of increased microbial activity in hydrocarbon contaminated ground, soil gas oxygen concentration is lowered and carbon dioxide concentration is elevated (compared to the atmospheric concentrations). Various inorganic processes may cause elevated carbon dioxide concentrations in the soil gas (Suchomel et. al 1990, Hinkle 1991). Presence of methane in the soil gas is evidence of anaerobic microbial activity (Conrad et. al 1999). Thus in an in situ respiration test the concentration of oxygen in the soilgas and the rate of microbial consumption of oxygen are used to evaluate the rate of hydrocarbon degradiation in the subsurface.

A respiration test is started by introduction of atmospheric air into the hydrocarbon contaminated subsurface until the concentrations of oxygen and carbon dioxide in the soilgas are at or close to the atmospheric level. Air introduction is then interrupted and eventual changes in the soilgas oxygen and carbon dioxide concentrations, that are caused by microbial activity, are measured. The microbial activity of the subsurface and the ability of the microbes to degrade organic pollutants are assessed by changes of oxygen and carbon dioxide concentrations in the soilgas (%/day). The feasibility of in situ bioremediation is estimated to be good if decrease in oxygen concentration and increase in carbon dioxide concentration is fast and the deviations large. Degradiation rates (mg/day or mg/year) for the hydrocarbons can be calculated from the changes in the oxygen concentration if the amount of the contaminated soil is known. (EPA 1995 a and b, Davies et al. 1998)

3. Description of the sites and method of analysis

3.1 General

This paper describes the results of the respiration tests from four hydrocarbon-contaminated sites situated in Uusimaa, Southern Finland. The geological setting of the sites is fairly similar. All sites are situated on glacifluvial deposits with mainly coarse-grained soils.

3.2 Site A

Site A is an active gasoline situated on the First Salpauselkä ice marginal formation in central Uusimaa in Southern Finland. Soil sampling indicated that the soil at the site is fine-grained sand at least to 15–20 m depth. Fine-grained interlayers were not detected. Depth of groundwater table is approximately 10 m below ground surface. The ground at the site is contaminated with mineraloil. Highest measured mineral oil concentrations were around 25 000 mg/kg. The contamination extends to 9 meters depth. Contaminated soil was excavated to 3–4 meters depth. Horizontal extraction line was installed to the bottom of the excavation and the bottom of the excavation was covered with impermeable plastic seal. The extraction line and a ground water monitoring well situated in the contaminated area with 2 meters of screen above the ground water table were used as soilgas sampling wells in the respiration test.

3.3 Site B

Site B is apartment building also situated on the First Salpauselkä. The soils at the site are mainly fine-grained sand and silt. Depth of groundwater table is approximately 8 m below the floor of the basement of the building. The boiler-room of the building is located in the basement. Approximately 4 000 litres of fuel oil leaked from a pipeline into the ground under the building. Highest mineral oil concentration measured were around 30 000 mg/kg. Contamination had not reached the ground water (3 years after the leakage) because of 2 m thick silt layer just above the groundwater level. Bioventing is the only cleanup method that does not require significant demolishing of floors and walls of the building. Respiration test was performed to evaluate the possibilities to use in situ bioventing at the site. An extraction well and 12 sampling wells were installed through the basement floor into the contaminated ground for the purpose.

3.4 Site C

Site C is also an active gasoline station situated on the First Salpausselkä. According to the drillings, soil sampling and grain size analysis of the samples the soils at the site are mainly medium and coarse grained sands with occasional gravel layers. Fine-grained interlayers were not detected. Depth of groundwater table is approximately 20 m below ground surface. The ground at the site was contaminated with dieseloil and to smaller extent with gasoline. Highest measured mineral oil concentrations were approximately 4 000 mg/kg and corresponding gasoline concentrations were 200 mg/kg. The contamination extended to approximately 14 meters depth. Thus excavation and ex situ treatment of the contaminated soil was discarded as remediation method. A soil vapour extraction system with 5 extraction wells was installed and volatile gasoline hydrocarbons were extracted from the ground. For the remaining mineral oil contamination a bioventing approach was suggested and a respiration test was performed to evaluate the feasibility of in situ bioventing. The extraction wells were used as sampling wells in the respiration test.

3.5 Site D

Site D is a closed gasoline station situated on a glacial esker. The soils at the site are fine and medium grained sands with occasional silty interlayers. Depth of the crystalline bedrock varies from 4 to 10 meters in the contaminated area. The groundwater table is at 7 meters depth. The ground is contaminated with mineraloil and gasoline. Highest analysed mineraloil concentrations were approximately 500 mg/kg and corresponding gasoline concentrations were 1 000 mg/kg. Gasoline has migrated into the groundwater as well. Majority of the contaminated soil was excavated. Soil vapour extraction and bioventing were chosen for the cleanup of the soil deeper than 5 meter and the soil under the building (still in use). Two vertical extraction wells and one horizontal extraction line were installed for the purpose. The volatile hydrocarbons were extracted from the sandy part of the ground (the silty layers remain contaminated) and respiration test was performed to evaluate feasibility of in situ bioventing.

3.6 Analysis method

Soil gas samples were extracted from the ground through the extraction wells and lines and monitoring wells by means of a vacuum blower. The samples were analysed with Geotechnical Instruments GA94 gas analyser. Both oxygen and carbon dioxide as well as methane concentration were analysed. Atmospheric air was used as reference assuming that oxygen concentration in atmospheric air is 20,9% and concentration of both carbon dioxide and methane is 0%.

4. Calculation of the degradation rates

The calculation of in situ degradation rates is based on the following stoichiometric relationship that describes the degradation of hexane (EPA 1995a):

$$C_6H_{14} + 9.5\ O_2 \longrightarrow 6\ CO_2 + 7\ H_2O$$

Based on the oxygen utilisation rates from respiration tests the in situ biodegradiation rate (hexane equivalent) mg/kg of soil/ day can be estimated with the following formula (EPA 1995 a and b).

$$-k_B = \frac{-\frac{k_o}{100}\theta_a \frac{1L}{1{,}000cm^3}\rho_{O_2}C}{\rho_k\left(\frac{1kg}{1{,}000g}\right)} = \frac{-k_o\theta_a\rho_{O_2}C(0.01)}{\rho_k} \qquad \text{(Eq. 1)}$$

Where:

k_B = biodegradation rate (mg/kg/day)
k_o = oxygen utilization rate (%/day)
θ_a = gas-filled pore space (volumetric content at the vapour phase, m^3 gas/cm^3 soil)
ρO_2 = density of oxygen (mg/L)
C = mass ratio of hydrocarbons to oxygen required for mineralization (1:3.5)
ρ_k = soil bulk density (g/cm^3)

The resulting formula used for calculation of the in situ degradiation rates in this study is:

$$k_B = \frac{-(k_0)(0.25)(1.330)(0.29)(0.01)}{1.4} = -0.68k_o \qquad \text{(Eq. 2)}$$

5. Results of the respiration tests from four Finnish sites

The measured respiration rates varied in the sampling wells installed into different parts of contaminated ground. Variations were observed also depending on whether extraction or injection technique had been used in areation of the contaminated ground prior the test. The following figures present the average changes of oxygen and carbon dioxide concentrations. The K_b values [mg/kg/day] were calculated as described earlier in the text and are given in the diagrams.

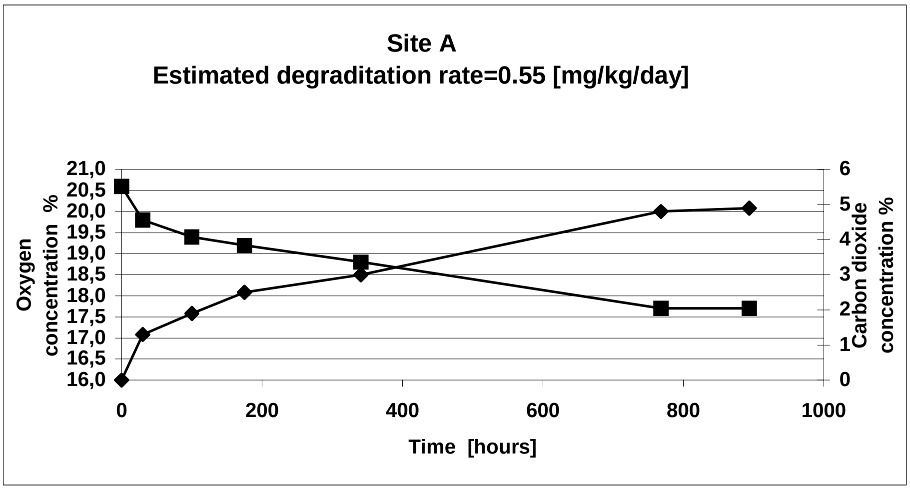

Figure 1. Average respiration tests results at site A.

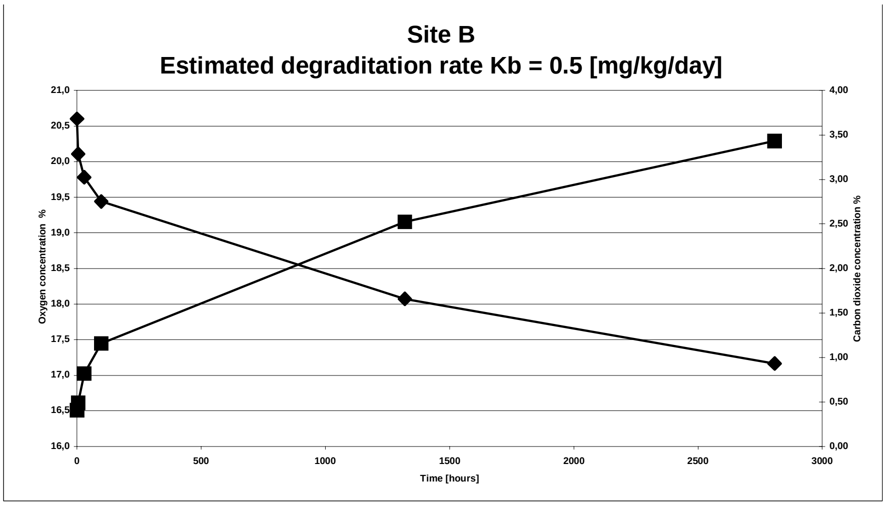

Figure 2. Average respiration tests results at site B.

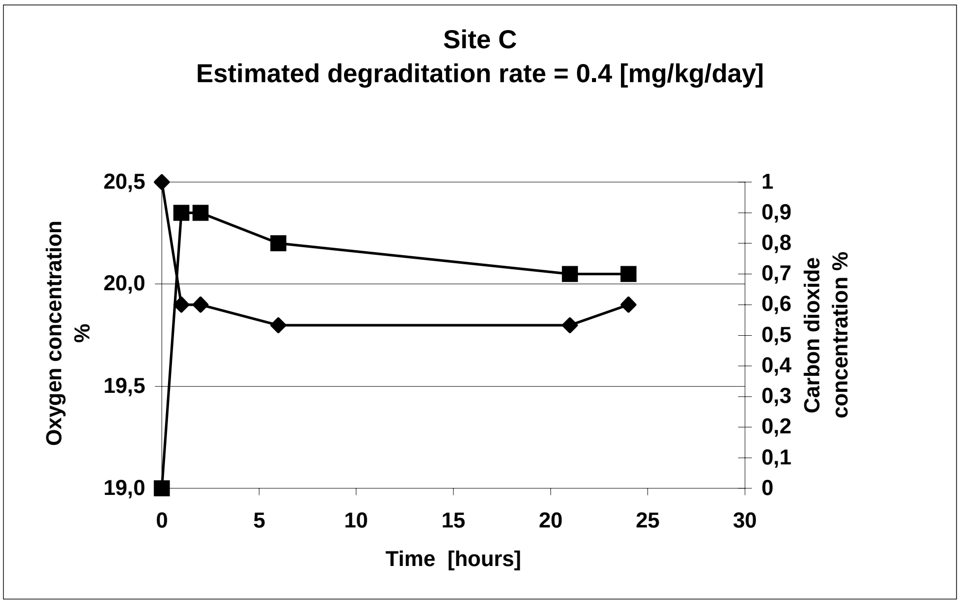

Figure 3. Average respiration tests results at site C.

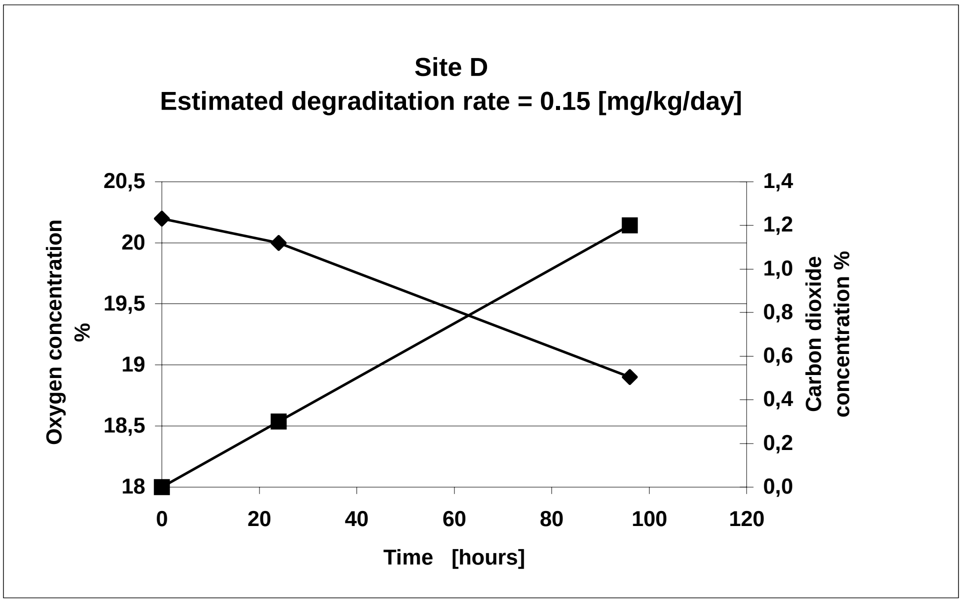

Figure 4. Average respiration tests results at site D.

6. Conclusions

Preliminary evaluation of the results of the respiration tests from the four Finnish sites indicate quite slow and small changes in the oxygen and carbon dioxide concentrations when only aeration and no irrigation or addition of nutrients were used.

Normally the decrease of oxygen concentration (%/day) in the extracted soilgas samples is calculated as indication parameter of the microbial activity in contaminated ground. The value (%/day) is calculated from the linear part of the curve using measurements made within the first 1–2 days after the aeration is stopped. Deviations of these parameters measured at the sites of this study are less than corresponding values reported in published articles. In this study the average decrease of oxygen concentration was less than 1%/day. Corresponding average rates during one year remediation time calculated from around 100 different cases given in the EPA manual (EPA 1995b) are 7%/day and median rates 3% /day.

The average degradiation rates calculated with Eq. 2 (without nutrient or moisture addition) varied in this study between 0,15 and 0,55 mg/kg/day. Davis et al. (1998) reported dieseloil degradiation rates calculated from in situ respiration test results that ranged from 13 mg/kg/day (no nutrient addition) up to 35 mg/kg/day (with nutrient addition). Corresponding average degradiation rates given in the EPA manual (EPA 1995b) are 5 mg/kg/day and median rates 2 mg/kg/day.

As a result of the above described slow changes in oxygen concentrations and low degradiation rates the calculated remediation times needed to reach the regulatory hydrocarbon concentrations at the sites described in this paper are generally from 10 to 30 years.

It is suggested that the main reason for the relatively low degradiation rates and the following long remediation times is the low temperature in the contaminated subsurface at the studied sites. The temperature in the Finnish subsurface at the sampling depths of this study is estimated to be around 7 °C (based on the statistics in published by Heikinheimo, M. & B. Fougstedt 1992) while Davis et al. (1998) refer to significantly higher temperature and suggested that temperature may be one of the key parameters effecting the degradiation rates. The effect of temperature on the degradiation rates was emphasized also by Zhou & Crawford (1995).

The loss of humidity in the soil matrix at test sites due to the soil vapour extraction preceding the respiration tests at sites A, C and D may also have effected the test results. The water content of investigated soil samples from sites A and B was less than 10% (sampling done before soil vapour extraction).

The respiration test results preseted in this paper indicate that when only soil aeration (by either injection or extraction of atmospheric air) is used to acclerate the in situ biodegradiation of hydrocarbons in the contaminated ground, the achieved degradiation rates are close to the intensity of natural attenuation in the same conditions. Thus injection of moisture and nutrients must seriously be considered if higher degradiation rates are desired. Furthermore the feasibility of natural attenuation as remediation approach in the Finnish geological and meteorological conditions should be studied.

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Environmental tomography – a research and modelling system for contaminated areas. Case: permanent 3-d resistivity monitoring system to control nitrate contamination

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ABSTRACT: The Environmental Tomography - a Research and Modelling System for Contaminated Areas Project is part of the Finnish Technical Development Centre's construction environmental technology programme. An environmental development project is being jointly conducted by Viatek Ltd. and Technical Research Centre of Finland/Communities and Infrastructure in connection with numerous pilot research projects during 1996–1998. Environmental tomography systematically looks for those soil - groundwater volume structure/properties that simultaneously satisfy point measurement values known from the volume being studied, correlations between different geodata (geology, geophysics and hydrology), the statistical behaviour of point properties and indirect measurement and test observations (groundwater elevations, geophysical responses, pumping responses, content distributions, tomographic inversion). As a result of this project there has been selected an approach method for investigation of contaminated areas. Also an integration and visualisation method has been selected during this project.

Introduction

There are about 200 fox (*Vulpes vulpes*) and mink (*Mustela vison*) farms situated above the important groundwater areas in Finland. They are serious risk for groundwater quality because they may cause a potential risk for local groundwater supplies. The objective of this paper is to present and study the possibilities to use permanent resistivity monitoring system in long-term monitoring of nitrate contamination and also to study the capabilities of the system for the potential future application to process control enhanced in situ bioremediation. Test site is located at Kaustinen, western Finland and this study is one part of an extensive demonstration project for investigating the techniques and models to monitor and control these nitrate problems. The expected changes in resistivity of groundwater occur only from migration of nitrate, because the stock breeding has finished in 1993 and the upper soils have been removed. There is no more surface sources for nitrate infiltration.

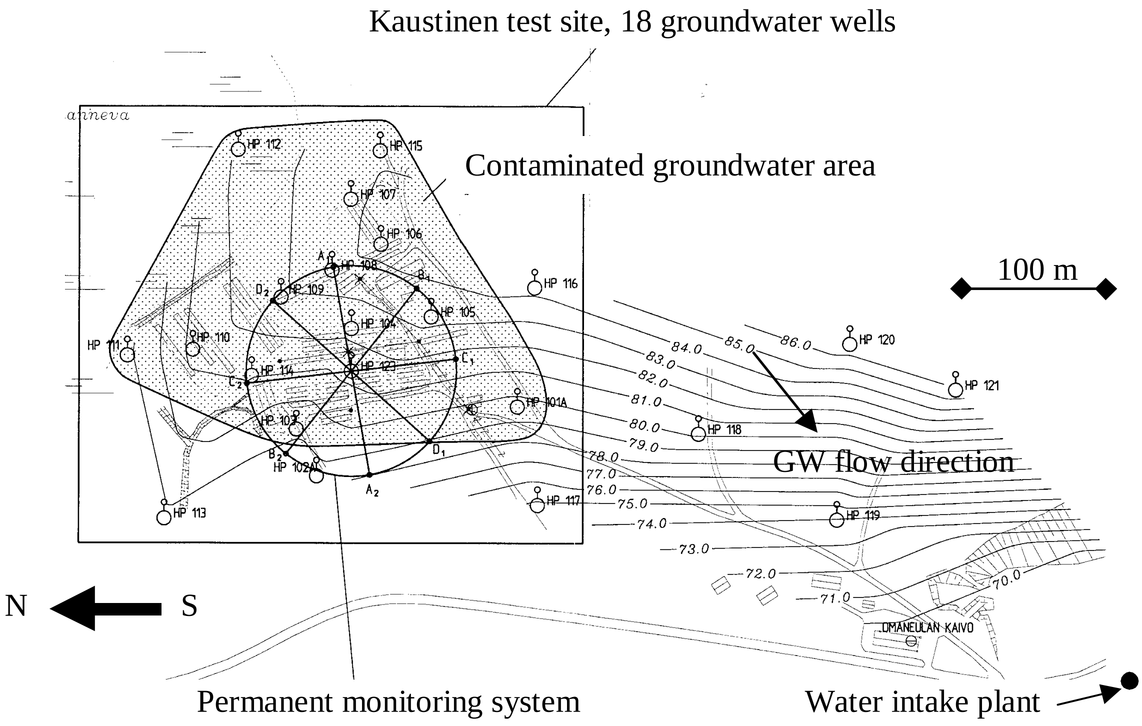

Figure 1. The location of the permanent monitoring system is in the middle of the most contaminated area (cross in the middle of the figure). Dark grey rectangles are former animal shelters and round figures with ID numbers show the location of groundwater monitoring wells.

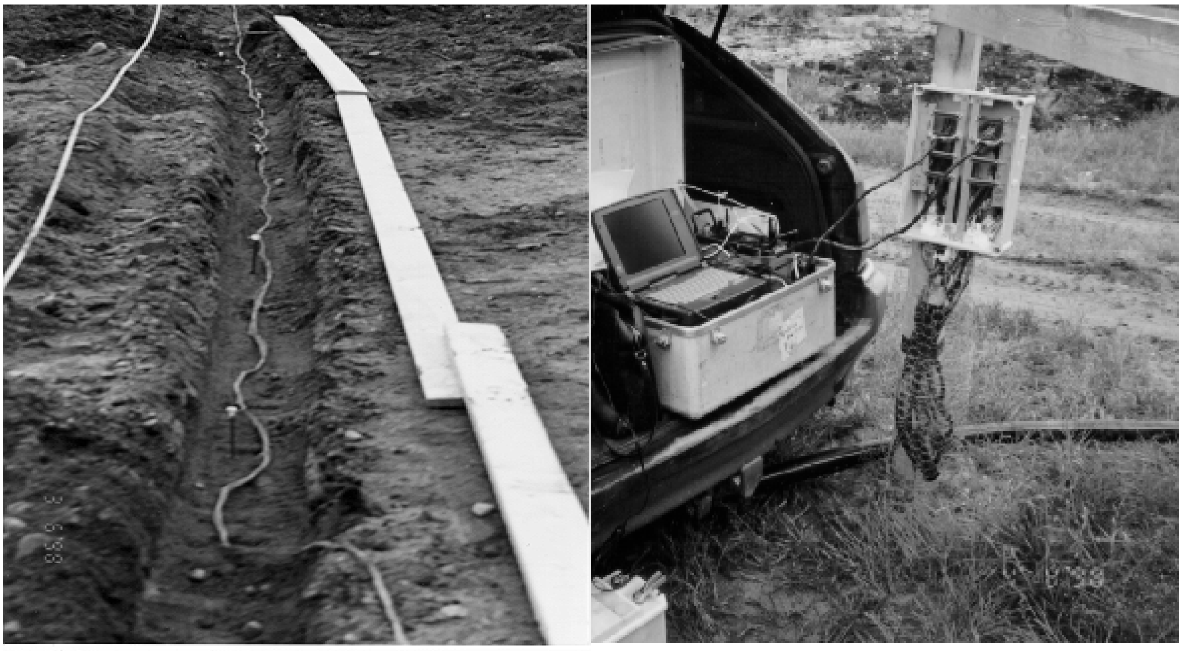

Figure 2. Electrodes and wires are connected to iron nails and are covered with silicone addhesive and protective planks (left figure). Weatherproof measuringbox is installed on a fixed plate and connected to resistivity monitoring and scanning devices (right figure).

Monitoring surveys and resistivity inversions

The first monitoring survey was carried out in the beginning of June 1998. In the beginning there were problems with some current electrodes because of the surrounding dry soil. The measuring matrix for 75 electrodes includes 900 discrete Wenner-α measurements. The actual measurements were carried out with the commercial resistivity measurement unit and with the scanner of 75 channels. It took about 2 hours to measure one line with 75 electrodes and about one field day to measure the whole monitoring program. The surveying depth of resistivity measurements in the middle of array was about 21 m.

The second monitoring survey was carried out two months later in the beginning of August 1998. The quality of these measurements were better this time because of the higher moisture content in near-surface soils.

The third monitoring survey was carried out five and a half months after the first measurements in the middle of november 1998. Weather conditions were changed dramatically and early winter had come. There were 25 cm snow on the ground and frost had penetrated in places deeper than the depth of electrodes. We were able to measure only two out of four lines and the quality of the data were not so good as in previous monitorings.

In order to produce meaningful images to compare temporal differences, every data in the monitoring sequence must be inverted in the same software settings and parameters. In this study, we have inverted the monitoring data using the almost standard 2-D approach of constrained nonlinear inversion that incorporates Tikhonov regularization without any geological constraints. This regularization penalizes model roughness based on the Laplacian of the model parameters. Figure 3 shows the true resistivity depth sections produced by inverting all the three monitoring phases of the line A.

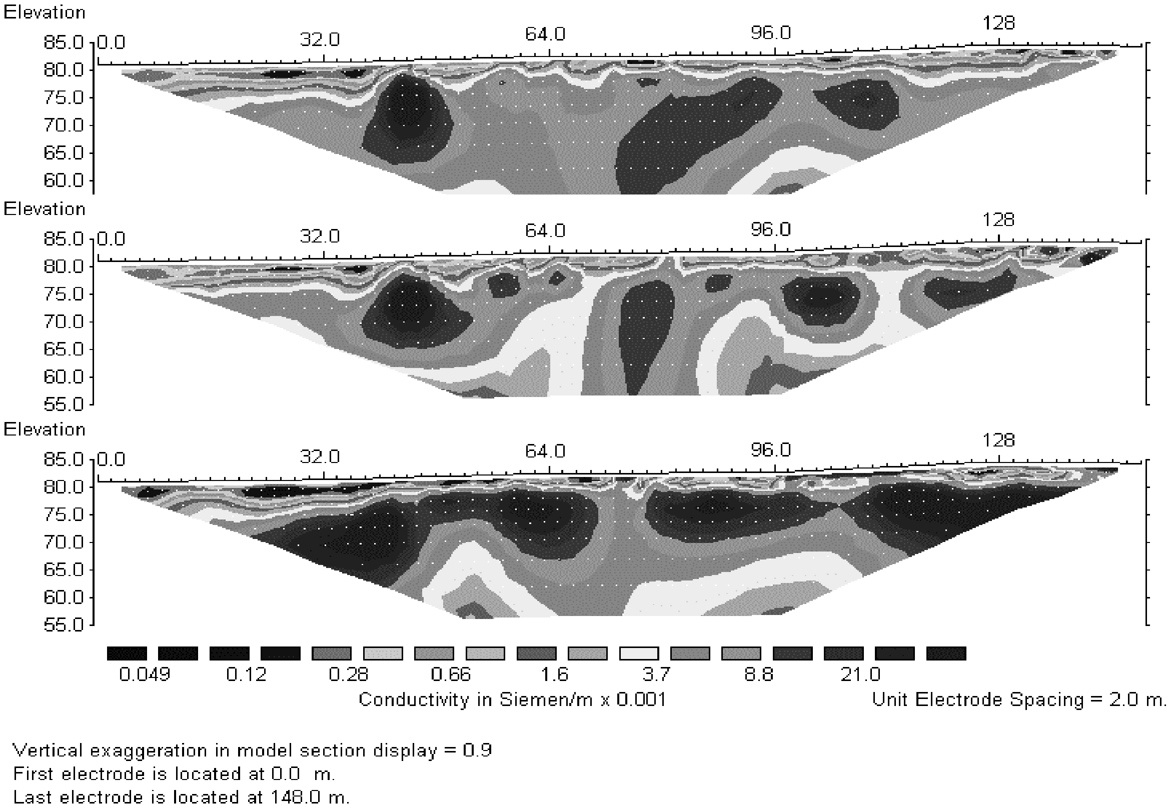

Figure 3. Inverted images of the line A measured during three monitoring phases of the study.

Data handling and integration with hydrogeological and chemical information

Inverted resistivity images were further studied, compared and integrated with the hydrological and chemical sample information. 2-D interpolation of groundwater sample data were calculated for groundwater electrical conductivities and nitrate concentrations. 3-D interpolation of resistivity monitoring results were compared against this information.

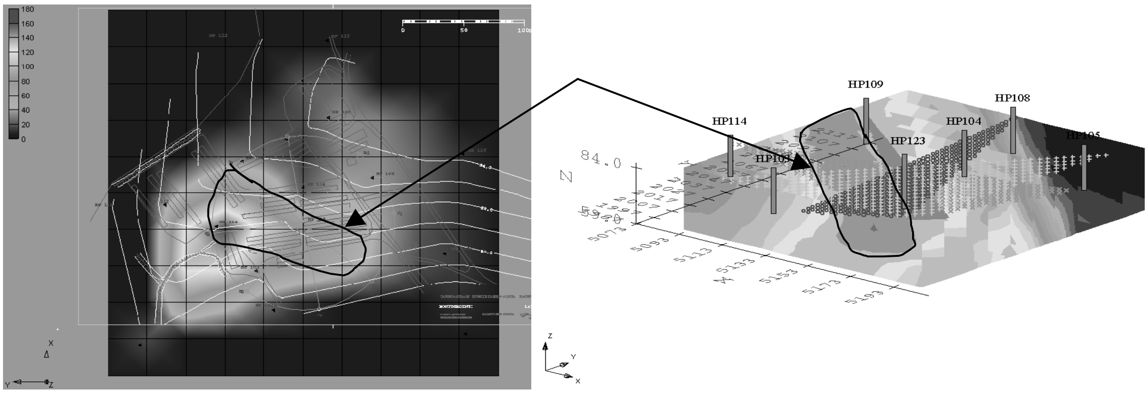

Figure 4. 2-D interpolations of nitrate concentrations in groundwater (samples taken 3.6.1998) are presented in the left figure and corresponding 3-D interpolations of resistivity data in the right figure. It is characteristic for both interpolations that the volume/area of very high electrical conductivities (>100 mS/m) and high nitrate concentrations (>100 mg/l in groundwater samples) coincide. This low resistivity area was also present in the data of the first monitoring campaign.

Results

Hydrogeological conditions of the site are quite homogenous. Surface soil consists mainly of sand and gravel from the depth of 2 meters down to the bedrock. This crystalline bedrock surface is in the depth level of 18–20 meters. The main soil type is sandy or silty till. Groundwater level is about 1,5 m below the surface and main groundwater flow direction is towards south and towards the water intake plant. The hydraulic conductivity is very low due to low permeability silty soil and therefore changes in nitrate levels during 6 months were expected to be small.

Nitrate additions into the groundwater system naturally lowers the electrical conductivities also in the groundwater samples and this allowed as to correlate successfully the results of chemical analysis with the inverted resistivity images (the soil structure is rather homogeneous). The results of inverted resistivity/conductivity images indicate that the soil is relatively inpermeable and most of the groundwater flow is in the upper two meters in the sand layers. Three monitoring surveys indicate also that very slight changes in resistivity had happened during 6 months. Integration of resistivity and hydrogeological and chemical data allowed us to determinate the nitrate contaminated area in three dimensions.

Discussions

The purpose of the study was to investigate the capabilities of the permanent resistivity monitoring system to map spatial and temporal changes in present groundwater quality and in this way validate its potential in long-term monitoring and in predicting nitrate advection. The benefit of using permanent monitoring system is in the lower signal-to-noise ratio because of the fixed and unchanged electrode locations and thus smaller resistivity contrasts can be detected.

We conclude that this kind of permanent resistivity monitoring installation combined with conventional point information has a great potential in the near future to process control and optimize in situ remediation activities in Kaustinen type aquifers.

Competition on the clean-up of the Kyläsaari area. Comparison of competition proposals and selection of the winner

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ABSTRACT: Helsinki City has been planning the land use of the Toukola, Arabia and Kyläsaari areas with a total surface area of c. 85 hectares. 29 ha of the area have been planned as residential quarters and 44 ha as parks. The historic use of the areas includes industrial production, energy production/waste incineration as well as filling the sea with different filling materials. In certain areas, the coastline line has moved c. 500 m to the east. In the Kyläsaari area the ash and slag fill of the former incineration plant contains harmful inorganic and organic substances. A change of the area in to a park is likely to require reparation measures concerning the soil. In connection with the handling of the zoning plan for the Kyläsaari, Toukola and Arabia areas, the Ministry of the Environment accepted a procedure in which the contaminated soil can be examined, its reparation planned and the necessary permits for the measures can be applied for by areas according to the progress of the construction work. There was thus plenty of time for planning the reparation of Kyläsaari. TEKES was conducting an environmental geo-technical programme relating to the reparation of soil, when Helsinki City and TEKES planned a technology competition to benefit different partners. The aim of the competition was to find solutions suitable for the reparation of the Kyläsaari area.

1. On the circumstances in the area

The geo-technical circumstances on the area are difficult; e.g. double embankment structures have been constructed along the shore and various foundation structure solutions have been tried in the Arabia/Toukola area.

For example dioxine and furan compounds have been found in the area. The highest concentrations are 160 ng/kg I-TEQ-ekv, and in the competition area the average concentrations are c. 40 ng/kg. Differing concentrations of PCB as well as lead, copper and zinc have been found, and according to the effect assessments, the presence of lead is the most significant potential health and environmental hazard. The preliminary risk assessment required a clean cover of at least 1 m, but the final need for reparation has not be determined.

2. Goals

The goal of the technology competition was to find as useful a method as possible for the reparation of the Kyläsaari area. In addition, the competition was looking for reparation methods that would apply new or present solutions and which could be implemented in an internationally competitive way.

One of the goals was also to involve the best domestic and possibly foreign actors to apply different techniques in solving the problem of the target in question. The aim was also to form and utilise a business operations chain, linking the parts of the project in a way required by international competition.

The areas of the technology competition were as follows:

- drafting of reparation plans for pre-determined Kyläsaari areas and their implementation
- the innovative nature of the plans and implementation solutions
- the technological expertise indicated by the solutions
- the economic efficiency of the solutions
- environmental improvements afforded by the solutions (e.g. environmental and health effects as well as risks)
- the integration of the implementation and planning to the other construction in the area with maximum mutual efficiency.

The technology competition for the renovation of the Kyläsaari was the first of its kind in Finland.

The preliminary competition schedule was as follows:

- Proposals to the Board 1 September 1997 (realised)
- Evaluation by the Board and decision on proposals selected for trial reparation 1 December 1997 (decision given in December 1997)
- Trial reparation in summer 1998 (realised in summer/autumn 1999)
- Decision of the competition by 27 February 1999 (postponed by one year)

3. Commissioners, competitors, competition board

The competition was commissioned by Helsinki City and the Technology Development Centre Tekes. As competitors the public press announcement invited *”domestic and foreign undertakings in the field with their own proposals ”*.

The Competition Board was composed of versatile experts. The tasks of the Competition Board where:

- Decision-making relating to the competition, responsibility for arrangements
- attending to secrecy obligations
- evaluation of the proposals and trial reparation
- publication of the results.

The arrangement of the trial reparation with the candidates chosen for trial reparation as lump-sum projects was the responsibility of the Helsinki City Building Office.

4. Competition procedure

4.1 Competition proposals

An open call for tenders was used to invite proposals of a project type. The proposals related to a pre-determined area of c. 250 m^2, but the proposal also had to include a cost estimate for the reparation of all of Kyläsaari.

The material concerning the target distributed to the competitors contained 11 different studies and reports. To implement the proposals, the competitors were to be prepared themselves to apply for the necessary environmental permits (trial permit).

The proposals were to be submitted anonymously and they had to include a sealed envelope containing information on the draftsman or draftsmen of the proposal. The Competition Board evaluated the proposals anonymously and the envelopes containing the names were not opened until after the results had been evaluated and the decision had been made.

4.2 Trial reparation

In advance a decision had been made to select 2–4 proposals from among those received for the trial reparation. The trial reparation area selected was a deliniated part of Kyläsaari, in which supplementary studies were made. The area selected proved to be ”cleaner” than expected and the actual ash/slag fill was under a clean layer of soil. The ground water restricted the reparation in the vertical direction.

For some time, the area had been a quarry storage and it was emptied before the preparatory work of the competitors relating to the trial reparation.

5. Comparison procedure of competition proposals and trial reparations

5.1 Two-stage handling

The participants of the trial reparation stage of the competition were selected from among nine competition proposals. At this preliminary selection stage, the competition proposals were not ranked in order. At the second stage of the technology competition, the results of the trial measures of the enterprises that had repaired the trial areas were implemented and estimated. After the evaluation, the trial reparation alternatives were compared and, on the basis of the results of the comparison, the winner of the competition was selected. The preliminary selection stage and the selection of the winner of the trial reparation were implemented by using a method aiding multicriteria decision-making.

5.2 The selection of the trial reparation options

Altogether 9 competition proposals were received. The evaluation of the proposals was conducted using the preliminary evaluation criteria presented in the competition programme. The Competition Board decided to use a multicriteria comparison method, which was implemented in the form of delphi rounds with regard to the selection of the final comparison criteria and in the form of a one-day final seminar with regard to the comparison of the options and decision-making.

The Board determined the comparison criteria further by using he so-called delphi technology (two rounds). The criteria selected to measure the different aspects were: the environment, innovative nature, project management, credibility and costs. The Board determined the implementation of the comparison criteria for all the options so that the implementation value given was the median value (at least 75% of the members shared the opinion) and, in the case of costs, the value or range obtained from the options.

The alternatives were handled with numbers without names. At first the members of the Board ranked the alternatives only in the light of their own preferences, at which stage only two members out of eight obtained the same order. This ”voice-vote method” would have chosen alternatives 2, 5 and 6.

After this the Board ranked the alternatives by the criteria and the criteria were weighted with three different methods on the basis of a questionnaire presented to the Board (direct weighting, AHP, direct replacement relations), which were mutually compared in order to obtain a viable result (no significant discrepancies, also deviations taken into consideration).

Also acceptability indices were determined by calculation and the ranges of the values given were taken into consideration.

The alternatives were ranked in accordance with the weighted values both on the assumption that the criteria values were exact and by taking into account the uncertainties for each member of the Board and in combination. The result was a unanimous decision on the competition alternatives selected, and the decision was based on a documented rational procedure using methods aiding decision-making.

The most important selection criteria were innovative nature, the environment and costs.

5.3 The evaluation and comparison of the trial restoration alternatives

The Helsinki City Building Office HKR concluded project agreements on the trial restoration with the draftsmen of the proposals selected on the basis of a further round of tenders. The candidates were paid the project contract prices for the trial restoration, and these prices were used as the basis for calculating the costs of the trial restoration. Each competitor applied for a trial permit from the Helsinki City Environmental Office YMK. Each of the competitors was given a competition area from Kyläsaari by drawing lots. The competitors were given competition instructions on the trial restoration containing the criteria to be used in the selection of the winner of the competition.

The trial restoration had to be implemented during a period indicated by the Competition Board and within the framework of the work programme presented by the competitor. The Board supervised the trial restoration by visits to the sites and by an evaluation of the interim reports submitted. A representative of the permit authority was also a member of the Competition Board.

In the evaluation of the trial restoration of the competition areas the following aspects were taken into consideration: the costs of the trial restoration method, a decrease in the amount of environmental hazards, project management and possibility to integrate with preliminary construction. For each aspect, the evaluation was implemented in accordance with the principles presented below. The final selection was also affected by the way in which the effects were weighted. The weighting took place in the way decided by the Competition Board. The way the weightings were taken into consideration is described below.

Each trial restoration alternative was evaluated with regard to effects agreed upon in advance. The valuation criteria of the competition proposals were:

- Costs
  - cost effectiveness
  - FIM/h, FIM/level of cleansing
  - FIM/amount of hazardous substances removed
  - cost estimate for cleansing the whole area
- The environment *and health*
  - amount of hazardous substances removed completely, Pb
  - change in the dissolution of hazardous substances before/after
  - health hazards, decrease of risks
  - permanence of dissolution and results
  - effects during the work
- Project management:
  - schedules
  - permit application process
  - activities during the work
  - quality control
  - sampling management
- Technical feasibility and operational certainty
  - applicability of the method
  - implementation period
  - operational certainty
- Ability to integrate to preliminary construction
  - ability to integrate
  - usability of the masses.

Each alternative was evaluated for the above criteria. By criteria, the evaluation proceeded in accordance with the following principles:

1. First a qualitative description of the amount of the effect (if ratio information could be given, the intermediate steps were omitted).

2. After that the qualitative information was made ordinal. On the basis of the qualitative description, the alternatives could be ranked in order of preference.
3. After that the distance between the ordinal numbers was determined. In practice it was estimated whether the difference between the best and the second best was equal to that between the second worst and the worst alternative. If this was not the case, the differences were described. These differences can be taken into account in later analyses.
4. After this the ordinal information was placed on an interval scale, where possible.
5. Ratio information was used whenever possible. Here, as well as in other information, the uncertainty was described, which can be taken into account in the comparison analyses.

5.4 Comparison method of the trial restoration alternatives

The alternatives were compared for all the criteria both separately and simultaneously using the information that, by criteria, could be described most reliably and which best described the effect and size of each criterion. The results can thus range from qualitative information to ratio information.

The comparison proceeded as follows:

1. The alternatives were compared for each criterion.
2. It was examined wherther, for some criterion, an alternative was so poor that the alternative could be excluded.
3. A dominance analysis was performed taking into account criterion-specific uncertainties and analysing whether an alternative alone dominated over the others. If an alternative dominated, it is alone the best with regard to all the effects examined. If an alternative is dominated, it is not alone the best with regard to any effect.
4. An SMAA analysis was performed to rank the alternatives in order with regard to different valuations; the valuations resulting in the selection of each alternative were described as well as the share of all the information (valuations and amount of the effects) that support the selection of the alternative being studied.
5. The criteria were ranked in an ordinal order on the basis of a pair comparison conducted by the Board.
6. A new SMAA analysis was performed taking into account the preference order of the criteria; the result obtained is the preference order of the alternatives.
7. Specification of the significance information by requesting as exact weightings as possible; an exact order of preference was obtained.

6. The comparison results of the trial restoration alternatives

6.1 Criterion-specific results by alternatives

The members of the Competition Board met for a comparison seminar. Before the seminar, the members had been distributed an expert summary of the evaluation of the trial restoration drafted by the secretary of the Board.

At the beginning of the comparison seminar, the results obtained were examined criterion by criterion. The aim was for each member of the Board to understand the criterion-specific results and especially the amount of change effected by the criterion in question from the poorest estimate or measurement result presented to the best estimate or measurement result presented.

An examination of the results gave a result complying with Table 1.

Table 1. The final evaluation results adopted by the Competition Board by alternatives.

Criteria 1,2,3,4,16,19 = **ration information**
Criteria 5,6,7,8,9,13,14.17,18: = **ordinal rank; 1 = the best**
Criteria 10,11,12,15 = **interval scale 1–5, average of grades given**

No	CRITERION	ALTERNATIVE I	ALTERNATIVE II	ALTERNATIVE III
	Costs			
1	Cost effectiveness FIM/m^2	2480	1120	5037
2	FIM/ton handled	2214	1105	2107
	FIM/hazardous material removed	criterion removed		
3	Cost estimate for restoring the whole area	300	300–350	750–780
	The environment and health			
4	Amount of hazardous substances removed completely Pb	40%	0%	88%
5	Dissolution of hazardous substances before/after	3	1	(2)1
6	Health risks, decrease in risks	3	1	(2)1
7	Permanence of solution and result	3	1	2 (1)
8	Effects during work	3	1	2
	Project management			
9	Schedules/delay	3	1	2
10	Quality of reports	1	1	1
11	Permit application process	3	2	1
12	Activity during the work	3	1	2
13	Quality control	1	1	3
14	Sampling management	1	2	1
	Technical feasibility and operative certainty			
15	Applicability of the method	2,2	4,4	2
16	Implementation period	17 weeks	4 weeks	20 weeks
17	Operative certainty	2	1	2
	Ability to integrate to preliminary construction			
18	Ability to integrate	2	1	3
19	Usability of the masses	60–70%	c. 100%	90–93%

6.2 Dominance analysis

Dominance analysis gives an opportunity to examine whether an alternative is one that it could not be chosen on the basis of information already presented. Table 1 shows that alternative I is the best when using criteria 3 (cost estimate for the whole area), 10 (quality of reports), and 13 (quality control). However, it is not the only best one under any one criterion, as with the same criteria, some other alternative is at least equally good and, under some other criteria, better than alternative I.

On this basis, alternative I is dominated, and, on the basis of the information now presented, it should not be chosen as the best alternative. The choice of alternative I is possible only in the light of additional information in favour of its selection.

6.3 The SMAA analysis

6.3.1 Description of the method

This work used the SMAA-O method. The method is based on a stochastic multiobjective acceptability analysis. The SMAA (**S**tochastic **M**ultiobjective **A**cceptability **A**nalysis) is a method supporting group decision-making, which clarifies different evaluations by simulating how extensively and with what weightings each alternative can be considered better than the others. The SMAA is especially suited for situations in which the criteria are uncertain or inaccurate and there is no knowledge of the weighting of the decision-makers or this knowledge is inaccurate.

The SMAA –O is a version developed from the original SMAA, and it allows the simultaneous handling of ordinal data, interval data and ratio data.

The SMAA-O is an inverse method, in which the evaluations of the decision-makers are assumed to be unknown or only partly known. It is also able to process ordinal criteria values in addition to cardinal values. The basic idea of the SMAA methods is simulation taking place in a weight coefficient space, establishing the relative share of he weight coefficients favouring each alternative by using hundreds of thousands of random weight coefficient vectors. This can be done using the whole weight coefficient space or a restricted part thereof if the decision-makers want to restrict it. Usually the preference of the alternatives is presented by in terms of a utility function, which gives the alternatives values ranging from 0 – 1 so that 0 is the worst. The utility function is thus dependent not only on the criteria values of the alternatives but also on the weight coefficients set on the different criteria aimed at describing the values of the decision-makers. The utility function of the SMAA methods can, in principle, be anything, but because it is in practice impossible to explain the form of a utility function to a group of decision-makers, an additive utility function is most commonly used. The partial utility functions used often include linear variations obtained by scaling each criterion from worst to best on a scale of 0 – 1. The criteria values need not be accurate; inaccurate/uncertain criteria values are presented as stochastic variables.

The indices obtained the SMAA methods are the following:

- *Acceptability index*; what part of all the weight coefficients favours the choice of the alternative in question (or what part favours the alternative to each position in the rank order)
- *Central weight vector*; describes the most typical weightings favouring a certain alternative
- *certainty coefficient*; describes the uncertainty and inaccuracy of the model. It is the probability that the alternative examined actually is the best if the central weight vector is used.

Compared to the earlier SMAA methods, the SMAA – O method adds the possibility to process ordinal criteria data. The idea is to examine all descriptions between the ordinal and cardinal scales that yield the given ordinal rank order. Thus, in addition to simulating known ordinal values, a large number, hundreds of thousands of corresponding random cardinal values are simulated, in order to obtain the indices of the SMAA –methods when the criteria are ordinal.

6.3.2 The SMAA analysis without a preference information on the criteria

At first the comparison analysis of the trial reparation proposals was conducted without any preference information of the criteria. Before this those criteria were removed that were not significant in the analysis. These were the criteria, with regard to which both alternatives II and III had been evaluated equally good. The SMAA analysis used the criteria indicated in Table 2.

The reader should pay attention to the differences in the numbering and names of the criteria between Tables 1 and 2.

Table 2. Criteria included in the SMAA analysis and criteria realisations.

Criteria 1,2,3,4,11,15 **= ration information**
Criteria 5,6,9,10,1314 **= ordinal rank; 1 = the best**
Criteria 7,8,11 **= interval scale 1–5, average of grades given**

No	CRITERION	ALTERNATIVE I	ALTERNATIVE II	ALTERNATIVE III
	Costs			
1	**Cost effectiveness, FIM/m^2**	**2480**	**1120**	**5037**
2	**FIM/ton handled**	**2214**	**1105**	**2107**
3	**Cost estimate for restoring the whole area**	**300**	**300–350**	**750–780**
	Environment and health			
4	**Amount of hazardous substances removed completely Pb**	**40%**	**0%**	**88%**
5	**Effects during work**	**3**	**1**	**2**
	Project management			
6	**Schedules/delay**	**3**	**1**	**2**
7	**Permit application process**	**3**	**2**	**1**
8	**Activity during the work**	**3**	**1**	**2**
9	**Quality control**	**1**	**1**	**3**
10	**Sampling management**	**1**	**2**	**1**
	Technical feasibility and operative certainty			
11	**Applicability of the method**	**2,2**	**4,4**	**2**
12	**Implementation period**	**17 weeks**	**4 weeks**	**20 weeks**
13	**Operative certainty**	**2**	**1**	**2**
	Ability to integrate to preliminary construction			
14	**Ability to integrate**	**2**	**1**	**3**
15	**Usability of the masses**	**60–70%**	**n. 100%**	**90–93%**

The results of the SMAA analysis are presented in Table 3 and in Figure 1. The table and figure show the acceptability indices, which indicate, as percentage points, the share of all possible evaluations and criteria realisations favouring the alternative for a certain rank. The table and figure show that 98% of all the information used favour alternative II for rank 1. The choice of alternative III for rank 1 is favoured by 2% and, as noted earlier on the basis of the results of the dominance analysis, 0% favour the choice of alternative I for rank 1. The same result is seen in Figure 1.

The acceptability indices favouring other ranks can be seen in the table and in the figure. The purpose of this research was to choose the winner of the technology competition, and so the other ranks are not interesting from that point-of-view.

Table 3. Acceptability indices of the alternatives for rank1..rank3.

Alternative	**Acceptability indices without preference information**		
	rank 1	Rank 2	rank 3
I	0%	34%	66%
II	98%	2%	0%
III	2%	65%	33%

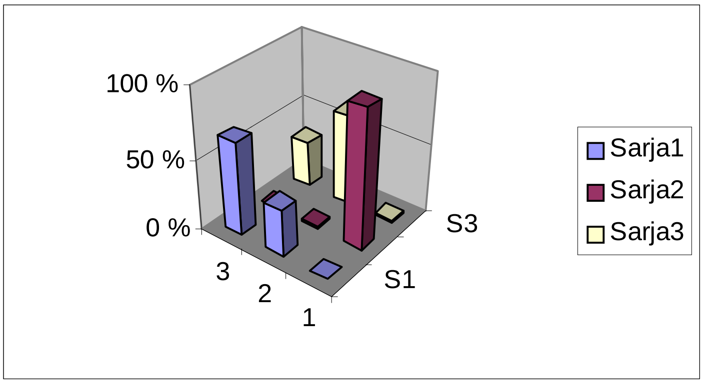

Figure 1. Acceptability indices of alternatives I, II, and III for ranks 1, 2 and 3.

6.3.3 The SMAA analysis using the preference information of the criteria

The Competition Board still had to place the criteria examined in an order of preference. The order was decided by applying a wall technique of a think-tank type. Two of the criteria were placed against each other considering which criteria value the group would first like to move from the worst to the best. The question is the same as which of the criteria is the more important. The question was asked in this way because evaluations are always tied to a time and place and because preference always has to be examined taking into account the changes that it will cause in each case. By examining the criteria against each other in this way, the result was the order of preference presented in Table 4. The Competition Board was unanimous on the order.

Table 4. Order of preference of the criteria as determined by the Competition Board.

Order	Criteria
1 The most important	**2** (FIM/ton handled), **4** (Total hazardous substances removed)
2 The second important	**11** (Applicability), **3** (Preparation costs for the whole area), **1** (Cost effectiveness FIM/sq.m.), **12** (Implementation period), **13** (Operational certainty)
3 The third important	**8** (Activity during the work), **6** (Schedule), **9** (Quality control), **10** (Sampling management), **5** (Effects during work)
4 The fourth important	**14** (Ability to integrate), **15** (Usability of the masses)
5 The fifth important	**7** (Permit application process)

Table 5 shows the results of the SMAA analysis when the preference order of the criteria set by the Competition Board was taken into consideration. Only alternative II rises to rank 1. In practice, taking into account the preference of the criteria, all the information favours the selection of alternative II as the winner of the competition. This makes it unnecessary e.g. to analyse the evaluations in more detail with regard to individual criteria, as the rank order gives sufficient information.

Table 5. The acceptability indices of the alternatives for rank1...rank3.

Alternative	**Acceptability indices with preference information**		
	rank 1	rank 2	rank 3
I	0%	54%	46%
II	100%	0%	0%
III	0%	46%	54%

7. Selection of the alternative

On the basis of the results of obtained, the Competition Board decided that the winner of the competition is competition alternative area II (HY:n Kehityspalvelut Oy [Development Services of Helsinki University Ltd], Innogeo Oy, Lemminkäinen Oy, Rejlers Oy and Tampere University of Technology TTKK).

Landfill settlement extrapolation using geostatistics

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ABSTRACT: In the early 90's a landfill for contaminated soil was established in the outskirts of Rotterdam. The disposal site has a final storage capacity of 2400000 m^3.
The calculated final settlements are 4 m on average, due to adding the weight of the disposal onto a total thickness of 17.5 m compressible clay and peat layers. As there is no vertical drainage system in the compressible layers, only 50% of the final settlements have occurred to this moment. Filling the disposal site has been taking place gradually, from '92 till now and the site will eventually close in June 2001.

The contaminated soil is required to stay 0.7 m above the highest groundwater level, which makes settlement monitoring an important issue. During the exploitation period, settlement monitoring has been taking place. The results, combined with the design data, are being used to adjust the filling strategy. Using geostatistics, the settlement data are interpreted, making it possible to attach a reliability to settlement expectancy.
A similar measuring and interpretation set-up could be defined for projects that extend over large areas in which a long term process needs an accurate prediction.

1. Introduction

In the 60's the need for harbour-sludge disposal increased. One site which was used for the disposal of harbour sludge was a polder situated in the north of Rotterdam. In twenty years of sludge disposal, the total thickness of the sludge became about 8 meters. Together with the already present clay and peat layers of the Holocene sediment, this made up a 15 to 20 m thick sequence of hardly permeable compressible layers.

Towards the end of the 80's the need for storage of contaminated soil increased. Plans were made to utilise a part of the old sludge landfill for the permanent disposal of contaminated soil.

In 1992 the first sections of the permanent disposal site were utilised for the acceptance of contaminated soil. Since 1995, landfilling occurs according to the 'Stortbesluit' law. This law prescribes various measures which should prevent the spread of the contaminants to the surrounding area.

The intended surface area of the site is approximately 40 hectare, meaning an average 6 m landfill thickness.

Capping the disposal site will start in 2001. The same legislation that prescribes the measures to restrict the spread of contaminants also defines the minimum criteria that should be met by the capping structure.

After capping the disposal site, the provincial authorities will be responsible for the after-care. To make this possible, the former owner of the site has to deposit an aftercare into an account managed by the provincial after-care organisation. This amount depends among others on the reliability and the sustainability of the capping construction.

2. Problem definition

As the exploitation period of the disposal site is nearing its end, several uncertainties and unknown factors needed verification or refinement.
The permitted amount of contaminated soil could not be stored without revising the settlement calculations, as the landfill should stay 0.7 m above a defined highest groundwater level.

Due to changes in legislation the aftercare plan had to be revised. The latest settlement predictions incorporating reliability contours were absent and were requested by the authorities.

The design of the capping structure needed an indication of differential settlement to make an economic and efficient (not over engineered) capping structure. At this stage there was only the rather pessimistic guideline of the 'Stortbesluit' regarding differential settlement which also had to be safe enough for municipal waste landfills. In the past no useful indication on differential settlement had been defined for landfills consisting of soil.
Measuring settlements is rather an expensive business. An indication for minimum density of the measurements was needed in order to take these costs into account in the aftercare finances. This information could also be utilised in other projects involving settlements over widespread areas.

3. Solution characteristics

A solution for these problems should:

- make a better settlement prediction
- indicate the spatial dependency of the settlements
- present the reliability of the settlement prediction in a clear and understandable way
- quantify the differential settlements, needed for dimensioning the cover structure

With these tools it must be possible to achieve:

- Optimisation of the permitted disposal capacity
- Reduction of the aftercare costs
- The most economic investment into final capping construction
- Reduce the monitoring costs

4. Description of the procedure

Settlement coefficient

The idea was to utilise the settlement data, which have been collected during the exploitation period, to verify the calculated settlements. Because the site has gradually been filled during the last eight years, this has resulted in a complex settlement behaviour in the area. The gradual increase of load is documented in the surface level monitoring.

The best way to calculate the expected settlement for a monitoring spot, each increase of load in time should have it's own time-settlement curve. The total settlement is the superposition of all time-settlement curves. It appeared to be impractical to perform this for each monitoring point.

Using a series of representative monitoring points, for which the settlement behaviour for each increase of load has been superposed, a general settlement coefficient has been defined. The combined time-settlement curve was compared with the measured settlement. At the latest measurement date, a comparison between observed and calculated settlement can be made. This coefficient is the real settlement coefficient.

The gradual increase of load can be replaced by a sudden complete application of the total load by adjusting the imaginary starting date of the filling sequence. The imaginary starting point was calibrated with the results of the representative monitoring points. It appears to be accurate enough to apply a standard adjustment of the loading time to all the monitoring points. In this way a simplified settlement coefficient has been defined for each monitoring location. This is the basis for all further procedures.

5. Geostatistical approach

The settlement coefficient does vary over the location. This is not strange because the settlement coefficient is partly the result of observations, making it vulnerable for observational extremities. For predicting the expected settlement behaviour of the landfill, we need the expected settlement on each spot, together with a bandwidth. Because the stratification of the subsurface underneath the site is rather consistent, it is justified to assume that the settlement behaviour has a rather good spatial dependence. The spatial dependence of the settlement coefficient has been defined using GeoEAS software. With a modelled spatial dependence, the expected settlement and it's corresponding bandwidth have been defined for each measurement point.

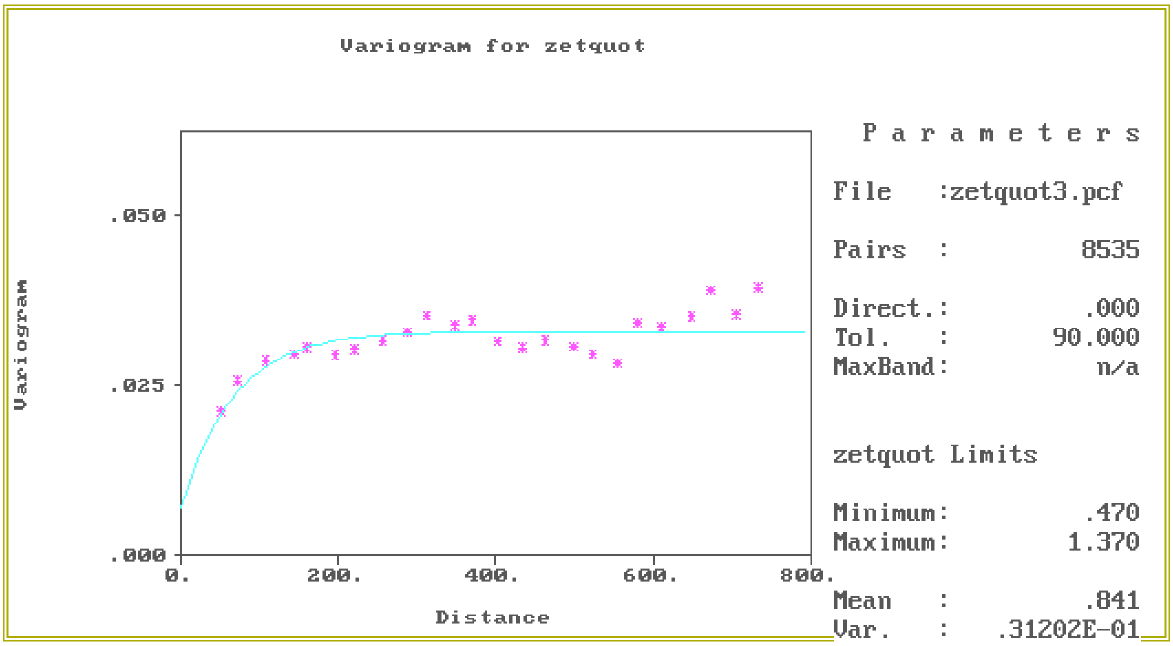

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Figure 1. Semivariogram of settlement coefficient.

6. Results

Settlement coefficient

The geostatistically interpolated settlement coefficient [figure 2] shows the expected settlement behaviour of the site, relative to the calculated settlement behaviour. A coefficient smaller than 1 indicates an area which will settle less than calculated. Likewise, a coefficient greater than 1 indicates an area with a tendency to settle more than calculated.

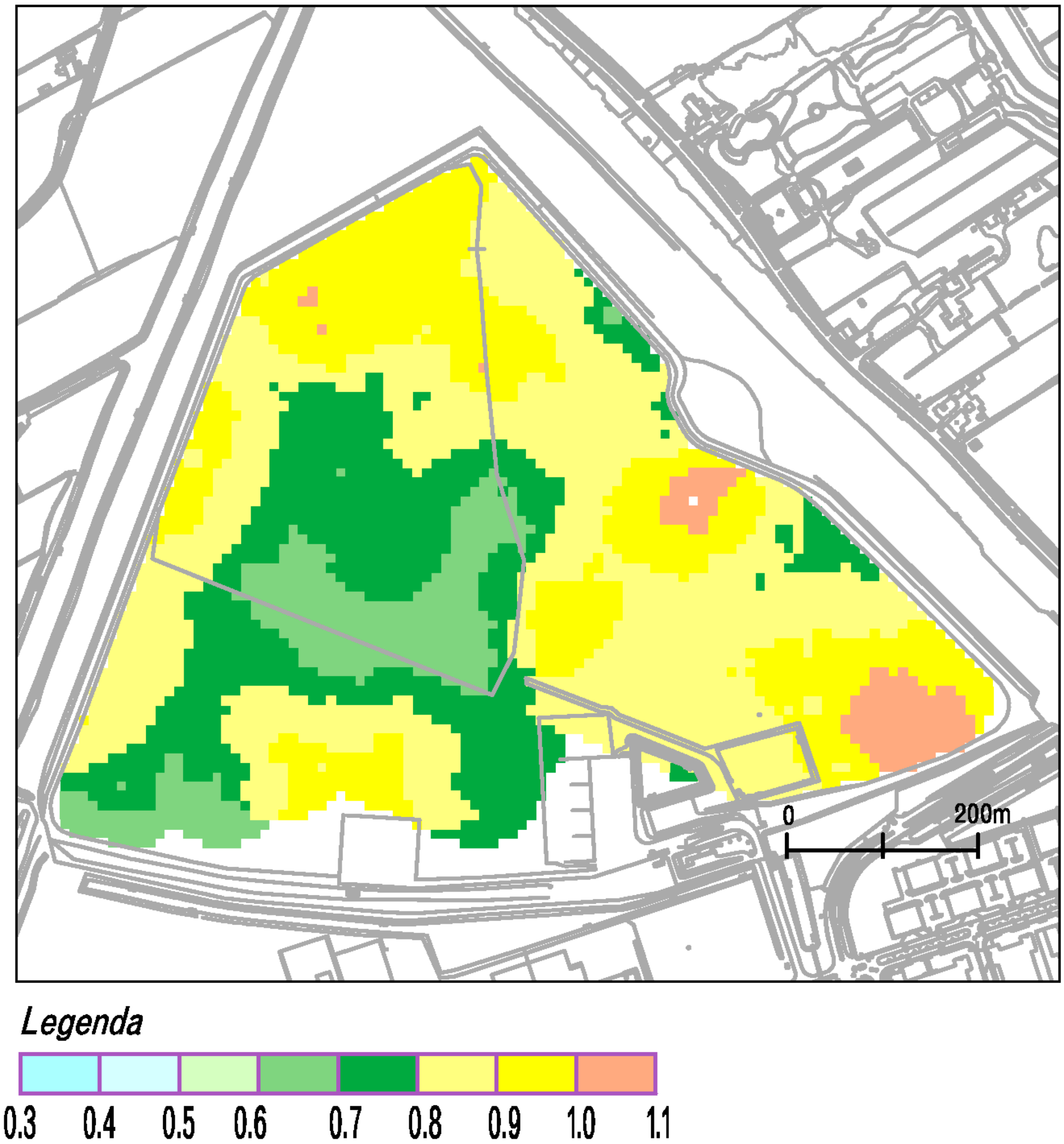

Figure 2. Interpolated settlement coefficient.

Bandwidth reduction

The bandwidth can be interpreted in reliability terms. In this case, we agreed with the authorities a 95% reliability. The bandwidth changes according to the required reliability.

The initial design had a 30% bandwidth for the expected settlement (which is not an unusual value for settlement calculations). By applying the processing of the settlement monitoring data as described, the bandwidth of the settlement prediction could be reduced to about 20%. Together with the adjusted (lower) settlement expectancy, the worst case settlement is much smaller than in the initial design [figure 3].

Figure 3. Indication of bandwidth reduction.

Settlement reduction

As becomes clear in figure 3, the maximum settlement will be less than initially accounted for. The reduction of the maximum settlement (in m) gives a good indication of the residual margin to the groundwater level. An overview of the settlement reduction is given in figure 4.

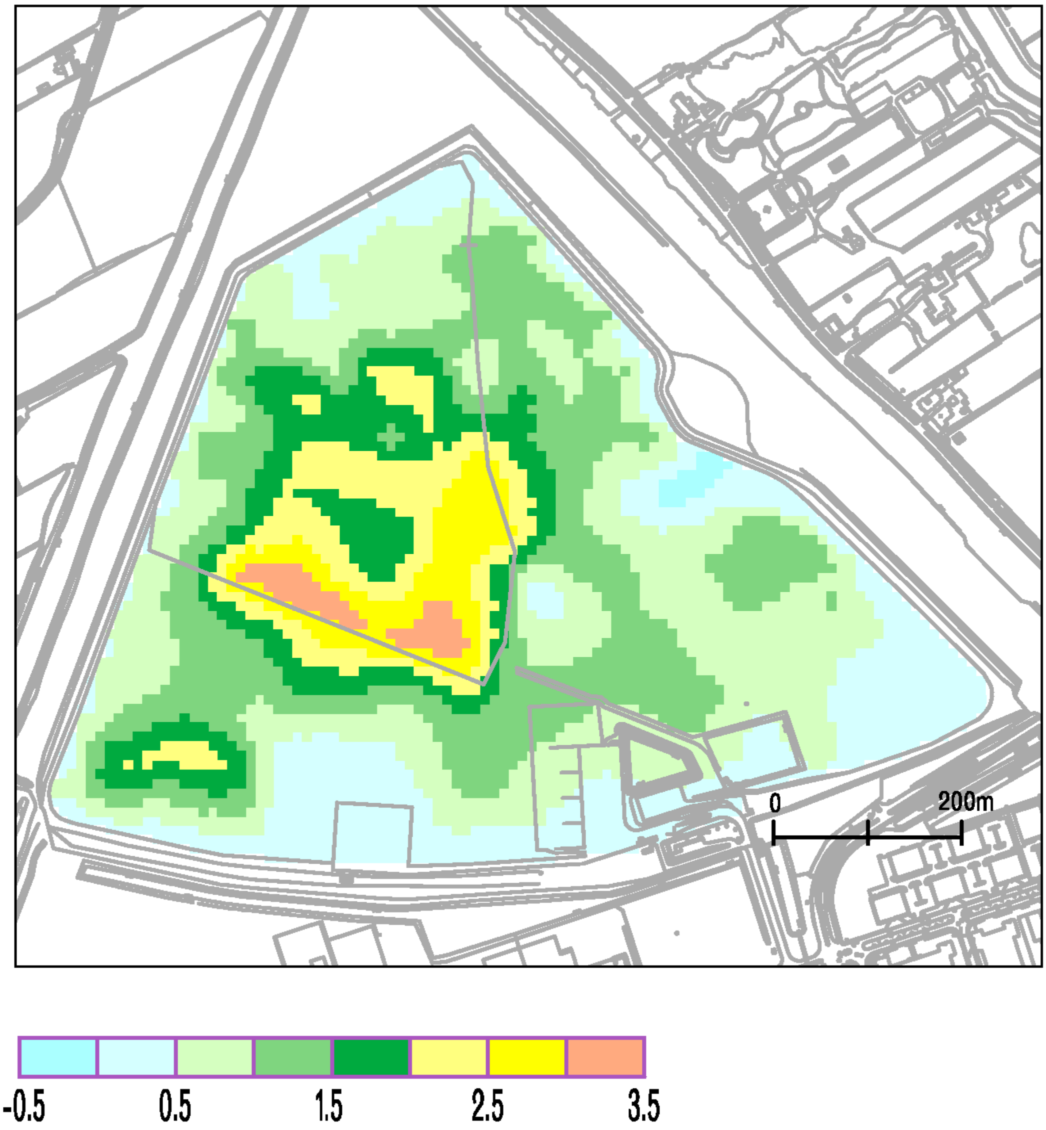

Figure 4. Reduction of maximum settlement in meters.

Additional results

With this method of interpretation it is also possible to present the total safety for groundwater clearance, which gives insight in areas that might need extra attention during the long term maintenance of the landfill.

The authorities have, based on these results, agreed on locally changing the landfill height which makes efficiently utilising the remaining capacity of the landfill possible.

7. Conclusions / Recommendations

Without the intensive monitoring of the settlements, it would not have been possible to define a settlement coefficient or spatial dependence of the settlement behaviour. There would have been no way to indicate the reliability regarding the groundwater clearance.

Geostatistics is very useful in such interpretation problems, because it shows the quality and density of the data and attaches a reliability to the interpretation results.

It became clear that the spatial density of the measurement data was sufficient. The settlement measurements in time could theoretically have been reduced. Reducing the measurement frequency has quite some influence on the monitoring costs. It is however important to start with a dense monitoring set-up and lower the sample rate later on.

When monitoring a similar site, the monitoring density (in space and time) should be reconsidered geostatistically in an earlier stage during the exploitation. The longer the measurements take place on an optimum space and frequency, the better the overall efficiency.

For a next large scale project it is profitable to arrange the monitoring and interpretation program in such a way that the settlement interpretation can be automated extensively.

The revised settlement prediction also proves useful for future use of the location as areas with high residual settlement rates can be avoided for building.

Advanced oxidation of PCDD/Fs, PCBs and PAHs in contaminated soil/ash matrix

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ABSTRACT: Two different innovative remediation techniques were compared for the treatment of cross-contaminated incinerator ash, which contained polychlorinated dibenzodioxins and furans (PCDD/Fs), and polychlorinated biphenyls (PCBs). The goal of the treatment program was to achieve the proposed Finnish guideline levels for both compounds (PCDD/Fs, 20 ng/kg and PCBs, 50 µg/kg). The amount of oxidants needed and the total treatment costs were estimated.

Ozonation in alkaline conditions and Fenton treatment were selected in laboratory-scale experiments. When the initial PCDD/Fs concentration was 240 ng/kg measured in International toxicity equivalents (I-TEQ) and PCB concentration was 395 µg/kg, ozonation removed 50 percent of the PCDD/Fs and 40 percent of the PCBs. The Fenton treatment removed 36 percent of the PCDD/Fs and 6 percent of the PCBs. Even though the proposed Finnish target levels were not reached in this experiments, ozonation under alkaline conditions appear to offer a viable alternative for the treatment non-biodegradable compounds in the soil matrix.

1. Introduction

A variety of organic compounds are refractory, toxic or inhibitory in nature. They can not be treated by conventional biological treatment methods. The existing method for the treatment of hazardous substances such as polychlorinated dibenzodioxins and furans (PCDD/Fs) and polychlorinated biphenyls (PCBs) has been excavation and off-site treatment by incineration or encapsulation (LaGrega et al. 1994). Some innovative treatment methods including advanced oxidation techniques (AOTs) have been studied recently for the decomposition of such refractory compounds with promising results (Watts et al. 1991). Removal efficiencies higher than 90% for PCDD/Fs have been achieved laboratory scale experiments when dioxin-spiked or soil-free samples are used (Isosaari et al 1997, Watts et al. 1991)

Advanced oxidation techniques are ambient temperature processes for treatment of contaminants, which involve the generation of highly reactive intermediates, usually hydroxyl radicals (Glaze et al. 1987). Hydroxyl radicals react with most organic compounds with rate constants of 10^7 to 10^{10} $M^{-1}s^{-1}$. (Buxton et al.1988). The list of various AOP techniques is presented in Table 1. Some of these AOT combinations are suitable for the in-situ or on-site treatment of contaminants in soils.

Table 1. Advanced oxidation techiques.

Ozone	UV	
Ozone	alkaline pH	
Ozone	Hydrogen peroxide	
UV	Hydrogen prroxide	
UV-vis	TiO_2	
Fe^{2+}	Hydrogen peroxide	Fenton's reagent
e- beam		

2. Materials and methods

Soil matrix studied

The aim of this project was to investigate innovative chemical oxidation techniques for the risk reduction of a PCDD/F, and PCB- contaminated site. The ash/soil material originated from old landfill site containing bottom ash from a waste incineration plant. The soil/ash matrix contained about 9–12% organic material, and high concentrations of metals including iron, lead and zinc. The pH of the material was slightly more than 8.

The concentration of PCDD/Fs varied between 200–300 ng/kg I-TEQ. The PCB-concentration was 310–480 µg/kg in the research area. Chemical analyses were conducted by the National Public Health Institute, Kuopio, Finland. The proposed limit values for PCDD/F and PCBs are 500 ng/kg (I-TEQ) and 500 µg/kg of dry weight, respectively. The target values for PCDD/Fs and PCBs are 20 ng/kg and 50 µg/kg (Assmuth 1997). The contamination of these compounds in the sampling area was between these two guideline values.

Chemical analyses

The samples were treated with 1 M HCl and dried and then extracted in an ultrasound bath in toluene, which was then replaced by hexane. The samples were purified in silica, activated carbon and aluminumoxide columns. PCDD/F standards used contained sixteen PCDD/F congeners, which were ^{13}C labeled. PCDD/F congeners were analyzed by a Hewlett-Packard 6890 gas chromatograph equipped with high resolution mass selective detector (VG 70-250SE) which was operated on a single ion recording (SIM) mode. The separation column was J&W Scientific DBDXN. The method used in the National Public Health Institute has been accredited. The detection limit for a single PCDD/F congener is 0,5 ng/kg in and for PCB congeners 50 ng/ kg of dry weight.

Treatment techniques

In this study the following AOTs were used: Fenton treatment (Fe^{2+} + H_2O_2 in acidic pH) and ozonation of ash/soil slurry in alkaline pH. Experiments were conducted in laboratory scale.

Fenton treatment

Thirty grams of contaminated material were collected from well-mixed sub-samples taken from the contaminated area. The pH was adjusted to 3 using 4 M H_2SO_2. Since the ash contained 46 g/kg total iron, no addition of $FeSO_4$ was needed. At the desired solution pH, sufficient Fe^{2+} ions should be present. Thirty-four ml of 30% hydrogen peroxide was added in three replicated doses at 2-hour intervals. The amount of reagents selected was based on the experiments reported for pentachlophenol spiked soil (Kwon et al 1999, Watts et al 1990).

Ozonation

Ozonation of ash was conducted in a gas washing bottle. Ozone was generated from pressurized air with a Sander Ozonizer Molel 200. The ozone concentration in the gas stream was measured by potassium iodine method (IOA 001/87). The pH of the sample was adjusted from the initial pH 8.1 to 10 using CaO. The extent of ozonation and the ozone dose required was estimated by using the organic matter content of the sample. Sampling took place when the ozone dose reached the value 0,5 g of ozone to one gram of organic matter in ash.

3. Results and discussion

The initial concentrations of identified congeners are presented in Table 2.

*Table 2**.** The initial PCDD/Fs concentrations and the reduction efficiencies in Fenton treatment (1) and in the ozonation in alkaline conditions (2). The sum of tetra, penta, hexa, and octa forms of dioxins and furans are marked with bold text.*

	Initial ng/kg	1) Fenton red-%	2) Ozone red%
2378 -TCDF	65,0	1,2	66,1
TCDF	**583**	**49,4**	**48,7**
2378- TCDD	13,1	0	44,5
TCDD	**65,3**	**56,2**	**62,6**
12378 -PF	63,6	5,9	39,2
23478 -PF	130	20,0	48,5
PCDF	**679**	**30,8**	**9,1**
12378 -PD	74,5	10,2	30,3
PCDD	**737,5**	**42,8**	**33,7**
123478-HF	87,6	-15,3	29,2
123678-HF	102,5	4,9	42,6
234678-HF	120,0	16,7	49,7
123789-HF	6,9	21,2	48,1
HxCDF	**798,5**	**-4,6**	**28,5**
123478-HD	77	30,0	60,7
123678-HD	266,5	25,9	58,1
123789-HD	288	56,3	77,4
HxCDD	**2715**	**29,7**	**56,9**
1234678-F	504	8,5	50,8
1234789-F	35	21,1	50,9
HpCDF	**715,5**	**8,3**	**49,3**
12345678-D	1248,5	35,7	61,0
HpCDD	**2755**	**46,3**	**66,4**
OCDF	**195**	**46,2**	**71,9**
OCDD	**3855**	**57,5**	**74,3**
Toxic PCDD/Fs	7130	43,5	66,5
Total PCDD/Fs	13050	40,0	58,0
I-TEQ ng/kg	**242,5**	**21,3**	**50,1**
WHO-TEQ	276,5	19,3	47,2

The PCDD/Fs in this material consisted mainly of dioxins. The PCDD/PCDF ratio was 3,4, which is typical to PCDD/Fs formed in combustion processes. The most dominating congeners were octa-, hepta, and hexachorinated dioxin, representing 30, 21 and 20 percent of the total PCDD/Fs, respectively. The most toxic congener, 2,3,4,7,8-TCDD consisted just 0,001 percent of the total PCDD/Fs.

The ozonation in alkaline conditions removed 50 percent of the PCDD/Fs measured as I-TEQ. The disappearance of various congeners varied between 10 and 75 percent being higher for dioxins and for highly chlorinated congeners. Fenton treatment gave less promising results. The removal of PCDD/Fs was just 20 percent measured in I-TEQ. In Figure 1 can bee seen the initial consentration and the concentration of the PCDD/Fs after Fenton's reagen treatment and ozonation under alkalinen conditions.

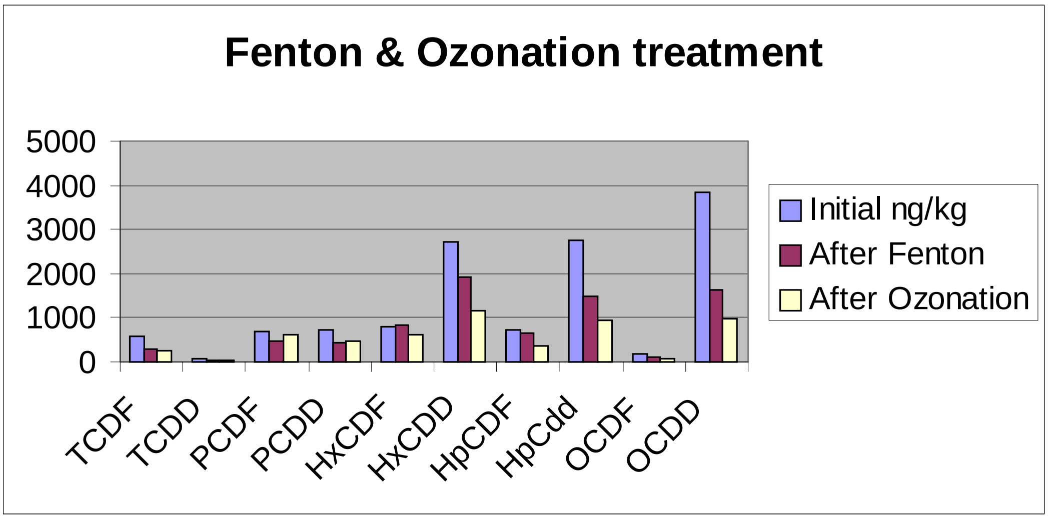

Figure 1. Initial concentrations of PCDD/Fs (ng/kg) and the concentrations after Fenton treatment and ozonation under alcaline conditions.

Table 3. Initial concentration of PCBs and removal efficiencies of Fenton treatment and ozonation in alkaline conditions.

	µg/kg	1) Fenton red %	2) Ozone red %
Total PCBs	395	6,1	36,2

The removal of PCBs was 36 percent using ozonation and 6,1% Fenton treatment. Besides the lower reduction efficiency, the Fenton treatment of this particular sample matrix was problematic. The initial high pH and buffer capacity of the ash caused especially high acid demand in order to drop the pH to the suitable range for the Fenton reaction (pH 2–3). In real-scale remediation projects the treated material should be neutralized which increases the chemical consumption. The acidification step of the treatment train can also mobilize the lead compounds from the ash matrix.

4. Conclusions

There were no data available for the calculation of engineering costs of either Fenton or ozonation treatments. Both of those techniques could be scaled up by using standard equpments and unit operations of soil handling and ozonation. In order to get an idea of the costs of compared to traditional disposal methods of PCDD/F contaminated soil, the costs of oxidizing chemicals were calculated.

The prices of chemicals needed to obtain the purification results were 1000 FIM/ton and 450 FIM/ton for Fenton treatment and ozonation, respectively. The estimated cost for the gaining the proposed Finnish target level is about 800 FIM/ton in this particular case by ozonation. The costs of treatment could be reduced by combining biological post-treatment to the pre-oxidation in a slurry reactor (Lee et al. 1992, Mckinski et al. 1999). The more suitable application of Fenton treatment can be a soil matrix which is acidic initially, have low buffer capacity and have no problem with mobilization of heavy metals. Modifications of the Fenton technique which involve the stabilization of Fe^{2+} by chelating agents (Sun 1993) or addition of solvent (Lee et al 1998) can offer viable alternative for iron and hydrogen based remediation alternatives.

5. Acknowledgements

The support of Helsinki University Development Services Ltd, Environmental Projects is kindly acknowledged. I also than Professor John Pithtel for his kind advises.

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Comparison of the environmental impacts of two remediation technologies used at hydrocarbon contaminated sites

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1. Introduction

Investigation and remediation of contaminated sites has rapidly increased in Finland during the last decade. Public organisations as well as private companies are investigating and remediating their properties, e.g. redevelopment or business transactions. Also numerous active and closed gasoline stations have been investigated and remediated during the last few years.

Usually the contaminated sites are remediated to limit values regardless of the risk caused by contamination. The limit values currently used in Finland for hydrocarbon remediation at residential or ground water areas are 300 mg/kg of total hydrocarbons and 100 mg/kg of volatile hydrocarbons (boiling point < appr. 200 °C). Additionally, compounds such as aromatic hydrocarbons have specific limit values.

Remediation of hydrocarbon contaminated sites is most often carried out by excavating the contaminated soil and taking it to a landfill by lorries. As distances from the sites to landfills are generally rather long, from tens of kilometres to few hundred kilometres, it is evident that this type of remediation has environmental impacts.

Another popular technology used at sites contaminated by volatile hydrocarbons is soil vapour extraction (SVE). SVE is a technique of inducing air flow through unsaturated soils by vapour extraction wells or pipes to remove organic contaminants with an off-gas treatment system.

The purpose of this study was to evaluate some of the environmental impacts caused by remediation of hydrocarbon contaminated soil. Energy consumption and air emissions related remedial activities of the two methods were examined in this study. Remediation of the sites used in this study were carried out by Golder Associates Oy in different parts of Finland in different seasons. Evaluation was made by using life cycle assessment based approach.

2. The scope of the work

The total number of the sites included into this study was eight: excavation was carried out at three sites, soil vapour extraction at four sites and both excavation and soil vapour extraction at one site. Remediation procedures were documented and they included the following steps:

a) Soil Ecavation

- excavation;
- loading of trucks and lorries;
- transportation of contaminated soil to landfill and returning empty to the site;

- treatment of contaminated soil at landfill was left out because enough data was not available;
- gravel intake;
- transportation of clean gravel to the site;
- filling of the excavation;
- vibrating the soil layers.

b) Soil Vapour Extraction

- installing the equipment;
- electricity consumption;
- transportation;
- air emission after treatment and filtering were expected to be zero.

c) Machinery

- working hours per operational unit;
- type and capacity;
- weather conditions.

Things like production of materials and machinery, production and transportation of fuel, laboratory analysis and evaporation of hydrocarbons during excavation were not considered. Also removal of asphalt was left out of the calculation because the emissions were estimated to be low and all of the sites did not have it. Filter regeneration was not considered in this stage of the study either.

The estimation of the hydrocarbon content of the soil at each site was based on the site investigations carried out prior to remediation and to the field and laboratory analysis made during the remediation.

3. Description of the Sites

3.1 Soil Excavation

Site 1: The site was located in the South Finland and it was rather small. The excavation was carried out in late autumn in a week. The total excavated soil mass was 770 tons and the total amount of hydrocarbons removed was 540 kg. The average hydrocarbon content varied between 45 to 370 mg/kg for volatile hydrocarbons and 300 to 1000 mg/kg for total hydrocarbons. Contaminated soil was transported to four landfills located 20, 55 and 110 kilometres of the site.

Site 2: The site was located in the Middle Finland and it was rather large. The excavation was carried out in early autumn within five weeks period. The total excavated soil mass was 2 830 tons. The total amount of hydrocarbons removed was 6 200 kg. The average hydrocarbon content varied between 300 to 9 700 mg/kg for total hydrocarbons and 0 to 2100 mg/kg for volatile hydrocarbons. The landfill was about 30 kilometres of the site. About 5% of the excavated soil was composted.

Site 3: The site was located in the South Finland and it was quite large and contained old contamination. The excavation was carried out in winter within three weeks period. The total excavated soil mass was 1 210 tons and the total amount of hydrocarbons removed was 3 730 kg. The average hydrocarbon content varied between 500 to 46400 mg/kg for total hydrocarbons and 44 to 990 mg/kg for volatile hydrocarbons. The most significant result of the excavation was that volatile hydrocarbons were found about two and half meters in clay. Contaminated soil was transported to three landfills which were located 5, 80 and 190 kilometres of the site. Approximately 10% of the excavated soil was incinerated. The emissions of the incineration were not included in this study.

3.2 Soil Vapour Extraction (SVE)

Site 4: The site was located in the Southwest Finland and it was rather large. The soil vapour extraction was carried out within six months period from early summer to late autumn. The content of volatile hydrocarbons in soil vapour was over 12 000 mg/m^3 before SVE. The SVE was finished when the hydrocarbon content in soil vapour was below 100 mg/m^3, which is the limit value set by the authorites. The total amount of hydrocarbons removed was 350 kg.

Site 5: The site was located in the South Finland and it was rather small. The soil vapour extraction was carried out in two periods. Both periods lasted six months from early summer to late autumn. The content of volatile hydrocarbons in soil vapour was over 24 000 mg/m^3 before SVE and over 170 mg/kg in soil. The SVE was finished when the hydrocarbon content in soil vapour was under 100 mg/m^3. The total amount of hydrocarbons removed was 1 700 kg.

Site 6: The site was located in the East Finland and it was rather large. The soil vapour extraction has been carried out over two years. The hydrocarbon contents before SVE were 17 000 mg/kg for volatile hydrocarbons in soil and about 28 000 mg/m^3 in soil vapour. The SVE has not yet been finished but the hydrocarbon contents are approaching 100 mg/m^3. The total amount of hydrocarbons removed so far is 7 920 kg.

Site 7: The site was located in the South Finland and it was rather small. The soil vapour extraction has been carried out for approximately two years. The hydrocarbon content before SVE was approximately 6 000 mg/m^3 for volatile hydrocarbons in soil vapour and about 350 mg/kg in soil. The SVE has not yet been finished but the latest hydrocarbon contents in soil vapour have been under 100 mg/m^3. The total amount of hydrocarbons removed so far is 2 040 kg.

3.3 Soil excavation and soil vapour extraction

Site 8: The site was located in the Middle Finland and it was rather large. The soil vapour extraction was first carried out within about four months period before the soil excavation because of the high volatile hydrocarbon contents in soil vapour and soil. The hydrocarbon contents before SVE were 11 700 mg/m^3 for volatile hydrocarbons in soil vapour and about over 3 700 mg/kg in soil. The SVE was finished when the hydrocarbon contents were under 100 mg/m^3. The total amount of hydrocarbons removed by SVE was 550 kg. After the SVE was finished the soil excavation was carried out in a week. The total excavated soil mass was 1 050 tons. The total amount of hydrocarbons removed by excavation was 630 kg. The average hydrocarbon content was about 600 mg/kg for total hydrocarbons. The landfill was located approximately 30 kilometres of the site.

4. Results

At the sites where soil was remediated by excavating and taking to a landfill, the main emissions were CO_2 emissions (Figure 1) and NOx emissions (Figure 2) resulting from transportation and soil excavation. Excavating caused also the biggest CO and hydrocarbon emissions.

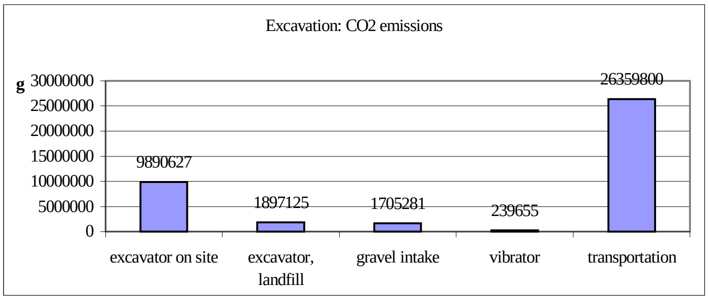

Figure 1. Total CO_2 emissions [g] at the sites 1,2 and 3, where soil was remediated by excavating.

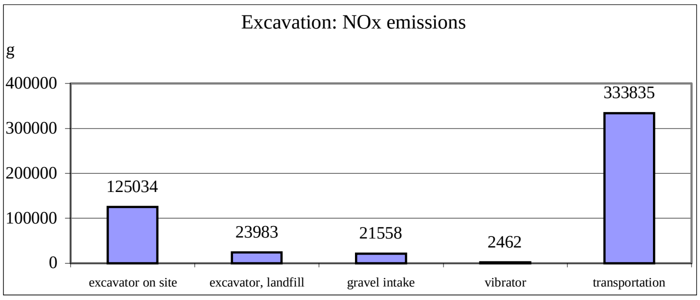

Figure 2. Total NOx emissions [g] at the sites 1,2 and 3.

At the sites where soil vapour extraction was carried out the main emissions were CO_2 emissions resulting from energy consumption. NOx emissions resulted mainly from excavating and electricity consumption. SO_2 emissions were mainly originating from electricity consumption and excavating.

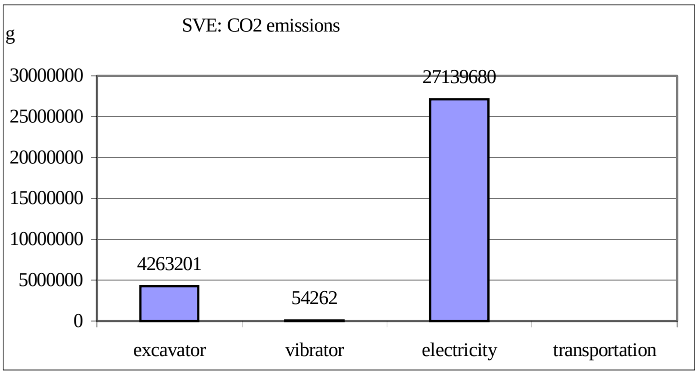

Figure 3. Total CO_2 emissions [g] at the sites 4,5,6 and 7, where soil was remediated by soil vapour extraction.

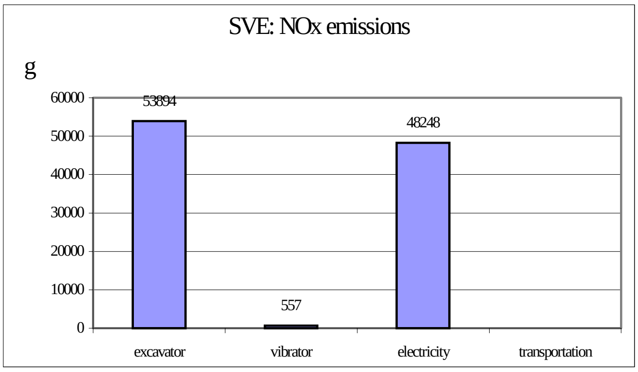

Figure 4. Total NOx emissions [g] at the sites 4,5,6 and 7.

At site 8 where both soil vapour extraction and excavating were carried out, the main emissions were CO_2 emissions the main source being transportation and also excavating was bigger source than electricity generation. The same applies to NOx emissions. Excavating was the main source of CO and hydrocarbon emissions.

The figures obtained from different steps were calculated together and adjusted to the total amounts of hydrocarbons removed at each site. The results are represented in figures 5 – 10 below.

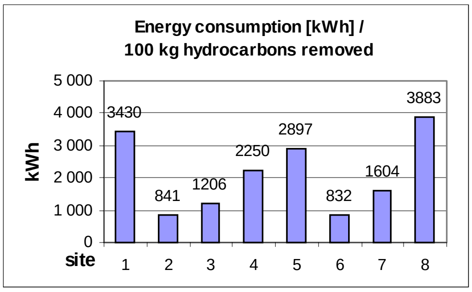

Figure 5. Energy consumption.

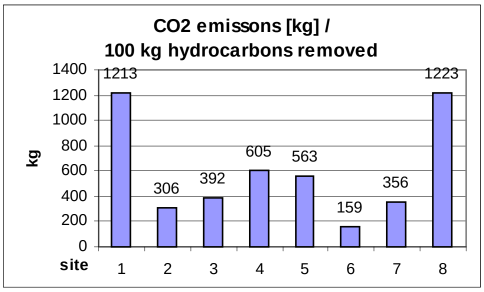

Figure 6. CO_2 emissions.

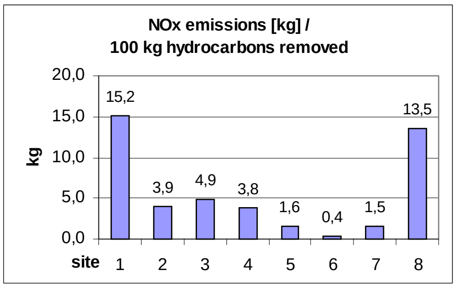

Figure 7. Nox emissions.

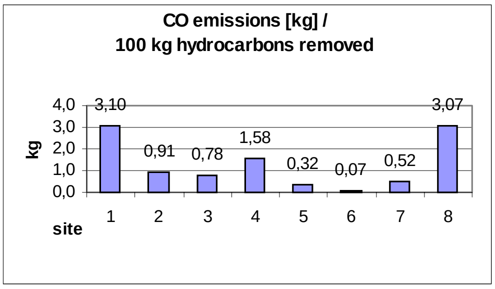

Figure 8. CO emissions.

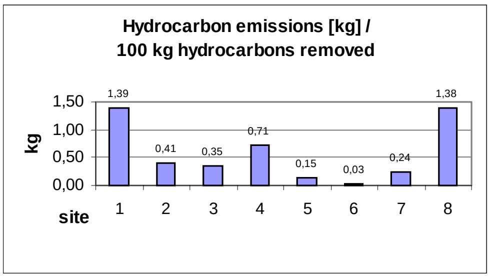

Figure 9. Hydrocarbon emissions.

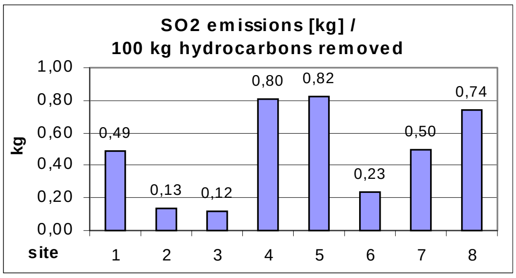

Figure 10. SO_2 emissions.

As expected the CO_2 emissions generating from fuel consumed during transportation and excavating and electricity generation were the most significant emissions at each site. The CO_2 emissions were highest at sites 1 and 8 where they exceeded 1 200 kg / 100 kg of hydrocarbons removed. The CO_2 emission was lowest at site 6 (159 kg/ 100 kg hydrocarbons removed).

Methane emissions were calculated and they were below 0,05 kg / 100 kg for all of the sites. NO_2 and particle emissions were also calculated and they were below 1 kg / 100 kg at each site. These emissions were highest at sites 1 and 2 and lowest at sites 5, 6 and 7.

5. Conclusions

The result of this study was that the two remediation technologies evaluated, excavation plus disposal and soil vapour extraction have similar environmental impacts. Sites with lower concentrations had higher emissions and energy consumption. Significant variation in emissions between sites, mostly related to level of contamination was observed.

Energy consumption was between 1000 to 4000 kWh/100 kg and CO_2 emissions were between 160 to 1200 kg/100 kg. All of the sites were remediated to limit values, regardless of risk caused. If the higher residual concentration in soil would be safe (as demonstrated by a risk assessment), then the air emissions and energy consumption would be reduced.

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Methodology and some results of the multifaceted evaluation of ecological risk of maintenance of oil and gas fields

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ABSTRACT: An inter-disciplinary methodology to investigate pollution from maintenance of oil and gas fields and to explore potential impact of new ones has been developed and tested at three oil and gas fields in Western Siberia and Mid-Volga region with different duration of exploitation. The investigations focused on the impact of oil, its derivatives and other chemicals on human health and biocenoses. The research included combination of methods of environmental geology, geophysics, bioindication, cytogenetics and analytical chemistry and is based on the idea that reliable control of concentration, regularities of sorption and the complete tracing of oil pollution in the environment from the source of contamination through the soils, ground and surface water, soil biota and via the food chains to small mammals and birds are needed to assess ecological risk. It is anticipated that direct determination of oil and its derivatives concentration in soil and ground water can provide a basis to understand the results of bioindication. The obtained data revealed the main regularities of the pollutants migration in soils and ground waters, the most dangerous sources of their contamination and demonstrated the impact of gas torches on soils, vegetation and soil-dwelling animals using new reliable and independent indices.

1. Introduction

An inter-disciplinary methodology to investigate pollution from maintenance of oil and gas fields and to explore potential impact of new ones has been developed and tested at three oil and gas fields in 1998–1999: Luginetzkoe oil/gas condensate field in Tomsk district, Samotlorskoe oil field in Tyumen district (Western Siberia) and Kuleshovskoe oil field in Samara district (Mid-Volga region). The investigations focused on the impact of oil, its derivatives and other chemicals on human health and biocenoses. The research included combination of different methods and is based on the idea that reliable control of concentration, regularities of sorption and the complete tracing of oil pollution in the environment from the source of contamination through the soils, ground and surface water, soil biota and via the food chains to small mammals and birds are needed to assess ecological risk.

Three studied fields have different duration of exploitation: Luginetzkoe is actively exploited only since 1987, but now there are already 480 wells; whereas Kuleshovskoe - since 1960 and the largest in the world Samotlorskoe - since 1965 (it was the first one in Western Siberia). Thus, we have 3 sites differing in natural conditions, methods and duration of active exploitation. The primary sources of pollution are: productive oil and gas wells, casing-head gas burning facilities (“torches”), oil reservoirs, local and main pipelines, pump stations and roads. Field studies included: 1) geo-environmental investigations: shallow drilling, soil and ground water sampling, soil permeability tests, 2) georadiodetective sounding of soils; 3) vegetation and soil biota studies; 4) catching of small rodents for bioindication and cytogenetic analysis. The subsequent laboratory investigations included study of soils mineralogy and properties; determination of concentrations of saturated hydrocarbons, phenols, amines and anions in soils and waters; 3) cytogenetic and model bioindication tests. The obtained data revealed regularities of the pollutants migration in soils and ground waters, the most dangerous sources of their contamination, the impact of gas torches on soils, vegetation and soil-dwelling animals was demonstrated using new reliable and independent indices.

2. Methodology

The research included combination of methods of environmental geology, geophysics, bioindication, cytogenetics and analytical chemistry. The most dangerous toxic compounds in oil/gas fields are polyaromatic hydrocarbons, phenols and amines. Resulting from multiple spills and accidental leakage of oil, light saturated hydrocarbons reach ground water table and spread laterally with water flux to the places of discharge, the heavy fraction is being sorbed on soil minerals. Only the direct determination of oil and its derivatives concentration in soil and ground water can provide a basis to understand the results of bioindication.

Site investigations, sampling of water and soils, determination of their density and moisture content, permeability tests, geophysical studies - georadiodetective sounding (GPR) of soils in the frequency range 25–25000 MHz, express-analysis of the quality of surface and ground waters (Eh, pH, salinity), geobotanical profiling, bioindication studies (capturing and identification of rodents, study of soil mesofauna) were carried out simultaneously. All the obtained information was used to develop the geographic information system (GIS) of the studied fields. This work included: a) study and processing of the available records, b) processing of new data from the numerical cosmic photos, c) positioning of investigation sites by the global positioning system (GPS) Magellan 2000, d) field refinement of the indicative attributes for decoding of cosmic materials, e) input of site positioning data into computer and integration of all the numerical layers into the general GIS.

2.1 Methods of soils and waters investigation

Observation and sampling points were related to the groups of productive oil and gas wells of different age, casing-head gas-burning torches, places of oil spills and leakage. All these points were positioned with the help of GPS. The upper part of soil profile has been studied by means of hand drilling to 7–12 m deep and in prospective pits 2–3 m deep. In cases of surface oil spills the upper part of aeration zone was studied in a pit 2–2,5 m deep. Soil samples were taken from all the drifts. Water probes were taken from the boreholes reached the ground water table, rivers and small creeks, and from all sources of long-term contamination. Additional soil samples were taken along the radii around the gas-burning torches from the depth of 5 and 30 cm. Soil samples were also obtained in the sites of bioindication studies from the depth of 5 cm. The subsequent laboratory tests included study of soils mineralogy, index properties and total carbon content (burning with potassium bichromate). Contamination has been evaluated using 4 most important from the environmental point of view components: total hydrocarbons content (HC), concentration of polycyclic aromatic hydrocarbons (PAH), phenols and anionic surfactants. Routine techniques have been used in this part of the study: anionic surfactants were determined in the form of ionic associate with methylene blue, phenols concentration by reversed phase high performance liquid chromatography (HPLC) with electrochemical and fluorescent detectors and dynamically modified sorbents; hydrocarbons with concentration less than 500 mg per 100 ml or 1 g of soil were detected by thin-layer chromatography using hexane as a mobile phase, and with higher concentration - gravimetrically; PAH were estimated to naphthalene content using the normal phase HPLC.

2.2 Methods of bioindication

Bioindication of the environment pollution was based on the evaluation of the present state of vegetation, soil invertebrates and rodents in the areas with different influence from the oil and gas production facilities and other sources of contamination.

Soil mesofauna was studied in the equivalent biotopes but with different pollution level near the old casing-head gas burning facility surrounded with oil spills. The relative number of different groups of soil invertebrates (segmented worms, earthworms, worms-nematodes, different groups of insects and their larvae, spiders, myriapods, mollusks, etc.) has been estimated according to the routine sampling technique: 16 specimens 0.25x0.25 cm each to the depth of the uninhabited mineral horizon were taken from each site. The number of samples in every series (16) is sufficient to obtain the reliable data. A model test has been also performed on the cultures of Enchytraeus crypticus and Eisenia foetida worms, sensitive to oil contamination and can be easily cultivated in laboratory conditions.

Small rodents were captured in animal traps 10 m from each other put into lines along the natural boundaries of the biotopes. Each line comprised of 25 traps. Some lines were located close to the contamination sources and others - far from such places. Then the weight, length and mass of internal organs of every animal have been determined. The internal organs index is found as a ratio of their mass to the total weight of the animal. The state and morphometry of internal organs including liver, spleen and digestive tract have also been studied. Animals of different species from different biotopes have been investigated. Samples of somatic chromosomes for the study of chromosome aberrations were prepared according to S. Ford and G. Hamerton modified technique from the marrow cells.

3. Contamination of environment

3.1 Patterns of soil contamination

Patterns of soil contamination varies sufficiently in different oil fields depending on: 1) subsurface soil profile, 2) technology of oil extraction (separate wells or groups of production wells, water/gas injection, etc.), 3) the scale of the field and 4) duration of its exploitation. The latter two factors determine, mainly, the overall probability of occurrence of large and sometimes catastrophic oil spills and pipelines failures. However, the influence of persisting industrial load on the environment is well pronounced over several decades.

It should be noted that al studied fields, though located in different regions, have mainly loamy soil profile. For comparatively “young” oil fields (like Luginetskoe) the contamination with different hydrocarbons has been revealed at the sites with the maximum industrial load in soil massifs adjacent to the groups of productive wells and situated along the ground water flux from the latter - to the first (3–4) meters deep. Below the concentrations of all components usually decreased by the order of magnitude. The most fine soils - loams and clays were found to be more contaminated (the maximum concentrations of phenols - up to 0.8–1.3 μg/g, PAH - up to 30 μg/g, HC - up to 10 mg/g, surfactants - 14 μg/g). Besides, all lenses of sands and sandy silts near the wells were, as a rule, were polluted at least 5–6 m deep.. Peats located along the ground water flux tend to accumulate toxicants, especially HC, due to the high water-retaining capacity. Though low barrier properties of poorly decomposed peats with respect to oil and its derivatives should be noted. Soils from the sites with reference conditions either contain practically no organic components under consideration or their concentration is below the maximum permissible level (MPL). It has been obtained that: a) the principal persisting source of soil contamination, especially with phenols and PAH, are drilling slime sumps; b) the duration (first years) of existence of these sumps and other pollution sources is very important; c) the most distinct barrier for oil migration from spills is the contact of sand fills and underlying clay soils.

For “old” oil fields with highly as a whole polluted areas due to not only tremendous amount of productive wells and associated numerous oil spills and accidental leakages but multiple pipelines failures as well, some spatial regularities of hydrocarbons distribution can be distinguished. For example, the pollution of one of the parts of Samotlorskoe field with PAH is very high at the certain points, whereas for all PAH bimodal distribution with distinct right asymmetry has been revealed (Fig.1). However, concentration of different PAH varies dramatically: benzene – from less than 19,2 μg/g (detection threshold) to 72576 μg/g, naphthalene – from less than 0,7 μg/g (detection threshold) to 3066 μg/g, phenanthrene – from <0,05 μg/g (detection threshold) to 19,6 μg/g, anthracene – from <0,05 to 207 μg/g. Approximately 25–35% of all studied samples contained practically no PAH, or their concentration was below detection threshold. No phenantrene was detected in 84% samples, thus meaning that this substance is typical for the spills rather than for the studied area as a whole. For about 50% of all studied samples from the above mentioned territory total HC content was found to be less than 100 mg/g, and they can be considered to be practically unpolluted.

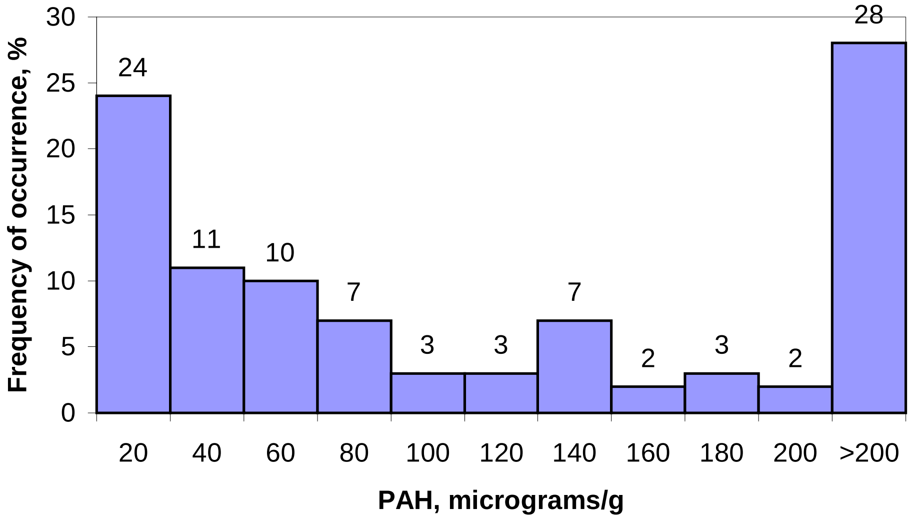

Figure1. Histogram of PAH content in soils of Samotlorskoe field.

The capacity of loams to sorb and fix PAH depends on their molecular weight and as a whole corresponds to the sequence: benzene>naphthalene>anthracene>phenanthrene. It is very important to note, that all studied pollutants tend to concentrate mostly in peats – over 60% of all peat samples contained more than 1000 mg/kg hydrocarbons. Moreover, areas with surface peat layers in soil profile 2–8 m deep were proved to be the most polluted ones, other conditions being almost equal (Figs.2–5). So, peats have high sorption capacity for hydrocarbons as well as for other pollutants typical for oil fields, they are good accumulators of oil contamination, which fact should be used in practice. The increase of molecular weight of PAH results in decrease of its concentration in peats according to the same sequence: benzene>naphthalene>anthracene>phenanthrene. Loams from the mineral bottom below thick peat layers contained almost no pollutants. Phenol appeared to be the most mobile pollutant, capable to migration through any subsurface soil.

Another important fact is the distribution of contamination from the casing-head gas torches. The zone of a pronounced influence of torches on soils for all studied oil/gas fields in different conditions appeared to be confined within the distance equal to 10 heights of the torch itself (300 m for the typical height of the facility 30–35 m). This is the distance, where the stable decrease of pollutants concentration in soils begins. A very informative index of contamination appeared to be the total organic carbon content, reflecting the sedimentation of gas black from the burning gas condensate. Its values varied, for example, from 0.7% for podzolic soil (2.3% for a marshy one) at a depth of 5 cm to 9–10% 300 m from the torch.

3.2 Patterns of water contamination

The major source of surface and, probably, ground waters contamination are slime sumps, puddles around old torches and technological oil spills, altogether forming a technogenic aquiferous horizon in sand fills of productive wells sites. Similar to soils a relationship between the duration of a wells group operation and pollutants concentration in ground waters is observed. In some lakes of heavy polluted areas benzene concentrations exceeded 1500 mg/l (i.e. several thousand times over MPL for fisheries), more than 0,3 mg/l of naphthalene (1200 MPL), over 3,9mg/l of anthracene (10 MPL) and up to 100–300 MPL for phenol. However, these extreme values are located near recent spills and for the major part of such areas the concentration of the above mentioned PAH is very low and sometimes – negligible. Only phenol – due to its high migration capacity – is usually detected in the whole area, and its concentration reveals no obvious relation to the sites of surface pollution.

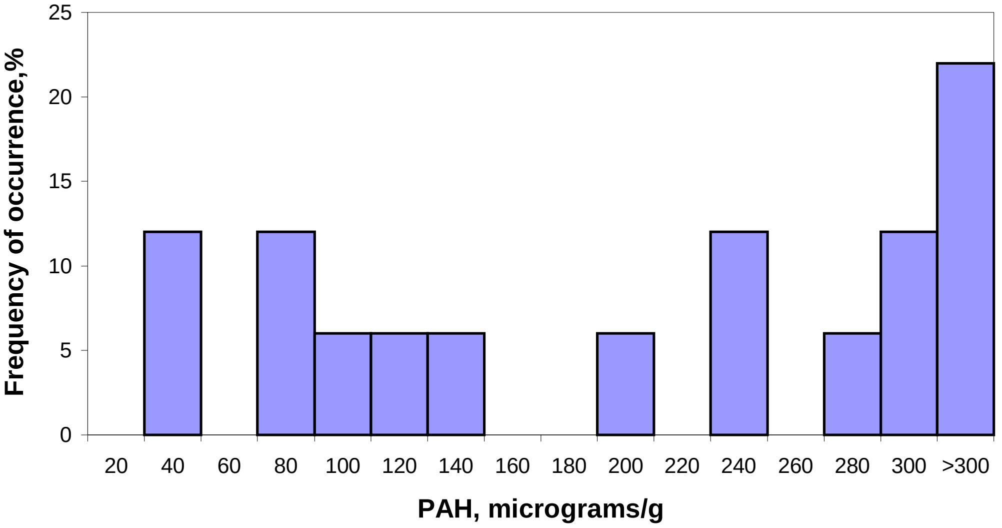

Figure 2. Histogram of PAH content in peats of Samotlorskoe field.

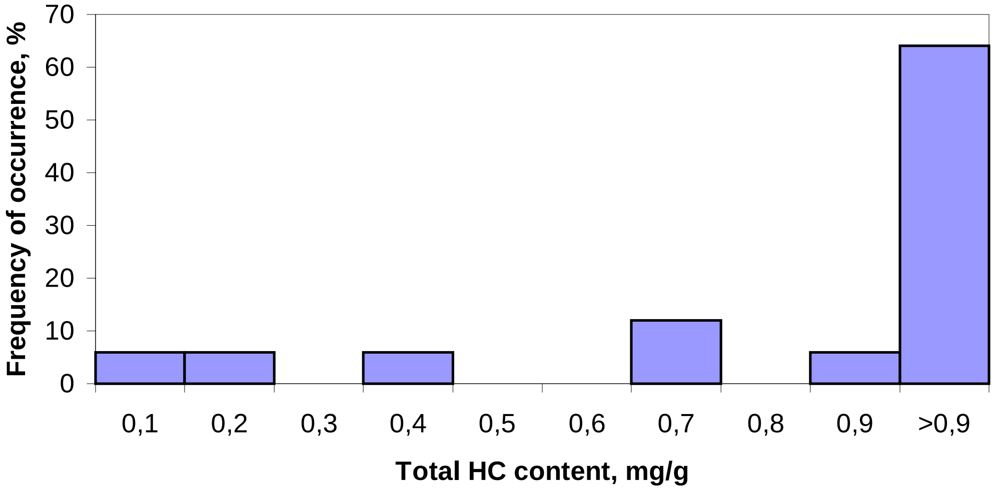

Figure 3. Histogram of total HC content in peats of Samotlorskoe field.

4. Impact of maintenance of oil and gas fields on the environment

Impact of oil and gas fields on the environment includes: 1) direct pollution with oil and its derivatives as well as with other substances, used in the technology, 2) mechanical distortion of ecosystem (wood cuttings, soil losses, disturbance of surface water flux), 3) “indirect” pollution (saliniszation of soils, lost of soil fertility, etc.).

4.1 Vegetation status

The major disturbances of vegetation are caused by the total destruction of plant communities followed by a partial disturbance of soil cover during the construction of wells. The principal chemical stresses for vegetation - sewage and burning gas - result in destruction of arboreal species and development of cat-tail and reed grass scrubs, stable to contamination and simultaneously contributing to purification of waters. The structure of forest communities does not change with the distance from the source of pollution, and morphological disturbances are observed only in regrowth. Both thermal and chemical influence of burning gas results in stackheadedness and necrosis of coniferous species, morphological transformations of the branches of leafy ones and in early partial of complete coniferous needles necrosis, especially in regrowth, as far as 120–300 m from the torches. Some species – like fir - are more sensitive to contamination than the others. In areas, where such species prevails in regrowth, the reproduction of forests in contaminated sites is endangered.

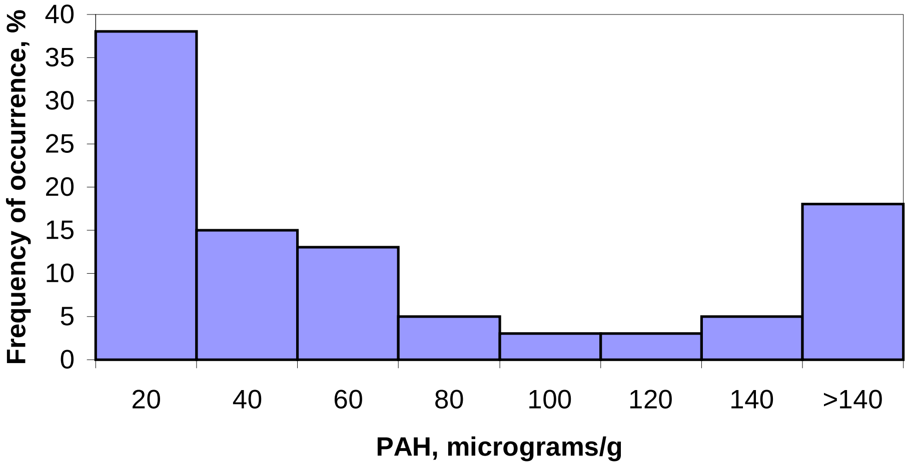

Figure 4. Histogram of PAH content in loams of Samotlorskoe field.

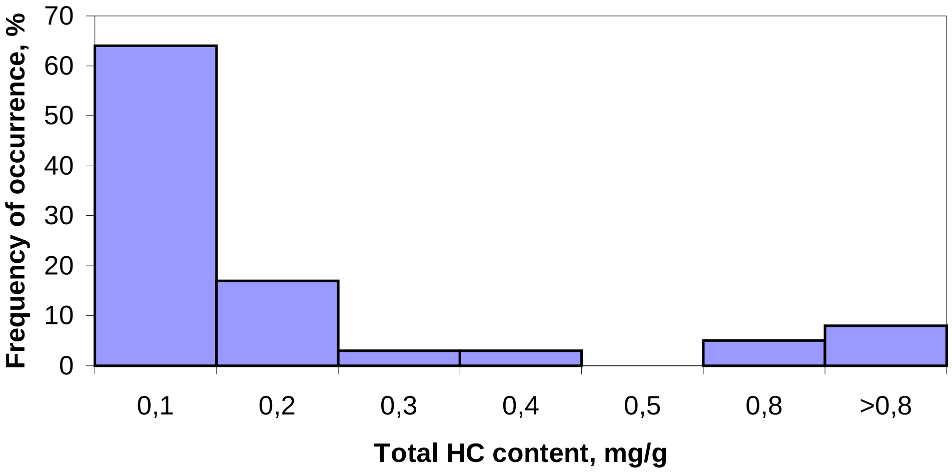

Figure5. Histogram of total HC content in loams of Samotlorskoe field.

It can be concluded, that mechanical disturbance and indirect contamination played the major role in the decline of vegetation in all studied fields. In the humid climate of taiga an important factor is vast swamping of the territory along the roads, sufficiently slowing down the surface water flow on a very flat topography. In arid steppes cutting of the upper parts of soils caused their secondary salinization and decrease of fertility. As a result salt tolerant phytocommunities took place of the original vegetation.

4.2 Response of soil fauna to pollution

The effect of oil pollution on the soil fauna has the following negative consequences (Fig.6): 1) disappearance of the soil-forming groups - segmented worms, earthworms (Lumbricidae) and Enchytraeidae; 2) two-fold decrease in number of the major soil-litter dominants - spiders and rove beetles (Staphylinidae) - the principal soil entomophages, causing the alteration of the trophic structure of the whole community; 3) abrupt decrease of biodiversity. Thus, the influence of oil contamination on the soil fauna is very dramatic, but local: no influence could be detected at 15–20 m from the boundary of oil spill. Torches, however, seem to have almost no impact on soil fauna, except the closest zone where thermal effect prevails. The model tests have demonstrated the highest death rate for adult soil animals with the highest PAH, HC and surfactants content. Surprisingly, however, the second generation of Enchytraeidae appeared to be more sensitive to soil acidity than to oil contamination.

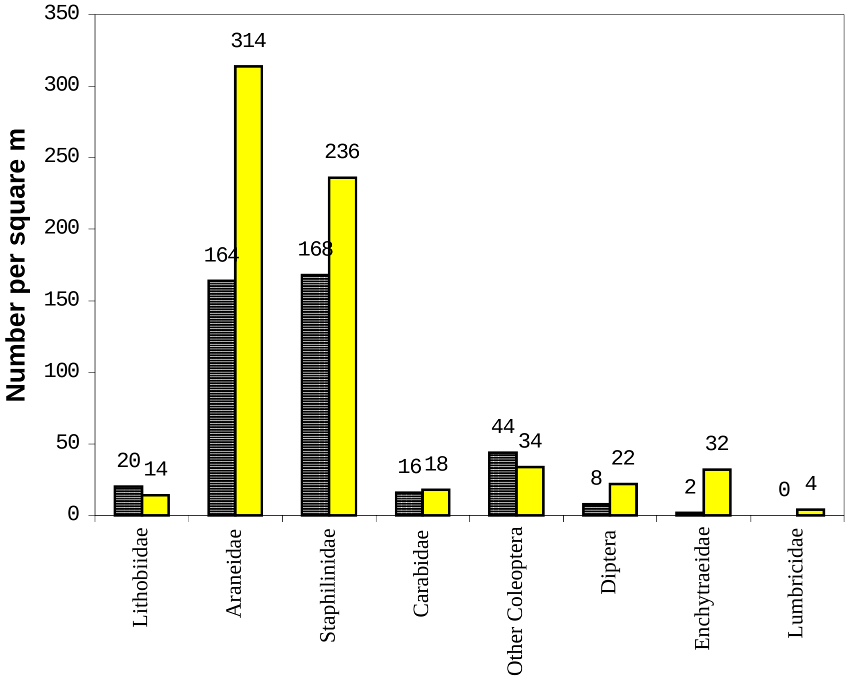

Figure 6. Response of the main groups of soil mesofauna to oil pollution.

4.3 Status of small rodents

Contamination of the territory has not influenced the sexual and age composition of small rodents (like voles, red voles, mice) populations. However, in areas with high industrial load biodiversity of small mammals is decreased and relatively higher number of females and youngsters was somewhere observed in field mice from reference sites. The reproduction cycles of animals in polluted areas can also be somewhat (for 8–10 days) shifted with respect to those in reference biotopes. Any of these responses of field mice to oil pollution may be an indicator in the system of monitoring, but needs further clarification. Laboratory studies revealed abnormalities in the architectonics of the mucous of the digestive tract. Increase in weight of liver, spleen and kidneys was found in red voles from the contaminated biotopes. The highest ratio of animals with abnormally big liver and spleen - 28.6% was characteristic for animals captured close to the torch. Near the oil spills this ratio comprised 22.2%, and for reference sites - it was below 10%. Change of the spleen colour - its clarification, giving the evidence of the distortion of hemogenesis, as well as change of liver colour and distinctly visible vascular texture were found in red voles from the polluted areas. However, no reliable chromosome aberrations were detected even for animals captured near the torches.

5. Practical measures for pollution assessment

Basing on the obtained results we have developed some 25 simple low-cost and effective practical measures for assessment of negative impact of oil and gas fields on the environment (Voznesensky et al 2000), requiring almost no additional funds.

Since the solid products of casing-head gas burning – gas black is carried to the distances about 100 height of the torch and the gaseous ones – to first kilometers, the optimal distance between the neighboring torches, S, with the given heights h_1 and h_2 can be calculated from:

$$S = 200 \times (h_1 + h_2)$$

which guarantees the existence of intact forest zone at least twice as wide as the radius of contaminated area. In addition, the torch should not exceed the height of the adjacent forest. Continuously acting torches should be positioned in the lest sensitive biotopes like marshes.

When recultivating the oil reservoirs it is recommended to fill them initially with peat, having high sorbing capacity to hydrocarbons, and finally cover it with the local loamy soils. This measure will facilitate the formation of forest bedding and new soil. This method can be very effective in the regions with vast development of peat massifs, like Western Siberia. Besides, the bottom of the reservoir should be at least 0.5–1 m above the groundwater table. This will contribute to the complete usage of the sorbing capacity of underlying clay soils.

Productive wells are usually located on sand fills, where the lenses of polluted water can form in cases of accidental spills. To prevent their spreading over the underlying low permeable soils it is recommended to make capturing trench barriers about 1 m wide filled also with peat around the embankment. Moreover, since the sandy embankment if often damaged by rainfalls and snow melt, carrying pollutants with them, it seems reasonable to make second embankment of local – better clayey soils –several meters from the inner one.

To reduce swamping along the roads in humid climate it can be recommended to construct them along the lines of natural interfluves where possible. This will minimize the impact on the surface water flow and, consequently, changes in the structure of phytocommunities.

6. Conclusions

This pilot study of three different oil/ gas fields revealed some important regularities in the migration of pollutants through soil and water, their primary impacts on the environment and enabled the development of a set of low-cost measures to assess its contamination:

1. In situations with heavy HC contamination of the territory all pollutants and especially PAH tend to accumulate in peats against a background of their random spatial distribution. Sorption capacity of soils to PAH increases with their molecular weight. Phenol appeared to be the most mobile pollutant of all the studied.
2. Casing-head gas burning facilities spread solid products of burning to the distance of approximately 100 height of the torch itself and notably influence the status of biota, especially vegetation, within about 10 heights of the torch.
3. Despite the fact that at the loci of heavy pollution distinct abnormalities in vegetation, soil fauna and small rodents have been detected, these changes are not hereditary, and the major impact on environment is caused by mechanical distortion of ecosystems and “indirect” pollution.
4. The applied multifaceted methodology to evaluate the impact of oil and gas field maintenance on various components of the environment is capable of providing not only more comprehensive information about the ecological situation, but also the basis for possible simple engineering measures to reduce this impact on the most sensitive biotopes.

Acknowledgement

The support of the Federal Program «Integratziya» (project # K0151) and the Institute for Sustainable Communities (project ROLL #051/4) is acknowledged.

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Remediation of sites with coal tar contamination – A case study

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ABSTRACT**:** The production and use of coal tar was tied to the industrial revolution and its dependence on coal for energy and as chemical feedstock for a large range of organic and inorganic products. Coal tar was produced, often as a byproduct, by coal gasification plants. The North American coal tar production in the mid 1950s was in the order of 25 billion litres. The production, handling, storage and use of coal tar and its derivatives generated a legacy of soil and groundwater contamination that today requires remediation at high costs. At one such site, coal tar was manufactured into a variety of roofing and tar-based products, as well as the production of creosote, oil stains, solvents and anhydrous ammonia. Over its 60 years of operation, a number of chemicals were leaked, dumped or released to the soil and groundwater on the site, of which the most significant was a brown dense non-aqueous phase liquid (DNAPL) with an oil-like viscosity. This DNAPL migrated from the fill, through a pre-development floodplain silt layer and into an underlying sand aquifer. Portions of the DNAPL moved along preferential pathways associated with the coarser material in the aquifer and reached the nearby river sediments, resulting in elevated concentrations of polyaromatic hydrocarbons (PAH). Site remediation was conducted mitigate risks posed by the coal tar. Remediation has included: in-place management of deep soil contamination, removal of shallow soil with high PAH concentrations (*i.e.,* 10 times the provincial concentration standards for commercial land use), control of dissolved contamination in groundwater, and recovery of free-phase creosote. The remediation also provided long-term protection of the adjacent aquatic habitat through a combination of groundwater and DNAPL control and recovery, removal of near-shore contaminated sediments, and containment and natural attenuation of far-shore contaminated sediments through the use of a layer of crushed rock placed as a protective cap over the sediments.

1. Introduction

The production and use of coal tar was tied to the industrial revolution and its dependence on coal for energy and as chemical feedstock for a large range of organic and inorganic products. Coal tar was produced, often as a byproduct, by coal gasification plants. The production, handling, storage and use of coal tar and its derivatives generated a legacy of soil and groundwater contamination that today requires remediation at high costs. Often these facilities were located at or near shorelines for receiving of coal and shipping of products. This led to contamination also of adjacent water bodies and sediments.

Coal tar was produced by coal gasification facilities that produced gas for city lighting and power usage, and the production of coke for the steel industry. The ready availability of coal tar provided ample supply for distillation into creosote for the wood preserving industry. Most major cities in the North America and Europe had coal gasification and coking plants. In the US, 1150 city gasworks were registered (Lotimer, 1992), and total coal tar production in the mid 1950s was in the order of 20 billion litres (Austin, 1984). The number of registered gasworks in Canada was approximately 150, and in Denmark 125 (Johansen, 1997).

Coal tar production led to the development of a large secondary industry for processing the tar, including: roof shingle and tar paper for construction; road tars for paving, wood treatment (both tar and creosote derived from tar), and coal tar derivatives used in paints and enamels. These secondary industries switched over to oil-derived tars and solvents in the 1950s, as the manufactured gas plants were being phased out in favour of electricity and petroleum fuels.

Coal tar from coal gasification plants was used by several industries, including the manufacturing plant formerly located at the site discussed in this paper. This plant shut down about 20 years ago and has recently been remediated for redevelopment for commercial use. This paper provides an overview of the contamination found at the site and the remediation approach selected.

2. Coal tar and its byproducts

Coal tar was commonly produced by high-temperature carbonization of bituminous coals (Austin, 1984). The coal tar was further processed to manufacture chemical feedstock for a variety of products including solvents, creosote, roofing materials and road tars. The main chemical components found in these products include:

- paraffins and cycloparaffins
- benzene, ethylbenzene, toluene, xylene
- low molecular weight PAH (naphthalene, 2-methylnaphthalene, phenanthrene, anthracene, 1-methylnaphthalene, biphenyl and fluorene)
- high molecular weight PAH
- heterocyclic aromatic compounds (HAC), which may have included quinoline, isoquinoline, carbazole, 2,4-diethylpyridien, acridine, 2-methyquinoline, 4-methylquinoline, pyrrole, pyrrolidine, benzo(b)thiophene, dibenzothiophene and dibenzofuran
- phenolics (phenol, cresols, pentachlorophenol, xylenols and 2,3,5-trimethylphenol)
- ammonia solutions
- sulfate, sulfide, thiosulfate
- cyanide, ferro-cyanide, thiocyanide
- carbonates and chlorides
- acids and bases
- metals including sodium, calsium, iron, and others

Physical properties of coal tar that largely determine its behaviour in the subsurface include its specific gravity, which is near that of water, its high viscosity, and low interfacial tension. The specific gravity of coal tar is typically around 1.05. Consequently, it is a DNAPL that will slowly sink when placed in water, although separation into both floating and sinking phases has been reported. Viscosity will vary widely depending on coal tar composition and temperature, but typically is much higher than water, ranging from that of a crude oil (about 20 centipoise) to that of thick molasses (perhaps 50 to 80 centipoise). Such viscosities reduce the velocity at which the coal tar can migrate through soil, although they will have little effect on the ability of the coal tar to flow. Coal tar migration through a porous medium is determined to a much greater extent by the interfacial tension between the coal tar and the soil porewater. Where coal tar has been recovered from soil, interfacial tensions are typically low, on the order of 5 to 10 dynes per centimetre. This suggests that coal tar may travel further and leave behind much lower residual concentrations in soil than would be expected for comparable petroleum-based heavy oil.

3. Main environmental issues

The bulk of the compounds found in coal tar are PAH. PAH are a diverse group of organic compounds composed of hydrogen and carbon atoms arranged in two or more fused aromatic (benzene) rings. PAH are grouped into two categories based on their molecular structure: 1) low molecular weight (LMW) compounds with fewer than four rings; and 2) high molecular weight (HMW) compounds with four or more rings. LMW-PAH are generally more soluble in water than HMW-PAH. At the site discussed in this paper, the coal tar DNAPL was composed of about 75% PAH, which were mainly LMW-PAH. PAH are also formed by a variety of other natural and anthropogenic processes including biosynthesis and incomplete combustion of organic materials.

Several studies have demonstrated that PAH associated with coal tar can pose risks to aquatic organisms. At sufficiently high concentrations, PAH can cause reduced survival, reduced growth, tumors, developmental effects, enzyme induction, behavioral abnormalities, habitat degradation, fish tainting, and ultraviolet-induced skin lesions (Sved et al, 1997; EAG, 1988; Eisler, 1987; and Neff, 1979).

Terrestrial activities are much less affected by PAH contamination found at these sites, as it is generally located at depth, and the hydrocarbons present in creosote are not sufficiently volatile to create soil vapour concentrations that would pose a potential threat to people, plants or animals.

4. Site characteristics

4.1 History and use

The site was used primarily for the manufacture of roofing, paving and other building materials. Manufacturing operations started near the turn of the century and continued for a period of about 60 years. Major products included:

- Roofing shingles, paving and waterproofing materials;
- building papers, roofing felts and roofing pitch;
- creosote, oil shingle stains and enamels;
- coal and tar pitch for road construction, repairs and maintenance;
- asphalt shingles and slate surface roofing;
- chemicals and solvents; and,
- anhydrous ammonia

Coal tar feedstock was provided from at least one manufactured gas plant. The coal tar was brought in by train and barge, and stored in above-ground tanks for processing and resale. The coal tar was distilled into a number of different grades: heavy distillates, used for paving materials (road pitch) on roads, and lighter grades of distillate (mixed with additives) to produce creosote oil, shingle stains, roofing pitch, and paints and enamels. Steam lines from a boiler heated the coal tar, which was stored in one of several large storage tanks, to liquefying temperatures so that it could be pumped. During the latter years, petroleum-based asphalts replaced coal tar as the principal feedstock. Asphalt was typically trucked in from local refineries and pumped directly into the asphalt storage tanks.

Over its period of operation, soil and groundwater contamination resulted from several mechanisms such as:

- spills, leaks, and drips during unloading, transfer, handling and storage of raw materials and distilled products;
- placement of materials from the property along the foreshore during foreshore filling;
- random on-site filling; and,
- releases of chemicals caused during the demolition and decommissioning of structures on the property.

The potential contaminants of concern identified from historical reviews of site operations included a) coal-tar derivative oils that were produced at various stages of refining and distillation, b) asphalt and road pitch materials, c) bunker C and other heating fuels, d) some liquid thinners, and e) metals from the granules used in the manufacturing of shingles. Of these, coal-tar derivative oil is the most significant. Coal-tar derivative oil is typically brown in colour and can have a consistency of a moderately light oil such as creosote. Coal-tar derivative oils contain mainly PAH and some monocyclic aromatic hydrocarbons (MAH). The MAHs include the benzene, toluene, ethylbenzene and xylene compounds. When present in a mixture with PAHs, the MAHs in coal-tar derivative oils are generally less soluble in water than would be observed in typical gasoline mixtures. Coal-tar derivative oil commonly has a specific gravity at typical soil and groundwater temperatures that is higher than but very near that of water. Consequently, when introduced into the environment it behaves as a DNAPL.

4.2 Regional geology

Regionally, the site lies within a geological bedrock basin that has been infilled with glacio-marine, alluvial (deltaic), swamp, and flood plain deposits (Figure 1). The infilled deposits are a few hundred metres thick near the river, and decrease in thickness to the north. Following the last glacial episode, sedimentation at the mouth of the river resulted in a thick sequence of fine-grained deltaic sand deposits that now comprise the river delta. The deltaic sands, which are laterally extensive, are typically between 20 m and 35 m in thickness. On the delta, natural sand levees that formed adjacent to the river channels deposited finer-grained silty sands and silts (overbank or floodplain silts) in the quieter areas upland of the levees. Consequently, the present topography at the site is characterized as relatively flat, with native silt and/or peat overlying a thick, interbedded sequences of sands which, in turn, overlie thick Pleistocene deposits.

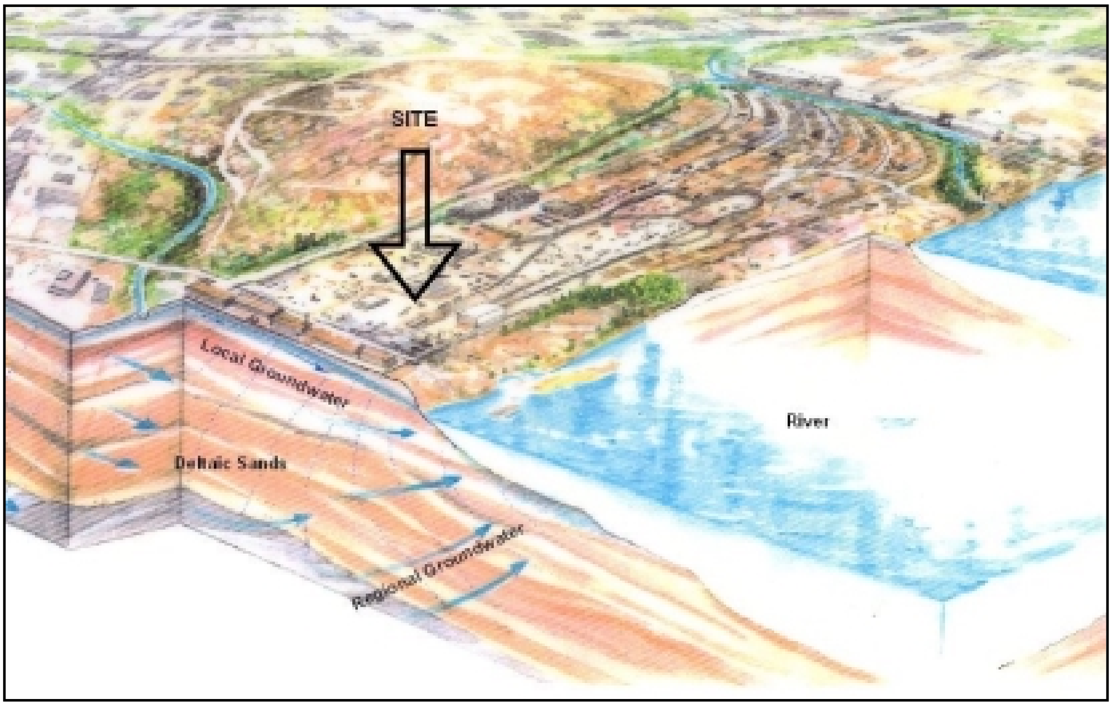

Figure 1. Regional hydrogeological diagram.

4.3 Sand aquifer

The deltaic sands comprise a regional aquifer. The aquifer is hydraulically connected to the river, and responds to diurnal fluctuations in water levels at the site caused by tides. Average groundwater flow is typically horizontal toward the river, and then upward into the river where it discharges. However, during periods in late spring when river flows are high and the water table is low, hydraulic gradients may reverse inland for periods of up to one or two months.

4.4 River sediment mobility

Sediments along the riverbed are eroded during large flow events and are replaced with sediment eroded from upstream areas as the flow event wanes. Contaminated sediments may be transported away from the site during the large flow events leaving behind freshly exposed contaminated sediments that will be subsequently reburied by newly arriving uncontaminated material from upstream. Fine sediments such as silts may accumulate over the site during the low-flow periods. These fine sediments form a surficial layer (veneer) that is re-mobilized during the next large flow event.

5. Site investigations

5.1 Scope and methods

Detailed investigations have been conducted at the site to characterize the physical, chemical and biological subsurface conditions, including an assessment of potential exposure pathways. This information has been used to facilitate the subsequent evaluation of a range of remedial alternatives including in-place management of the contamination. Approaches that have been used in characterizing of the site are described elsewhere (Patrick and Anthony, 1998), and include conventional shallow excavations (test pits), hollow stem drilling and sampling, and the use of push technologies (cone penetrometer testing) and continuous soil coring to define stratigraphy, soil chemistry, and the presence and extent of NAPL. Groundwater assessments have included conventional nested well installations as well as vertical chemistry profiling using, for example, the Waterloo Profiler™. Continuous water-level monitoring of tidal-response and damping in the aquifer, as well as conventional pumping tests have been conducted to evaluate aquifer properties, hydraulic gradients, and groundwater flow velocities and flux.

Continuous coring using the rotary sonic drilling method as well as Macro-Core™ methods (Geoprobe Systems) has been used extensively at the site to allow detailed stratigraphic description and direct observation of NAPL, where present. Typical coring depths have ranged from 5 m to 30 m, providing information through the full thickness of the sand aquifer. Characterizing river sediment has been largely conducted from a barge using a conventional hollow-stem drill rig and shallow coring and dredging devices.

Where obvious NAPL is observed in soil or sediment cores, it is found almost exclusively in medium to coarse sand, and appears as viscous dark-brown to black globules or oily coatings. However, extensive areas of much lower NAPL concentrations are often revealed in fine sands by weak sheens, soil staining and strong odours. Occasionally, root holes stained by NAPL may be observed in cores of overbank silts located within source zones.

5.2 Contamination sources

The known and inferred extent of the zones of NAPL is illustrated in plan and in section in Figure 2. Each NAPL zone contains a heterogeneous distribution of coal tar, where concentrations may range from absent to several percent. Lateral spreading has occurred through relatively coarser grained strata bounded on the bottom by apparent capillary barriers of finer-grained material. The deepest zones of vertical penetration appear to have been limited to the areas where chemicals were released (*i.e.*, within those areas where chemical use and handling were greatest). NAPL has reached depths of about 12 to 15 m.

5.3 Dissolved PAH

Dissolved PAH emanating from the NAPL source zones are found in both shallow fill onshore, and within the Sand Aquifer both onshore and beneath the bed of the river. Concentrations of dissolved PAH within the source areas approach the expected solubility limits and, in some cases, appear to have exceeded solubility limits where sampling using conventional practice (*e.g.*, purging using foot-valve samplers or bailers) may have entrained NAPL micelles and/or PAH sorbed to sediment in the water samples. PAH concentrations in sediment a few metres beneath the discharge zones at the river are commonly one to two orders of magnitude lower than concentrations measured at the source zones. As discussed below, further reductions are observed within the riverbed prior to discharge, likely as a consequence of tidal pumping and natural attenuation.

5.4 DNAPL mobility

A concern at the site was the possibility that NAPL was continuing to migrate from source zones toward and into river. For the most part, the soil chemistry data and stratigraphy suggested that the potential for NAPL migration under natural hydraulic gradients was low, and that the majority of NAPL represents residual, immobile product. However, NAPL has been recovered from wells at each of the sites. Mobility of DNAPL would be difficult to demonstrate, mainly because the NAPL velocity would probably be very slow (*e.g.,* perhaps on the order of a metre per year). Such low velocities are to be expected because of the high NAPL viscosity, weak stratigraphic slopes along which the NAPL moves, and the NAPL density near that of water.

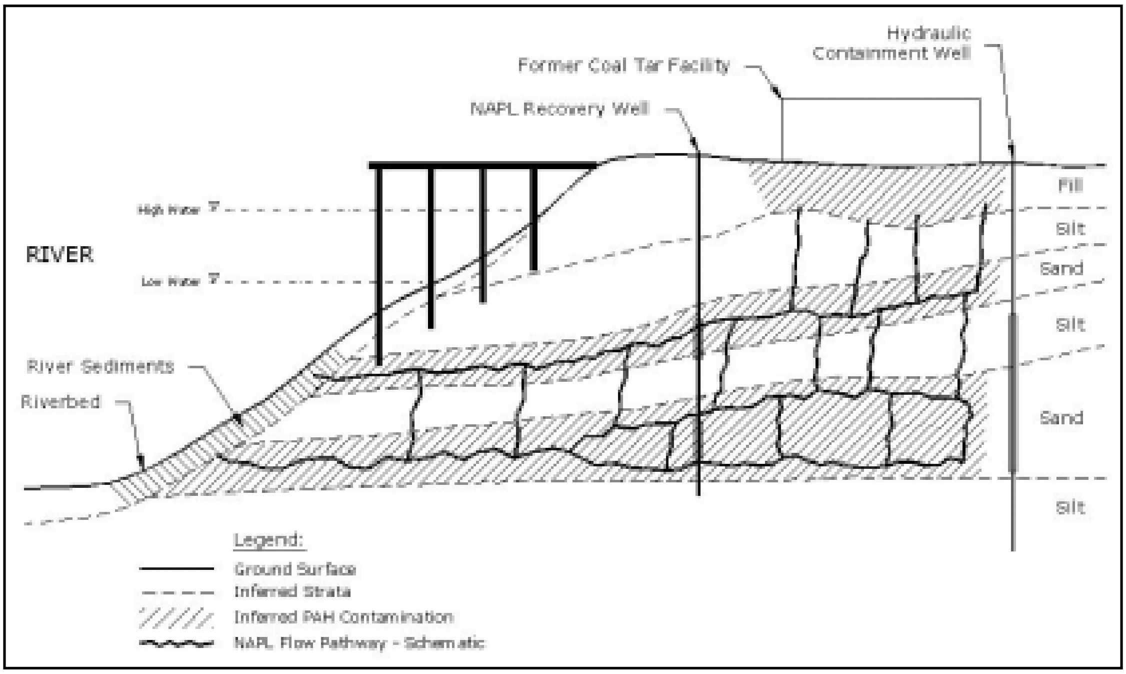

Figure 2. Schematic crosss section of typical site conditions.

5.5 Natural attenuation

Natural attenuation processes are likely occurring within dissolved plume. The plume extends from the NAPL source onshore to zones of groundwater discharge within the river, within 20 m of the shoreline, (Figure 2). With the exception of a thin mixing zone in the bed of the river, the plume is anaerobic, and composed mainly of naphthalene. At the river, a groundwater-river water mixing zone is created by tidal pumping, which effectively dilutes the plume and introduces dissolved oxygen and river water. The thickness of this zone is variable, depending on the permeability of the riverbed, and has been measured to be about 0.5 m thick. As a consequence of mixing, PAH degradation is promoted and the sediment porewater often has low PAH concentrations.

5.6 Sediment

NAPL occurs randomly in river sediment over an area measuring about 20 m in width, and extending about 130 m to 160 m in length. Within these NAPL areas, the surficial sediments (to 0.6 m depth) have mean total PAH concentrations ranging between 100 mg/kg and 200 mg/kg, although much higher concentrations are occasionally reported. Total PAH concentrations in deeper sediments can be much higher, probably reflecting less weathering and higher NAPL mass, and higher concentrations at depth related to preferred NAPL migration through deep, gravelly lenses in the sand aquifer.

Outside of the primary PAH zone, a “halo” of surficial PAH-contaminated sediments exists. This secondary surficial contamination is the result of ongoing natural river processes of erosion, deposition, and tidal influences, which have mobilized and redistributed PAH-contaminated sediment from the primary zone. The mean total PAH concentrations within these secondary zones are typically around 10 mg/kg or less.

The riverbed along the foreshore is generally dominated by silt and sand, with little overhanging or instream cover (*e.g.*, riparian vegetation, boulders). Fish spawning and rearing habitat is, therefore, limited. Although the river is a migration corridor for salmonids, it is species such as starry flounder and peamouth chub that use the area for rearing and migration. Common benthic invertebrates found in these sediments include oligochaetes, chironomids, nematodes and copepods.

6. Site remediation

6.1 Remediation constraints

Site conditions posed a number of significant constraints on possible remediation options. These included considerations of minimizing disturbance to on going site operations, and ensuring the stability of site structures. The adjacent shipping channel with heavy commercial (tugboats with barges and log booms) and recreational traffic also posed some restrictions on potential sediment remediation options.

Constraints were also imposed by a number of natural conditions including: riverbank geotechnical stability concerns related to dredging or cut-off wall construction; presence of cobble layers beneath the sediments at depth, which could impede the installation of sheet pile cut-off walls; and the erosion and mobility of the river sediments caused by annual freshet flooding.

6.2 Remediation strategy and implementation

Based on the considerations discussed above, the remedial strategy involved a series of steps to achieve source control and risk reduction. This strategy reflected the knowledge of where the leaks and spills likely occurred, such as the vicinity of storage tanks and piping, and the science of coal tar migration. The source locations were easily identifiable based on historical information, and then targeted for investigation, remediation and/or containment. The remaining contamination beyond the main sources was significantly more diffuse as a result of random dumping of waste materials as fill or natural migration.

Source control involved groundwater pumping and treatment systems to hydraulically control dissolved chemicals and to recover DNAPL from the upland source zones. With these controls in place, the approach to final remediation was based on defining actual risk to human health and the environment posed by the contamination, and on developing and implementing remedial works that a) reduce the risks to acceptable levels and b) meet the regulatory requirements for permanency and contaminant mass reduction. A large part of the remedial effort was, therefore, focussing on identifying areas of potential mobility of DNAPL, implementing DNAPL control and recovery measures, and defining ecological risks posed by DNAPL and dissolved components to benthic communities in the river bed.

6.3 Interim contamination controls

Several interim contaminant controls were implemented prior to the completion of the site investigation. These were aimed at controlling or reducing potential environmental impacts, particularly those associated with discharges of dissolved contaminants and DNAPL to the Fraser River. The temporary abatement remediation works included:

- installation of a groundwater collection well and pump-and-treat system to control the offsite discharge of dissolved constituents in groundwater entering the river; and
- excavation of shallow contaminated soil and sediment from the foreshore and beach area.

6.4 Removal of shallow contaminated soil

About three metres of fill were placed over native soil when the site was first developed for industrial use. As discussed earlier, part of this fill became contaminated with coal tar over the 60 years of operations at the site. Soil with high levels of PAH contamination (typically ten times higher than the standard for commercial land use) was removed. The remaining soil was safely managed in-place by preventing surface exposures through construction of concrete building slabs, placement of low-permeability caps, and restrictions on land use, as well as control of local groundwater using shallow interceptor trenches.

6.5 Hydraulic control of dissolved PAH and DNAPL

Dissolved PAH contamination in the deep sand aquifer has been controlled by pumping groundwater from wells, and treating the water on-site using activated carbon with pretreatment to remove naturally occurring iron and manganese. Treated water is discharged to the sanitary sewer.

Hydraulic control was also effective in arresting potential DNAPL migration, and in recovering DNAPL. DNAPL recovery from the deep aquifer is enhanced through cyclic stressing of the aquifer by pumping. Groundwater modelling and on-going monitoring indicate that the hydraulic containment and control system in place provides an effective control with a reverse groundwater gradient away from the river ranging from 1% at low tide to 2% at mean tide. This reverse gradient is sufficient to arrest or reverse the flow of NAPL and capture the entire dissolved-phase plume.

6.6 Sediment removal or control

Contaminated sediment in the intertidal zone was removed by excavation and treated offsite by thermal desorption. For contaminated sediment in the subtidal zone, it was concluded that containment by capping would provide an effective level of protection. The selection of this option was based on regulatory considerations, the results of the aquatic risk assessment, source control measures that were already in place (*i.e.,* mass reduction and hydraulic control of NAPL and dissolved PAH), and specific site constraints such as: mobility of river sediments, river slope stability concerns if disturbed, and increasing PAH contamination to a depth of 4 m to 5 m below the surface of the sediments.

The designed sediment cap consists of an engineered layer of crushed rock. The cap will prevent erosion and downstream transport of contaminated sediments, provide a layer of protection between the contaminated sediments and the aquatic community, and provide a dispersion and attenuation zone for groundwater that may contact sediments if groundwater containment by pumping was terminated.

7. Conclusions

The site has been successfully rehabilitated for continued industrial and/or commercial use through the partial removal of contaminant sources and in-place controls, especially in the shallow soil. Long-term site improvements are expected through recovery of mobile DNAPL from NAPL recovery wells. Protection of the aquatic habitat has been achieved through removal of intertidal sediments, capping of contaminated subtidal sediments, and control of dissolved PAH and DNAPL releases by groundwater pumping. Over the long term, as the mobile DNAPL is removed, it is predicted that pumping of groundwater will no longer be required. Natural attenuation and dispersion of PAH during migration through the ground and through the crushed rock cap are expected to reduce dissolved PAH concentrations to levels that do not pose risk to the aquatic habitat.

Complete removal or reduction of PAH contamination to applicable clean-up standards was not practical at the site with today’s technologies. Even if the removal or reduction of all accessible contamination had been pursued, this would have resulted in a lengthy and very costly process. The partial removal of sources and containment of the less accessible contamination in the ground and sediment have provided for an effective remediation at reasonable cost. The remediation includes long-term operation and maintenance of the hydraulic control system and the sediment cap under an environmental management system for the site, and financial security that is required by the provincial government to ensure adequate funding for its continued implementation.

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BARRIER STRUCTURES FOR LANDFILLS AND GROUNDWATER PROTECTION

Sealing function of waste substances immobilized with waterglass

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SUMMARY: This article describes the development and technical background of a novel sealing technology for landfills based on the use of waste materials. Important characteristics such as the mechanism of waterglass sealing, the durability of the system, the suitable waste types and the implementation of this new technology in practice are discussed here.

1. Introduction

Sections 2–5, discuss the development and technical background of a novel top sealing technology for landfills based on the use of waste materials. This paragraph describes the implementation of the new developed technology in practice.

Following extensive laboratory tests, four test-fields were constructed in Holland in the summer of 1994. For each test-field, a different waste composition was used. The selection of the waste material was based on quality and commercial availability of the waste products. The Dutch Ministry of Environment subsidized the project.

The sealing mixtures always contain mechanical de-watered sewage sludge, a coarse fraction such as contaminated soil, fine particle size material such as fly ash and a minor quantity of waterglass. These test-fields are still monitored and show an improved K-value over time.

The results were presented to the Dutch Committee of Waste Treatment. In 1997, this resulted in the first major commercial order to cover a 54 hectares size landfill near Eindhoven in seven years period. Meanwhile 16 hectares are completed, using 180.000 tons of a waste/waterglass mixture (Hydrostab). This landfill cover did meet the quality standards as set by the government. Construction of a second capping at a 42 hectares landfill in Den Bosch commenced in 1999.

BKB operates two mixing plants to produce the waste mixture for these landfill covers. The majority of the suitable wastes from South Holland are processed here at much lower costs when compared to the traditional alternatives. In addition, the construction costs for the landfill cover are lowered by 30% when compared to the traditional technologies. Thus creating a win-win situation for both the waste supplier and the landfill owner

At this point, the annual production is 100.000 tons of mixture per plant. The waste is collected in an area with a radius of Apr. 100 km. The construction period is between early April and late October.

In case you need further information or want to visit the landfill site, please contact Mr. Beukema fax 31 529-435824.

2. The concept of water glass hardening

Technically, water glass is produced by melting together stoichiometric quantities of sodium carbonate (Na_2CO_3) or potassium carbonate (K_2CO_3) with silicon dioxide (SiO_2). Under pressure, the resulting alkali silicates, e.g.

$$SiO_2 + Na_2CO_3 \rightarrow Na_2SiO_3 + CO_2$$

$$2\ SiO_2 + K_2CO_3 \rightarrow K_2Si_2O_5 + CO_2$$

will dissolve in water. Owing to the low degree of acid strength of silicic acids, solutions of water glass such as these undergo hydrolysis and show a strong alkaline reaction. Even the carbon dioxide present in the air and a decreasing pH value (< 9) can cause an increase in condensation or polymerization of the dissolved silicic acid species, leading to unstable and insoluble polymeric silicate structures. These compounds aggregate to form silicic acid particles retaining on their surfaces reactive silanol groups which may encourage further condensation reactions. In the course of these reactions, the sol is slowly transformed into a gel whose silicon atoms forms a three-dimensional cross-linkage via oxygen bridges. The resulting three-dimensional tectosilicates intercalate water molecules. Through further abstraction of water (exsiccation), there eventually results a solid $SiO_2.\ x\ H_2O$. The use of water glass for the preservation of eggs by way of airtight sealing of their porous shells – formerly widespread – is based on the procedure set out above.

In this context, it seems important to point out the following: when water glass is being used as a mineral sealer for dumping grounds, the polymerization process, instead of being allowed to continue to complete exsiccation, is stopped as soon as gel formation has set in. This is because the sealing properties of the method described hereafter depend on the formation of these so-called soft gels.

This method uses water glass type Hydrostab-TA of Akzo-PQ Silica as an aggregate. Hydrostab-TA is incorporated into the mineral substrate material so that it may form a water glass solution with the soil water. The sealing system of silicic sol and silicic gel is reached by way of condensation reactions and other reactions with gel-forming ingredients in the soil water.

The water glass solution penetrates into the soil material's cavities and pore spaces, filling them up and gluing the soil particles together by means of the soft gel formation described above. This effect is not only due to the cavities being sealed, but is itensified by the silicic acid gels forming tight chemical bonds with the OH-groups of mineral soil constituents (iron and manganese oxides, clay minerals). The resultant coagulation structure is compact and has a very favorable effect on the permeability index. As experiments have shown, soft gels resulting from 5% water glass solutions have permeability indices of 10^{-11}–10^{-12} m^2/s.

3. Stability of silicate gels

The chemical and biochemical stability of the material is an important aspect of the use of waterglass-conditioned sealing systems in the construction of dumping sites. An insight into the physicochemical interactions and microbiological processes is an essential prerequisite to an adequate judgment of the sealing systems' long-term performance in view of aggressive dumping site percolation water and microbial attacks. As is generally recognized, water glass and the silica gel types derived from it are resistant to most chemical compounds.

Investigations have shown that silica gels are not dissolved by the inorganic and organic substances contained in percolation water, such as salts, heavy metal ions and heavy metal complexes, halogenated hydrocabons, organic acids and esters, phenols, PAH's, BTX's, amino compounds and surfactants. The exceptions are hydrofluoric acid (HF) and solutions which show a strong alkaline reaction.

It may be assumed, then, that water glass hardening guarantees chemical stability of the mineral sealing layer, and that a notable change in coagulation or condensation structure is unlikely to appear provided that the percolation water has no strongly alkaline properties and the water glass is not exposted to substances with a high pH value.

Biologically caused damaging of materials is mainly to be attributed to a microbial degradation of organic substances. All standardized methods of quantifying degradation rates proceed on the assumption that the substance under investigation acts as a carbon source. This is why the existing literature on biological degradation is in fact a bibliography of organic substances. However, it is possible also for solid inorganic substances such as minerals to be decomposed by bacteria. Among other agents, microorganisms are responsible for the weathering of rock in geological dimensions. Provoked by chemolithothrophic bacteria, the corresponding processes normally require oxygen.

As a rule, silicate minerals are susceptible to microbial attacks. We do not usually find a single mechanism at the root of weathering induced by bacteria, but a combination of several processes. The following factors warrant special attention:

- Lowering of pH value caused by formation of organic and inorganic acids;
- Formation of complexing substances.

As a result of both these mechanisms, alkali metals and alkaline-earth metals will dissolve out from their solid phases, thus destroying silicate minerals. In the case of an amorphous polymeric silicate structure as formed by silica gels, this mode of attack is not available.

On solid surfaces, bacteria may develop to form structured symbioses. In the tail water are of a dumping site, these will be dominated by sulfate-reducing and methanogenic bacteria. The formation of a biofilm on the metal-water interface is a prerequisite of anaerobic biological corrosion of metal. It may be assumed by analogy that such biofilms are also likely to appear on a mineral system used for sealing off the base of a dumping ground.

Anaerobic degradation reactions will result in reduction of nitrate, manganese oxide, iron oxide, sulfate and carbon dioxide. A reduction of silicic acid seems unlikely for energetic reasons and has not been known to occur. In nature, deposits of silicic acid appear almost exclusively as diatom insertions. Withered algae turn into sediments. In these sediments, most organic matter is then broken down by microbes, with a more or less pur silicic acid remaining. As may be concluded from these observations, silicic acid will not be attacked by bacteria.

4. Pollutant retention through water glass conditioning

The retaining power of the ingredients dissolved in the dumping ground’s percolation water is as important a characteristic as the chemical and biological resistance. The interfacial chemical processes discussed above, such as ionic exchange, surface complexing, physical and chemical sorption, take priority in this context. Inorganic hydroxo complexes and organic compounds with hydrophilic functional OH-, COOH-, or NH_2-groups may be attached, and firmly bonded, to the OH-groups of silica gels by way of formation of hydrogen bridges. In adequate concentration, polar organic compounds and large non-polar molecules may be physically adsorbed and so prevented from penetrating into the deeper layers of the sealing materials. As laboratory tests have demonstrated, the sorption properties of silica sols and silica gels correspond to those present in active clay minerals.

By virtue of their stability, compactness, and sorption properties, silicate soft gels formed through water glass hardening made suitable additives or binding agents. These can be turned to good use in encapsulating processes for the purposes of pollutant retention.

This applies both to the encapsulating of waste and to the production of mineral sealing layers.

In water glass hardening, the pore water is transformed into the silicate soft gel. This process causes the pore space to be sealed off. By adding agents suitable for soft gelling, the process of sealing off pore space may be controlled and optimized. The high compactness of the silicate soft gels under discussion may be considered a main reason for the shielding effect of the waterglass-conditioned mineral sealing layers as a consequence of sealing off pore space.

It is this pronounced compactness of silicate soft gels that causes the pollution retention required for the encapsulation of suitable wastes or contaminated soils. This applies to corresponding inorganic as well as to certain organic pollutants. Thus, most transition metals (e.g. heavy metals) will form silicates that dissolve only with difficulty. It should also be noted that the surface groups of silica gel show a pronounced sorption effect.

As pore water is transformed into the silica soft gel, metal ions as well as organic molecules and other pollutants (such as precipitates in polymer structures) will be immobilized. This fact is clearly indicated by the effective diffusion coefficients which as a rule are of the order of 10^{-11} m^2/s or less. No chemical fixation occurs in monovalent cations and anions. This fact is based on the nature of water glass reaction, in the course of which alkali ions and anions are released, so that leaching of additional ion quantities can only be limited through a decrease of the water permeability of the densified product.

$$Na_2SiO_3 + CaCl_2 + H_2O \bullet\ CaSiO_3 + H_2O + 2\ Na^+ + 2\ Cl$$

The quality of pollution retention inherent in silica soft gels has found applications elsewhere too. The American CHEMFIX-process, for instance, is based on the immobilization of pollutant-bearing wastes by means of water glass, and is chiefly used with inorganic pollutants.

A high water content in the compacted, waterglass-conditioned cover layers, such as may be caused by rainfalls occurring during construction works or through lasting contact with supernatant percolation water at the base of dumping sites, will not negatively affect permanent stability. It has been shown in the course of long-term investigations and excavations of built-in coating layers permanently exposed to tail waters and percolating waters that, given time, the sealing effect is likely to increase rather than decrease. Thus, when permeability indices of different types of clay and water glass were determined, first during construction of a dumping ground and a second time by means of an excavation taking place after about 8 years, K values were shown to be of the order of 10^{-10} m/s, and after excavation generally about 10^{-11} m/s. Despite a permanent effect of a head of seepage backwater from the dumping site, water contents of the excavated sealing layers were considerably lower than $W = 24\%$ by weight (saturation).

Another striking fact is that within the limits of error, the water contents of sealing systems based on hardened water glass did not change over time, whether or not a head of seepage backwater was present. These results seem to indicate, firstly, that the water contained in hollows and pore spaces is very efficiently bonded in a matrix of silica gel; secondly, that any penetration of supernatant water into the sealing layer is of a quite superficial nature. The possibility of penetration of dissolved organic or inorganic pollutants, of nutrients or similar degradable substances required for a microbiological attack may therefore be excluded. We may therefore with justification predict that mineral sealing systems based on hardened water glass will form a permanently efficient barrier to pollutants.

5. The use of waterglass-conditioned materials for surface sealing

By adding finely powdered water glass, the following soil types can be hardened and thus developed into sealing layers with permeability indices equivalent to those of clay: tenacious fine-grained soils such as meadow loams, high water loams and loess loams with a fine-grain content of about 40%, mixed-grain soils, highly silty sands and fine gravels, slope wash or boulder clay types with a silt content of 30–35%. The economic advantages are obvious. Compared to clay, the merits of loamy soils consist in a ready availability as well as in the fact that, considering the low transportation costs involved, they constitute in many cases an economically more favorable solution to the construction of sealing systems for dumping grounds.

In addition to subsurface barriers being erected on dumping sites with a view to protecting ground water, the surface sealing of ancient dumps and of disused, polluted industrial sites is another point likely to become a vital concern in the future.

At such sites, often with defective base sealings, it is important to cut off the development of percolation water and thus to prevent any further discharge of pollutants into the deeper layers of the subsoil or into the ground water.

This is another problem for the solution of which the process developed by BKB Reststoffen Management may offer interesting alternatives and applications.

Certain mixtures consisting of recyclings and waste material have the properties of finegrained, tenacious soils, thus lending themselves to the production of sealing materials. An essential prerequisite for water glass hardening is a mixture having a particle size distribution and with sufficient water content which is still compactable in itself. Prepared slags or ashes may be used as carrying matrixes. Filter dusts and finer ashes make suitable fillers provided they do not enter into any chemical conversions with the silica gel (strongly alkaline reactions).

Preconditioned clarifier sludges, hydrological sludges, or industrial sludges possess a soft or medium plastic consistency which contains the intercalated organic substances in a very finely dispersed, fibrous form. Hence, these sludges cannot be incorporated on their own, and can be stored only up to a certain point. By working a dry or earth-moist particle-distributed carrying matrix into the pore spaces, however, a mixture with sealing and compressible properties may be produced. Water glass may further increase this sealing effect significantly.

Depending on mixing ratio, it is possible to produce sealing layers with permeability indices of 5×10^{-9} m/s to 5×10^{-11} m/s. As tests of more than 8 years' duration have demonstrated, such mixtures show no changes of K value. It may be deduced from these experiences that, with high compactness preventing a nutrient supply sufficient for keeping microorganisms alive, aerobic or anaerobic degradation is unlikely to occur in this type of sealing system, which therefore suggests itself as a suitable material for cover sealings with permanent stability.

This type of waterglass-conditioned mineral cover layer, composed of residue and suitable sludges has the merits of good plasticity properties and of a high crack resistance, comparing favorably to sealing layers composed of natural minerals, which is of essential importance for the surface coverage of ancient dumps as well as abandoned polluted areas. Since crack formation does not depend on the plasticity of the sealing mixture so much as on shrinkage, the water-holding influence of the soil mixture involving clarifier sludge and silica gel manifests itself as a solution to such situations as well.

Shrinking processes such as these are especially observed in clay sealings with water contents ranging from 24 to 28% and corresponding Proctor densities ranging from 93 to 95%. As tests have shown, a change in water content of 1–2% in mineral sealing layers such as loess loam, meadow loam and clay will considerably increase susceptibility to cracking. For this reason, the Kügler-Belouschek system of active cracking prevention through self-repair – reinforcement of a mineral sealing layer using a suitable polyaramid tissue not causing a separation of sealing layers – is important as an additional safety factor. On installing this system, the sealing layer is additionally covered with a suitable fine-sanded silty infiltration layer. In the event of fine cracks occuring in the sealing layer, they will be sealed by seepage water issuing from the infiltration layer. A typical infiltration layer would consist of a distinctly fine-sanded medium or rough silt with a value of I_c • 0.5. According to DIN 18 300, such soils may in water-saturated state be classified as belonging to soil class 2 “soft grounds” in view of their high flowability. It is a fact based on experience that such infiltration soils will not incrust and will retain their flowability.

Long-term investigation of an alternative surface-sealing system with an enhanced mineral clay liner and an underlying capillary barrier at the sanitary landfill Karlsruhe-West (Germany)

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ABSTRACT: At the sanitary landfill Karlsruhe-West an alternative surface-sealing system with an enhanced mineral clay liner and an underlying capillary barrier is employed. A macro-scale lysimeter was used to obtain water balance data for more than six years. The data of the long-term investigation show that the alternative surface-sealing system is an effective and an economic way for covering a landfill and so reducing the seepage water infiltration rate to an minimum.

1. Introduction

Due to subsurface contaminations in the vicinity of the sanitary landfill Karlsruhe-West, the city of Karlsruhe was forced to realize a comprehensive remediation concept for this site. The central concern of this concept was the implacement of a qualified surface-sealing system covering the entire 22 hectare area of the waste site.

Due to the steep slope angles of 1:2.3 (23.5°), the installation of the regular sealing system involving a combination out of a polymeric membrane with high density (PE) on a highly compacted mineral clay liner as defined in the Technical Instruction for Domestic Waste (Technische Anleitung Siedlungsabfall, TA-Si, BUNDESMINISTERIUM FÜR UMWELT, NATURSCHUTZ UND REAKTORSICHERHEIT 1993) was not applicable. Therefore, an alternative surface-sealing system comprised of an enhanced mineral clay liner with an underlying capillary barrier was utilized as the main sealing unit.

For alternative surface-sealing systems, the TA-Si explicitly requires proof of equivalence. To provide such proof, a test field of 2.2 hectare, including an integrated macro-scale lysimeter of 10 x 40 meters, was built at the landfill Karlsruhe-West in 1993. This lysimeter is used to obtain water-balance data on the alternative sealing system. The processing of the data and the fieldwork is done by the Department of Applied Geology, University of Karlsruhe.

2. Test field (Lysimeter I)

2.1 Structure

In 1993 the lysimeter I was built in the southern part of the landfill (fig. 1). Its length is 40 m and its width is 10 m which results in a base area of 400 m^2. The surface is sloped with a gradient 1:2.3 (23.5°) to the south. In figure 2 the schematic structure of the lysimeter I is shown.

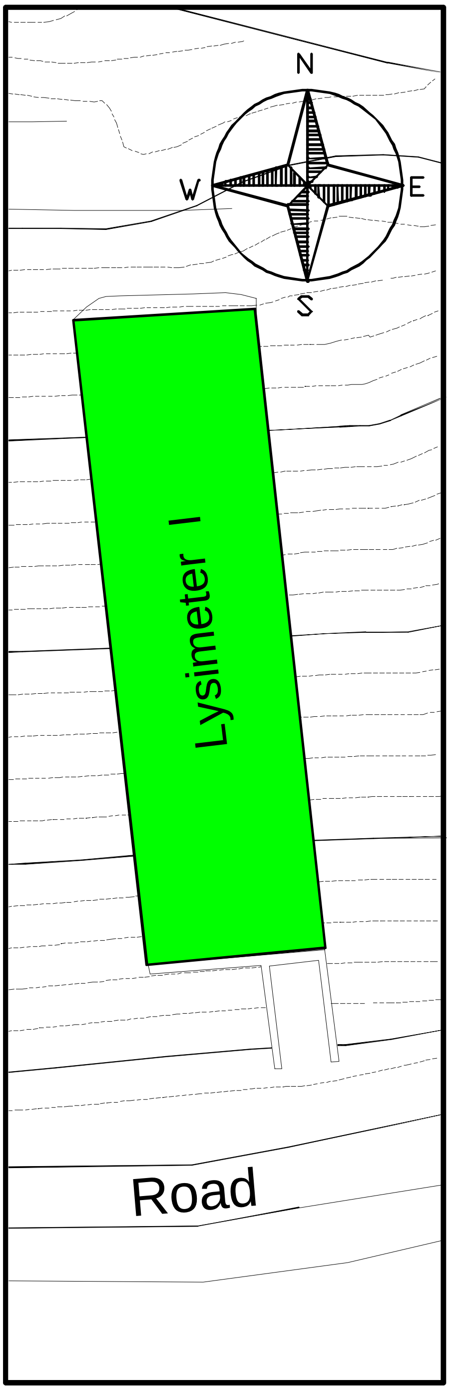

Figure 1. Site plan of the Lysimeter I.

2.2 Extent of the investigation

The extent of the performed investigations and the necessary measuring equipment at the sanitary landfill resulted from the following objectives:

- Proof of equivalence for the alternative surface-sealing system in comparison to the standard composite liner system postulated by the TA-Si regulation.
- Gaining data for a soil water balance with special emphasis on the vegetation support layer.
- Determination of the effectiveness of the capillary barrier system and of the whole alternative surface-sealing system.
- Long-term investigation of the hydraulic conductivity of the enhanced mineral clay liner.

The main input parameter is the daily precipitation depth. It is measured with three separate standard precipitation gauges. The daily depths of discharge for each different layer of the lysimeter were measured at a central measuring equipment and manually fed in the computer for processing.

On the lysimeter test field, four pipes (NS1 – NS4) for the use of a neutron probe were installed. The neutron probe was used for the weekly radiometric determination of the soil water content. The variation of the soil water content is an important factor for calculating the soil water balance.

Near to the test point NS 2 nine tensiometers were installed to measure the soil water potential and the hydraulic gradients in the unsaturated zone. From the data collected conclusions about the saturation conditions and the direction of water movement in the unsaturated zone are possible. The tensiometers measure water tension and soil temperature every four hours in several depths.

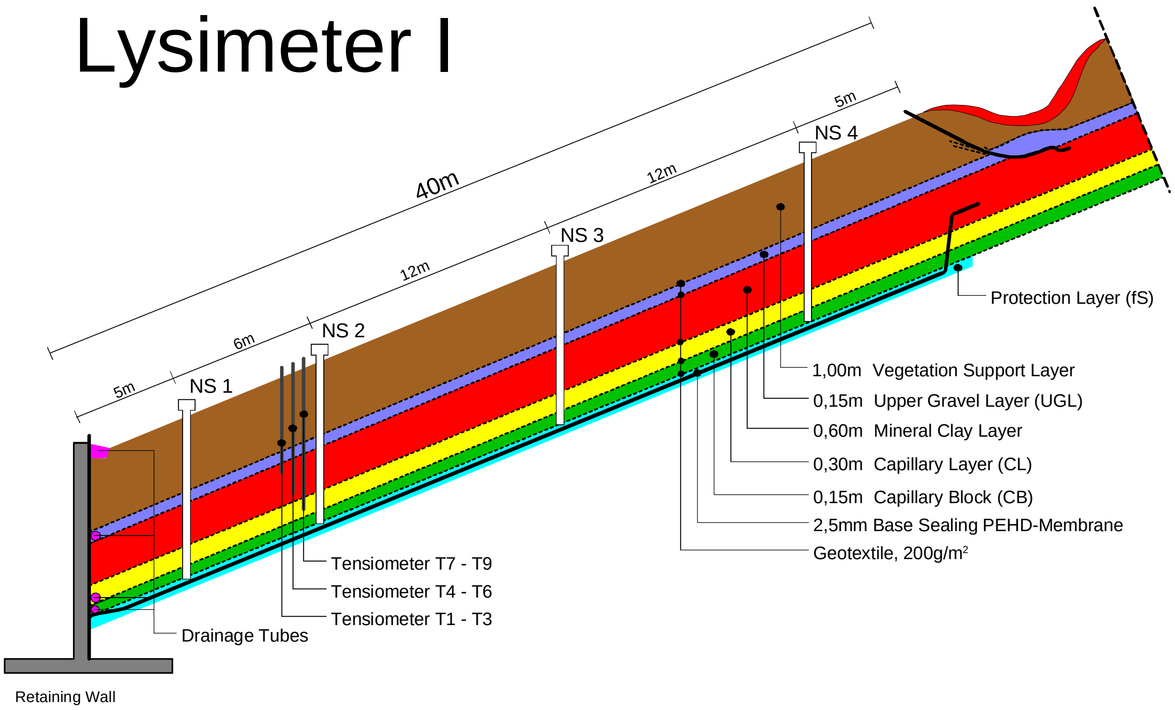

Figure 2. Schematic cross section of the Lysimeter I with the permanent measuring equipment.

3. Results of the long-term investigation

Precipitation (Prec.): Figure 3 shows the daily precipitation distribution for the entire observation period. The precipitation situation is characterized by a quite uniform and constant precipitation distribution which only occasionally exceeds a precipitation depth of 30 mm in 24 h. The absolute maximum was observed in February 1997 with a precipitation depth of more than 80 mm a day. The monthly and yearly precipitation sums are given in table 1. The listed data show that in the past period of measurement four years (1994, 1995, 1997, 1999) were characterized by a higher year sum than the long-term average (739 mm) and in two years (1996 and 1998) a lower year sum was observed. Hence the surface sealing in the period of observation was exposed to rather wetter weather conditions with respect to the long-term average.

Actual evapotranspiration (ETa): The difference of all water balance factors can be used for the computation of the actual evapotranspiration. For the undertaken measurements, data ascertained after WENDLING et al. (1984) was compared to the data for the actual evapotranspiration derived from the lysimeter measurements. For the individual water balance years this resulted in satisfying to good conformity. For the entire period of observation the actual evapotranspiration comes on an average to 83.5% of the precipitation.

Surface runoff (Q_{SURF}): For the surface runoff of the test field its considerable decrease and finally complete absence is remarkable. This phenomenon can be explained with the increasing density of the vegetation on the test field, but was not expected accounting the steep slope. However, an intensive check of the measurement unit which was undertaken several times confirmed the correctness of the determined data. The long-term water balance (table 2) shows that an average of approximately 0.3% of the precipitation runs off at the surface. In 1998 the surface runoff has stopped totally.

Upper gravel layer (Q_{UGL}): The upper gravel layer is normally supposed to drain the main amount of percolating water in this kind of system. The layer was emplaced with a reduced thickness of 0.15 m compared to the TA-Si standard (0.3 m). It is striking that for the period of observation the discharge in the upper gravel layer was considerably reduced and only small peaks are still observable. The discharge maxima correlate well with stronger precipitation events.

Over the entire period of measurement on an average 8.2% of the whole precipitation are drained in the upper gravel layer. For the last three years the upper gravel layer discharge lies below the one in the capillary layer. The development of the data gives a clear indication that the mineral clay layer looses its property of being mostly impermeable with time, because increasingly higher amounts of percolating water pass the mineral layer and are drained in the capillary layer.

Capillary layer (Q_{CL}): Figure 3 shows the discharge for the entire period of observation. A yearly change is clearly visible in the way that during the main precipitation period (November/December to April) the highest discharge intensities occur. This is characterized by a discontinuous curve due to precipitation and percolating activity of varying intensity. After this high discharge activity a normal discharge behavior develops, which can be compared to a storage hydrograph (ZISCHAK 1997). In the period of observation about 8.1% of the precipitation was drained in the capillary layer. It is apparent that the relation between the upper gravel layer discharge and the discharge of the capillary layer clearly shifted towards the latter. This indicates again the retention and draining property of the capillary layer.

Capillary block (Q_{CB}): The lateral discharge beneath the capillary block is equivalent to the sealing property of the whole system and in the end gives the amount of the potential percolating water recharge of the landfill. In the entire period of observation 0.6% of the precipitation runs off in permanent discharge activity. The permanent measurable low discharge beneath the capillary block is a result of the not optimally adjusted grain sizes in the capillary layer and the capillary block (ZISCHAK & HÖTZL 1996). With optimally dimensioned materials only smallest amounts of percolating water pass the boundary layer and these are merely added to the adhesion water. A measurable discharge is supposed to occur exclusively due to a failure during a hydraulic overstrain.

The four pronounced discharge peaks correlate well with the discharge maxima in the capillary layer and occurred only in periods of clearly higher precipitation activity. But even during these break-through events the daily discharge depths stayed relatively low. By far most of the time the daily discharge heights were below 0.025 mm. The low discharge depths in the capillary block show clearly that practically the entire percolating water is drained reliably by the capillary layer which fulfils its function as a sealing system within the capillary barrier.

Soil water storage (Δ_{SW}): The development of the soil humidity for the observation period is characterized by a pronounced decrease of the water contents in the summer months and a following rapid increase. This development is observable in all layers, including the mineral clay layer. The measurements of the water contents in the mineral clay layer indicate a persistent dry-up of this layer. This drying behavior is documented by neutron probe measurements in 1998 and 1999. All together the soil humidity decreased in the period of observation by -36.6 mm (-0.7% of the entire precipitation).

Hydraulic gradients: Tensiometers were used to determine the hydraulic gradients in the unsaturated zone. The calculation of the hydraulic gradients were undertaken with the capillary block as a reference level. This means that positive gradients show a water movement from top to bottom and negative values a motion vice versa. The development of the gradients between the first and the third layer of the mineral sealing confirm the fore-mentioned statements about the soil water conditions and the dry-up behavior of the mineral clay layer.

The tensiometer data show that in summer time the mineral clay layer experiences a strong negative hydraulic gradient which means it looses water. This result, in combination with the discharge data and the data of the neutron probe, are a strong indication for the at least partial dry-up of the mineral clay layer which leads to the observed increase in hydraulic permeability.

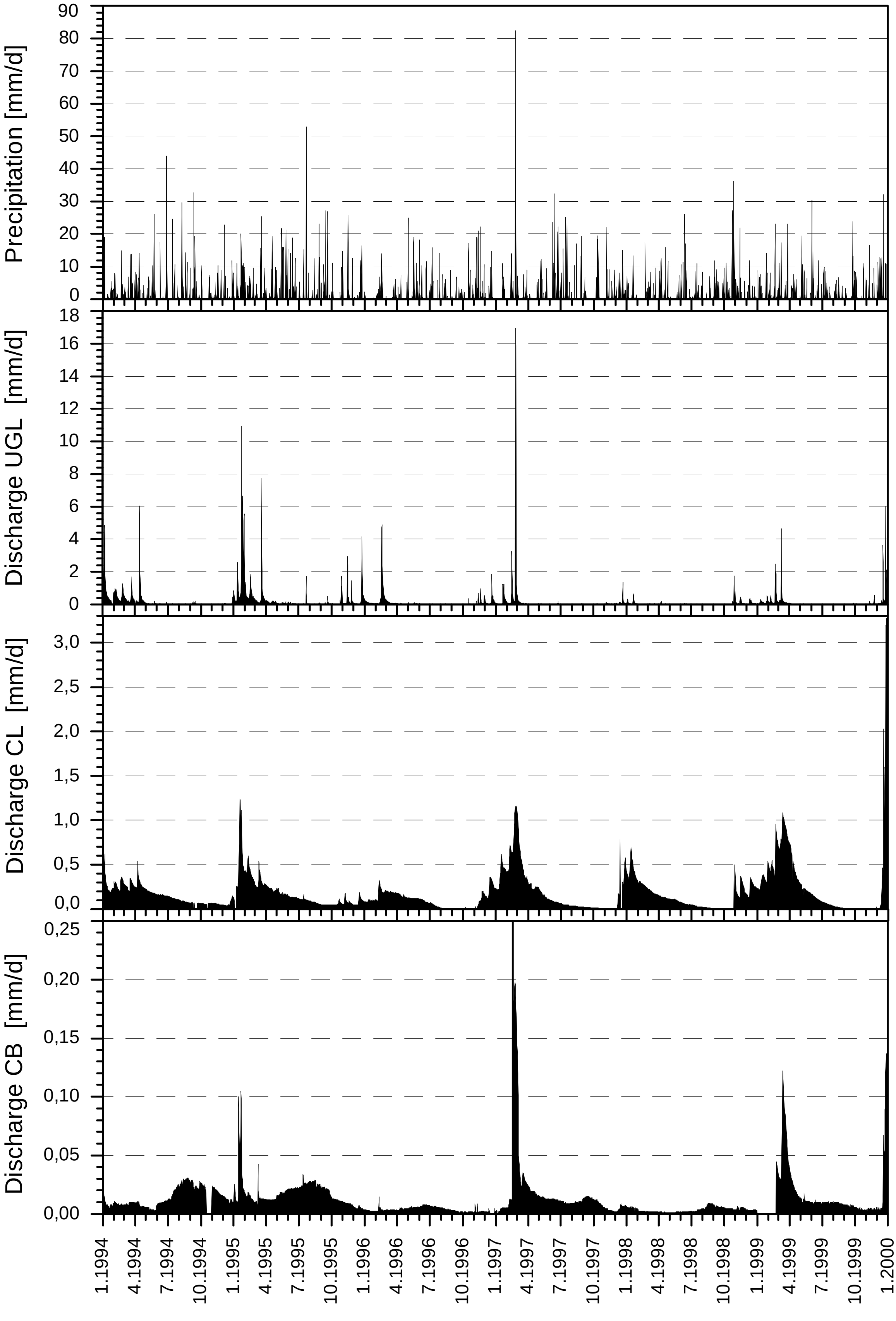

Figure 3. Daily precipitation and discharge depths in [mm/d].

4. Water balance of the alternative surface-sealing system

The following table 1 shows the monthly water balances, the yearly sums and the percentage of the precipitation (% of Prec.).

Table 1. Monthly soil water balances (all data in mm).

1994	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Sum	% of Prec.
Prec.	61.6	49.7	71.2	69.0	79.7	78.5	52.4	83.1	107.5	38.4	42.3	79.2	812.7	
Q_{SURF}	0.2	0.3	0.8	0.3	0.6	0.7	0.3	0.5	0.3	0.0	0.0	0.3	4.2	0.52
Q_{UGL}	32.4	17.1	11.7	21.1	1.3	0.5	0.1	0.0	0.0	0.0	0.2	2.7	87.2	10.73
Q_{CL}	8.9	7.0	8.4	8.4	6.5	4.9	4.2	3.0	1.5	1.8	1.9	1.5	58.1	7.15
Q_{CB}	0.3	0.2	0.2	0.3	0.2	0.2	0.4	0.8	0.8	0.6	0.5	0.4	4.9	0.60
Δ_{SW}	6.0	2.3	-16.3	-17.0	-39.6	-29.0	-25.3	-6.0	17.0	1.9	0.0	41.5	-64.5	-7.94
ETa	13.8	22.9	66.3	55.9	110.8	101.1	72.6	84.8	87.9	34.1	39.8	32.8	722.7	88.94
1995	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Sum	% of Prec.
Prec.	133.6	63.2	90.3	77.2	123.3	96.6	136.8	71.1	106.4	31.5	79.9	57.5	1067.5	
Q_{SURF}	0.9	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.0	2.2	0.20
Q_{UGL}	63.3	19.4	21.4	4.7	1.9	1.4	2.8	0.3	1.6	4.1	11.4	13.6	146.0	13.68
Q_{CL}	12.6	13.4	10.1	7.5	6.0	4.4	3.7	2.7	1.6	1.8	2.6	2.5	68.8	6.44
Q_{CB}	1.0	0.5	0.4	0.4	0.5	0.6	0.8	0.8	0.7	0.4	0.3	0.2	6.7	0.63
Δ_{SW}	41.9	-10.8	-1.0	-14.4	1.8	-24.0	-27.6	-17.5	34.3	15.8	13.4	17.0	28.9	2.71
ETa	13.9	40.5	59.2	78.9	112.9	114.0	157.0	84.5	68.1	9.4	52.2	24.3	814.9	76.34
1996	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Sum	% of Prec.
Prec.	5.1	66.4	21.7	23.1	111.7	74.0	69.3	41.9	19.0	62.7	127.4	37.8	660.1	
Q_{SURF}	0.0	0.0	0.0	0.0	0.4	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.6	0.10
Q_{UGL}	3.7	22.6	3.6	1.0	1.2	0.2	0.1	0.0	0.0	0.5	4.7	7.1	44.7	6.77
Q_{CL}	2.9	4.7	6.0	5.0	3.9	3.2	1.7	0.3	0.1	0.1	1.1	6.9	36.0	5.45
Q_{CB}	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	1.5	0.22
Δ_{SW}	-13.0	17.0	-13.8	-9.0	-2.3	-70.0	-39.2	-9.7	-19.3	31.3	91.4	26.5	-10.1	-1.53
ETa	11.4	22.1	25.7	26.0	108.3	140.3	106.4	51.1	38.1	30.7	30.1	-2.8	587.4	88.99
1997	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Sum	% of Prec.
Prec.	37.2	155.6	36.6	24.8	62.8	165.0	112.1	62.1	13.8	65.7	73.1	70.4	879.2	
Q_{SURF}	0.1	0.2	0.0	0.0	0.0	0.2	0.1	2.8	0.0	0.0	0.0	0.0	3.3	0.37
Q_{UGL}	8.1	45.7	4.4	0.1	0.2	0.5	0.1	0.0	0.0	0.2	1.1	4.5	64.8	7.37
Q_{CL}	10.4	15.5	23.7	8.4	6.0	2.9	1.8	1.1	0.7	0.4	0.3	3.0	74.3	8.45
Q_{CB}	0.1	1.6	2.8	0.7	0.5	0.4	0.3	0.3	0.4	0.4	0.1	0.1	7.6	0.87
Δ_{SW}	6.4	34.9	-45.2	-30.8	-50.9	45.1	-24.5	-26.3	-38.9	37.7	52.2	26.0	-14.3	-1.63
ETa	12.2	57.7	50.9	46.4	107.0	115.9	134.4	84.2	51.6	27.1	19.4	36.7	743.5	84.57

1998	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Sum	% of Prec.
Prec.	62.5	23.8	39.8	94.0	14.8	96.5	45.5	26.8	71.1	143.1	61.7	37.8	717.1	
Q_{SURF}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Q_{UGL}	3.9	0.4	0.3	0.8	0.0	0.3	0.1	0.0	0.0	2.9	4.0	2.8	15.5	2.15
Q_{CL}	14.9	8.8	6.6	4.4	3.5	2.1	1.1	0.5	0.2	1.0	7.0	7.3	57.4	8.01
Q_{CB}	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	1.4	0.20
Δ_{SW}	10.9	-7.0	-15.9	-31.9	-53.1	-25.3	-4.8	-13.4	14.4	100.6	18.0	12.5	4.8	0.66
ETa	32.6	21.5	48.7	120.7	64.3	119.4	49.0	39.5	56.3	38.4	32.6	15.1	638.0	88.97

1999	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Sum	% of Prec.
Prec.	77.1	67.1	93.0	49.3	66.1	79.7	52.0	36.8	67.0	49.3	48.0	160.1	845.6	
Q_{SURF}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Q_{UGL}	4.6	11.6	12.1	0.8	0.2	0.0	0.0	0.0	0.3	0.2	1.7	21.2	52.7	6.23
Q_{CL}	9.9	16.0	26.5	13.9	6.7	3.8	1.9	0.7	0.1	0.1	0.1	31.4	111.1	13.14
Q_{CB}	0.2	0.5	2.0	0.7	0.3	0.3	0.3	0.3	0.2	0.1	0.1	1.4	6.4	0.76
Δ_{SW}	27.5	8.6	-5.0	-113.7	18.2	-29.3	-27.1	-13.1	-0.3	27.2	40.2	89.2	22.7	2.68
ETa	34.9	30.4	57.4	147.6	40.7	104.9	76.9	48.9	66.7	21.6	6.0	16.9	652.7	77.19

For the past period of observation, an over-average hydraulic strain for the surface-sealing system results from the relative richness in precipitation (four wet years 1994 with 812 mm, 1995 with 1068 mm, 1997 with 879 mm and 1999 with 846 mm) and two dry years (1996 with 660 mm and 1998 with 717 mm).

The water balance term ETa results from the difference of all other terms of the water balance with ETa = Precipitation - ΣQ - $\Delta_{\text{soil water}}$ (= variation of soil water content) directly from the lysimeter measurements.

The data in table 1 demonstrate clearly, how the discharge behavior in the individual layers of the alternative surface-sealing system changes within the period of observation:

1. The surface runoff decreases progressively and could not be observed anymore from 1998 at all.
2. The relation between the discharge in the upper gravel layer and the discharge in the capillary layer shifts progressively towards the capillary layer.
3. The discharge of the capillary block, which resembles the percolating water infiltration rate of the landfill, always stays below 1% with respect to the yearly precipitation, in low precipitation years even below 0.25%.

Setting up a water balance for the entire period of observation results in the data given in table 2.

Table 2. Soil water balances for the entire observation period 01.01.1994–31.12.1999.

	[mm]	**[% of Prec.]**
Precipitation	4982.1	
Q_{SURF}	12.5	0.25
Q_{UGL}	409.6	8.22
Q_{CL}	404.8	8.12
Q_{CB}	28.5	0.57
$\Delta_{Soil\ Water}$	-32.6	-0.65
ETa	4159.3	83.48

The calculation of the average efficiency factor E_{cap} of the capillary barrier system from the equation

$$E_{cap} = 1 - \frac{\sum Q_{CB}}{\sum Q_{CL} + Q_{CB}}$$

gives a value of 0.93 for the period of observation. The average efficiency factor E_{tot} of the entire alternative surface-sealing system can be calculated from the equation (P = Precipitation)

$$E_{tot} = 1 - \frac{\sum Q_{CB}}{\sum P} = 0.994.$$

5. Conclusions

On the basis of the presented field data there are several conclusions with regard to the results of the long-term investigations on the alternative surface-sealing system with an enhanced mineral clay liner and an underlying capillary barrier (BREH & HÖTZL 1999):

- The presented data proof that the realized alternative surface-sealing system at the sanitary landfill Karlsruhe-West is an effective and economic surface-sealing system which reduces the amount of leachate in consequence of precipitation to a minimum. The results of the long-term investigation convinced the proper authorities to approve the employment of this alternative surface-sealing system.
- An increase of the thickness of the vegetation support layer from 1 m to 2 m should have positive consequences for the whole surface-sealing system because it increases the transpiration capability of the vegetation, it reduces the risk of root penetration and has a positive effect on the retardation of the percolating water.
- A thickness of 0.15 m for the upper gravel layer (TA-Si standard is 0.3 m) is sufficient for reliable draining of the percolating water in this layer.
- The development of the discharge distribution between upper gravel layer and capillary layer in favor of the latter as well as the results of the neutron probe and the tensiometer measurements are a clear indication that the hydraulic sealing properties of the mineral clay layer, even in enhanced form (thickness 0.6 m instead of 0.5 m), are already medium-term (within three years) significantly reduced. It is therefore to be further investigated by which technical precaution the required properties of the mineral sealing can be secured long-term or in what way the mineral layer is to be substituted by another sealing component, e.g. an asphalt layer, or to be omitted completely.

- A better adjustment of the materials of the capillary layer and the capillary block should result in a further increase of the efficiency of the capillary barrier system.

All these conclusions resulted in a modified alternative surface-sealing system for the landfill site Karlsruhe-West.

For the investigation of the modified structure and for demonstration of the equivalency according to TA-Si, the concept for an additional lysimeter test field (lysimeter II) was developed together by Ingenieurbüro Roth & Partner and the Department of Applied Geology Karlsruhe, Prof. Dr. Hötzl. The construction of the lysimeter II was completed in April 2000. The first results of the lysimeter II will be presented at a later date.

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Engineering proofing of territories by artificial hydrogeological insulation of ones

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ABSTRACT: At present a certain discrepancy exists between spreading of different natural and technogenous ecological problems on rather great territories and limited possibilities to cope with those problems by proprietors of separate grasps on these territories. This discrepancy may be removed by creation of artificial hydrogeologycally insulated territories with boundaries coinciding with ones of separate grasps. An artificial hydrogeologically insulated territory includes cutoff curtains along its boundaries in combination with controlling drainage on both of mentioned curtain's sides, absorbing structures and (if necessary) low banking. An artificial hydrogeological insulation of limited territory allows controlling groundwater level within the boundaries of this territory lower as well as upper of its natural elevation.

1. Introduction

At present, a certain discrepancy exists between spreading of different natural and technogenous ecological problems on rather large territories and limited possibilities to overcome these problems by proprietors of separate economies and farms.

The above-mentioned problems include:

- fouling of rivers, reservoirs (during discharges into them) and underground water (during infiltration into it substances of dissolved in water) by manure and fertilizers, pesticides, soil erosion products, sewage from storehouses and storage of toxical waste including spoil banks of rocks, accumulating ponds of highly by mineralized water from oil extracting plants, industrial facilities, under flooding of cemeteries, cattle and radioactive waste graves;
- presence of aggressive underground water in large territories;
- unsatisfactory (deficient or excess) natural soil humidification;
- droughts;
- floods;
- soil erosion and ravines forming;
- swamping and second land salinization under water filtration from irrigating canals or under excess irrigation, simultaneously with unsatisfactory quality or absence of drainage system at the irrigated territories;
- depression or excessive rise of underground water levels at cities due to different reasons;
- dewatering of territories near open castes;
- flooding and underflooding of great territories under creation of large artificial reservoirs and under rise of a sea level (for example, Caspian one);
- slide phenomena at river and reservoir banks (particularly owing to regulation of river);
- forest and peat fires, etc.

Execution of necessary measures on the whole territory (for example, a subject of administration division) demands often very great expenses exceeding the possibilities of local and State budgets. This obstacle reduces the effect of economic activity everywhere, reduces the land cost, makes this land unattractive for residing, etc.

At the same time, if to refuse the intention of directed change in ecological conditions in great territories right away, then it is possible to implement it in principle in separate lots in borders of separate facilities, farms or settlement territories.

By analogy, it may to adduce a practice of fencing along private estates borders for property right guarantee, with creation inside of the fenced in lots of architectural-vegetable landscape, which is distinctly different from ones in the present locality. Another example of this my be the layout of greenhouses with creation of optimal conditions for cultivated plants.

The common feature of the above examples is an artificial insulation of the own territory (or part of it) from the environment. This particular approach for directed change of ecological conditions is being considered here.

A successful change of ecological conditions in some insulated lots can be executed according to possibilities of individual proprietors. That may be considered as the initial stage of consistent improvement of ecological situation in the whole given territory.

A steady population growth of Earth with simultaneous desertification, accompanied by distinct tendency of the climate warming, are the acknowledged processes. Demanding divelopment and implementation of effective measures, aimed at preserving the land areas, fit for civilized life, normal economic activity as well as regaining areas, taken out of economic turnover due to different reasons.

2. The proposed conception of artificial hydrogeological insulation of territories

The combined analysis of above-mentioned ecological problems shows that their possible engineering solutions may be brought down to one common technical task: underground water levels control in restricted territories in relation to their natural evaluation (above or lower). This analysis adduced in following issues of this work.

The known methods of underground water levels control, for example, drainage, wellpointing, subirrigation, artificial flooding used for achievement of local results improving the ecological situation in restricted territories, in individual economies, often cause negative side phenomena. They are underflooding, second salinization, soil erosion, fouling of rivers and reservoirs, unproductive fresh water losses. And this, in its turn gives rise to additional expenditures (not considering economic detriment due to ecological situation deterioration).

In our case it is of principal importance that the above-mentioned level control must be executed not in the whole territory, but in part of it that is in relation to real underground water levels elevation in the surrounding locality.

Thus, to realize the above idea, what is required is a restricted territory, physically insulated from the environment, where underground water levels control can be carried out. By an artificially insulated territory we understand a territory cordoned off along the perimeter (in several cases - along perimeter's part) by cutoff curtains, which are cut into an impervious bed. If necessary, it can fenced too by dams, with cutoff curtains being placed inside dam's bodies. In special cases (absence or very deep location of a natural impervious bed) a complete insulation of the territory is provided additionally by execution of underground, horizontal impervious screens. An artificially hydrogeologically insulated territory is shown in general view Figure 1.

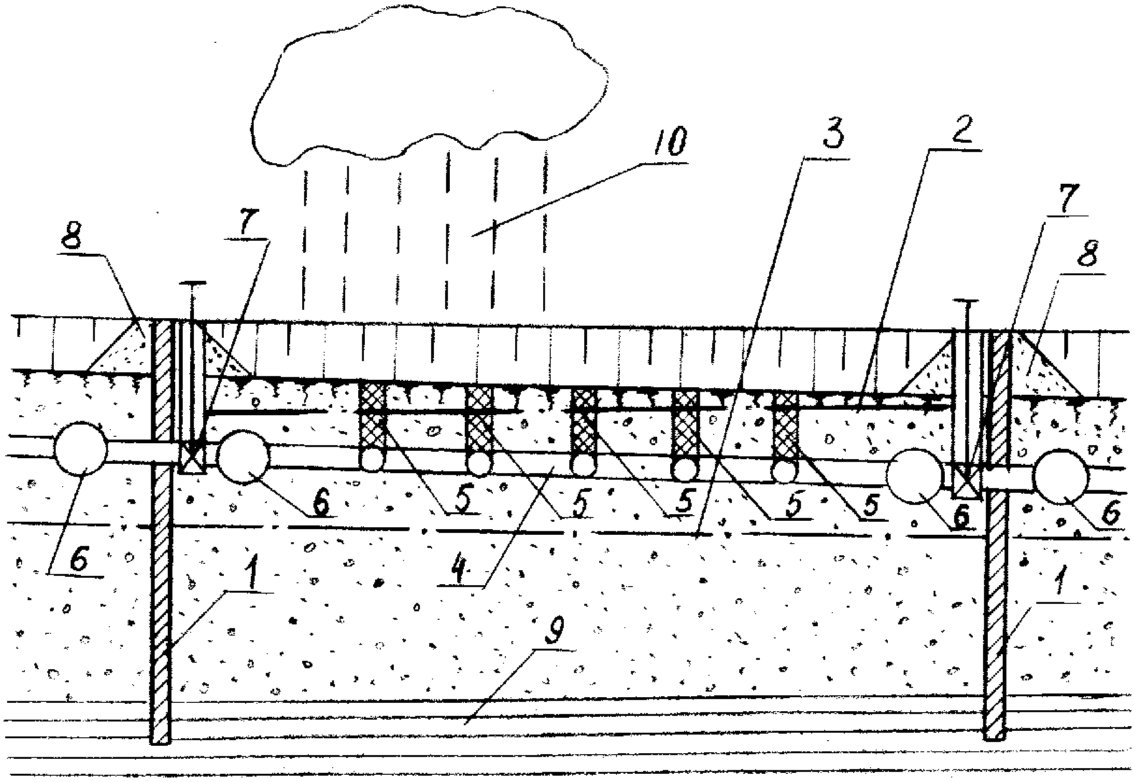

Figure 1. General view of artificially hydrogeologically insulated territory.
1 – cutoff curtain; 2 – artificially set up level of underground water; 3 – natural level of underground water; 4 - drainage-distribution network; 5 – absorption structure; 6 – drainage collector; 7 – controlling valve; 8 – fencing dam; 9 – impervious bed; 10 – precipitation.

A system for underground water levels control at an insulated territory can be executed (in general case) as a drainage network, for example, with drains of two-side operation, including drainage collectors at the entrance and exit of the drainage network. Drainage collectors must also be located outside insulated territory contour, that is on the other side of exterior sides of cutoff curtains. Drainage collectors at both sides of the curtain must be connected by bypassing tubes equipped with control valves. In general, absorbing arrangements connected with drainage network are also executed in an artificially insulated territory. In concrete cases, - all mentioned arrangements and works or several of them are used.

Water arrives at the territory with precipitation or with natural underground water flow, which is transferred from contiguous territories to the insulated one (for example, in a flood period, also from the above located territories or other artificially insulated ones). It can be used for forced underground water levels rising. When necessary, other exterior water sources can be used.

For forced underground water levels lowering in an artificially insulated territory a drainage network (with free or forced water dumping) is used.

A required underground water level inside the insulated territory is set up at necessary elevation with the help of control valves on bypassing tubes. The lowest level position is in agreement with depth of the drainage network horizon, the topmost level position is determined by fenced dam height.

At present the mentioned systems in artificially insulated territories are used in practice in a number of cases (for example, at storage for toxical wastes), however it is consistent conceptual method of approach allows to range of their applications and universalize the solutions of ecological problems.

3. The evaluation of technical and practical possibilities

Although a sufficient quantity of adequate technical means for drainage systems construction exists at present, the use of most wide spread ones for construction of cutoff curtains of great length is connected with unjustified great expenses and a long period time.

Therefore it is necessary to use optimal on a productivity and on cost technologies of cutoff curtain engineering for equipping artificially hydrogeologically insulated territories.

Apparently, jet grouting method corresponds well to the mentioned requirements. The essence of the mentioned technology is a directed horizontal soil washing out by high-speed water jet inside artificial air stream. It feeds from bore holes drilled in the soil beforehand, with narrow slot formed in the soil. Under that washing out device, jet monitor, is slowly lifted, with withdrawing of washed out soil through the holes and with synchronous filling of the slot as far as one is formed by hardening solution.

Jet grouting method of thin cutoff curtain executing is shown in Figure 2.

The mentioned technology has been mastered well in Russia. The important circumstance is that it was in Russia that technology has been adapted successfully to quantity-produced constructional equipment characteristics (for example, pumps with pressure of 6...10 MPa). While in other countries equipment of unique characteristics (for example, pump with pressure of 50...100 MPa) is used for this aim. With that the substantially larger length of one cutoff curtain section, up to 5 m under two-side washing out we have produced due to optimal relationship between a pump pressure and one's productivity. This is attributed by the fact, that super-high-speed and very thin liquid jets are sprayed at a short distance from the nozzle, and jets with lesser speed but greater diameter keep their compactness along a greater distance. Under two-side washing-out the working productivity of this technology, can achieve up to 2,5 m^2 per a minute. The approximate price of a thin cutoff curtain constructing by this method in Russia equals to \$15…20 per 1 m^2.

The technology of thin underground horizontal screens at a given deep (artificial impervious stratum) has been developed at present, but its practical mastering is impending. Our improved jet grouting method also allows to create drainage without pipes, including at a great depth.

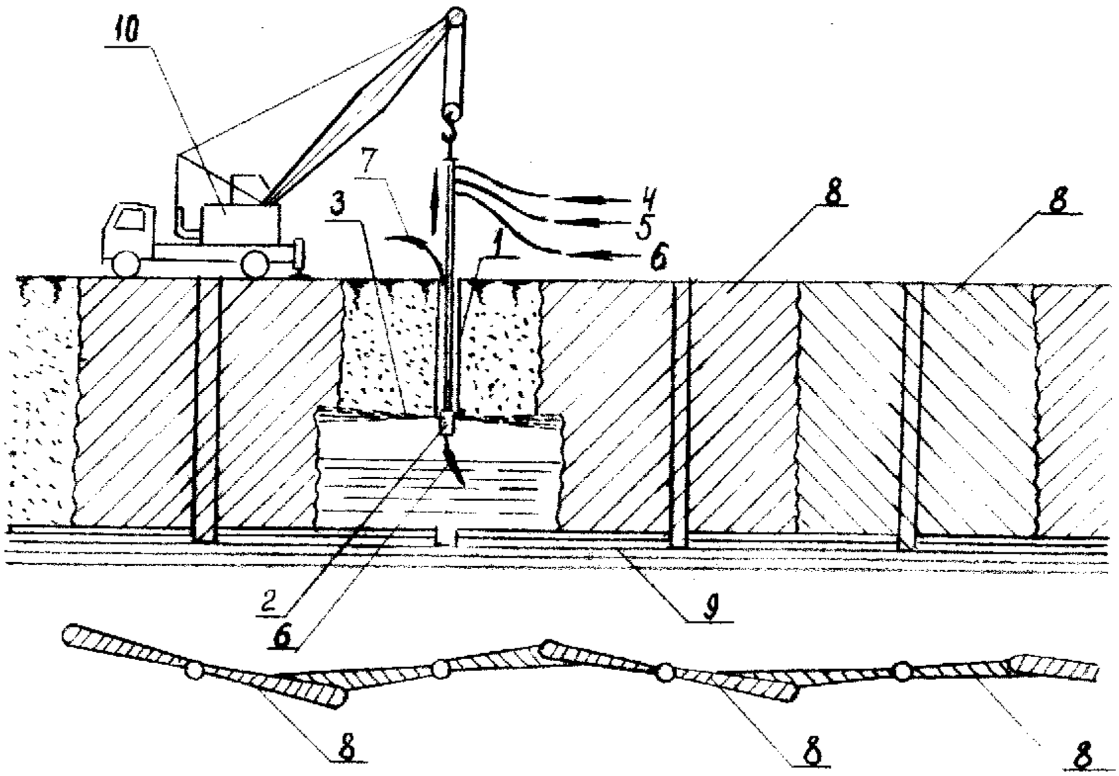

Figure 2. Jet grouting method of thin cutoff curtain executing.
1 – bore hole; 2 – jet monitor; 3 – high-speed jet inside artificial air stream; 4 – pressured water; 5 – compressed air; 6 – hardening solution; 7 – pulp of washing out soil; 8 – section of cutoff curtain; 9 – impervious bed; 10 – lifting crane.

4. Proofing of territories against fouled and mineralized underground water

For proofing of an artificially hydrogeologically insulated territory against a fouling it is necessary to keep the underground water level above its evaluations in the environment. The excess of levels can not be large. So a specified consumption of pure water will not be large too, even in the cases of local breaches in the curtain. It is worth using a clay-concrete material for curtains.

With presence of aggressive underground water in the environment, in several regions most of communications have to be installed on earth surface (for example, in Kazachstan). In those cases a proofing of restricted, insulated territory is obviously more worth, than protection of each individual underground structure or individual construction.

A similarly proofing of spacious seaside territories, where underground water mixed with sea water, can be curried out. This circumstance deteriorates essentially conditions of local water supply and agriculture.

As a perspective example, Jalama beach in Azerbaijan can be pointed out, where abundant underground water moving from the Caucasus Mountains, runs out into the Caspian sea in the form of numerous submarine springs. A lush vegetation with great foliage forests can be bound in the zone of 25 km, while adjoining on both sides extensive sea beach territories are a burned out steppe. A constructing of a cutoff curtain along the sea beach at the mentioned and adjoining territories will allow converting the great areas of lifeless earth into flowering land.

In cases, when large-scale mining or production is curried out or large plants producing a toxically waste are situated, the following can be curried out. An artificial hydrogeological insulation of the territory must be created. With underground water levels maintenance above the levels of fouled underground water in surrounding industrial areas. It allows to reduce in a large degree the negative influence of the mentioned factors on the quality of drinking water and agricultural production, human health, state of flora and fauna. Thus, green plantations in cities can be protected, where they perish due to wastes containing toxical anti-icing solutions of salt.

5. Underground water storage

A desertification process and, in wider understanding, increase of territories, unsuitable for a normal economical activity, are at present steady tendency. Those processes can be stopped and, more over, the lost lands can be regained on the basis of artificially hydrologically insulated territories creation.

An underground water storage can be carried out in porous soil, for example, in countries with hot and warm climate. It allows using a natural surface and underground water sources including temporary ones, precipitation, structures for atmospheric condensation accumulation, bailing of water from deep layers.

Water losses on evaporation and filtration are less in hydrogeologically insulated soil massif by contrast to water storage basins. Artificial oasis can be created, using underground water storage in combination with measures on soil cover reclamation. And water losses on filtration under an irrigation of agricultural plants (achieving up to 65%) will be returned into the underground space of the insulated territory. In countries with monsoon climate, where long-duration droughts follow the rain season, those insulating territories will be especially effective. A prevention of territories located near open castes problem can be solved by similarly.

An abrupt depression of underground water in city territories due to different technogenous reasons can result in (and it has been the case in Russia) houses breakdown on loose basis. Creation of artificially insulated territories in cities, within some districts will allow proofing against a underground water levels depression.

6. Insulation of fouling sources

An artificial hydrogeological insulation must be created for industrial plants producing toxical wastes, industrial and domestic wastes storage, graveyards, rubbish heaps, territories of potential ecological catastrophes with underground water levels control by lower elevation of them on surrounding localities. It will allow to prevent positively a fouling spread in great territories. It is necessary to create purification structures. In Russia there are numerous storage-houses of radioactive and high-toxical wastes, and unequipped open storage areas of solid domestic wastes, whose summary volume exceeds at present 80-milliard m^3. A creation of artificially hydrogeologically insulated territories is especially actual here.

7. Proofing of territories against imperfect melioration, flooding, slides etc.

An artificially insulated territory creation for lowering of underground water levels in a concrete districted area can be very effective. This is because that does not require simultaneous lowering of the levels in great surrounding locality, as it takes place in usual drainage systems. In the later case, it leads to great useless fresh water losses, besides big waste expenses. In cases, when it is necessary to remove drainage water with use of pumping, discharges of the pumping will be hundreds of time less in comparison with the usual drainage.

Thus, in these cases, quick expenses compensation for artificially insulated territories creation can be expected.

Using of artificially insulating territories equipped with drainage systems, absorbing structures and dams allows eliminating a soil erosion and reservoirs fouling, it also allows accumulating water supply into ground massif due to precipitation and snow water.

With a great quantity of areas with artificially insulated territories, in the river basin accumulation of large water volumes in soil massifs allows fairing the flooding peaks and preventing the catastrophic flooding. This, in its turn, will decrease the necessity to create water storage basins, which give rise the great ecological problems. Great flooding at Europe and USA in 90-th years is explained by many specialists as a sequence of excessive consolidation of soil upper layers, and as a result surface flow of precipitation and snow water into the rivers direct.

Construction of cutoff curtains along arterial and distributing irrigating canals will allow preventing a swamping of adjusted areas. Creation of artificially insulated territories in concrete economy areas will allow avoiding of a soil second salinization under when irrigation norms in neighboring economies (for example, at Central-Asian region) are not absorbed.

A possibility of underground water levels control in artificially insulated territories with aim of irrigation (subirrigation) can be used with extreme-care, taking into account the local soil and hydrochemistry conditions.

Proofing against slides includes creation of artificially insulated territories in places, which have a danger of slides, and draining of underground water seeping through the cutoff curtains. These insulation territories are located beyond the falling prism boarders. It is known, what usual drainage piracies not more, than 50% of filtration stream discharge. In our case an absolute volume of common filtration discharge is reduced by multiply, which would be reflected positively on dangerous slope stability.

In North regions, where icing fields, ice mounds and ground icing present a serious danger for different objects, an artificial hydrogeological insulation of residential and economic objects territories can to prevent the icing forming.

8. Proofing against flooding and underflooding of territories by water storage or sea

After creation of new water storage basins an underground water levels rise of several years can caused underflooding of great adjoining territories (for example, in Russia), including settlements, industrial plants, agricultural plantations. With the active rise of the Caspian Sea level in the last few years, many domestic and economic objects have found oneself in flooding zone.

In the mentioned cases, it is worth carrying out a proofing against underflooding of separate territories by their hydrogeological insulation with fencing dams construction. With this systems of polder type are formed. Discharge of pumping of underground water flowing from the polder will be comparatively very small due to the cutoff curtains. Dams and cutoff curtains in such territories lay not with-out tail along closed contour, if the territory is contiguous with a natural slope of the locality. However, in those cases it is necessary implement to piracy of underground water from above-lying territories by drainage on the elevation, exceeding the flooding levels.

9. Proofing against forests and peat fires

A reason of forest and peat fires in a hot time of the year is a drying up of soil upper layers, rotten woody-pulp and an ignition of the dry material from occasional sources.

A proofing against such fire can be carried out in separate artificially insulated territories. It can be made by time delay of spring flood and precipitation up to end of most high temperatures, with following natural discharge of excessive groundwater, in order not to allow swamping of the territories. With that a forest and peat soil surface will remain moist during the dangerous period, and a fire rise possibility will be eliminated practically.

10. Conclusion

The analysis of possibilities of artificially hydrogeologically insulated territories using for engineering proofing and reclamation of them confirms the important conception of this work. That is overcoming of many different natural and technogenous ecological problems can be achieved by unified method: by underground water levels control into borders of the proofing territory. For executing of the mentioned works existing equipment and an existing practical experience on cutoff curtains and drainage systems can be used.

Preliminary economical evaluations show, that the a cost of works on artificially hydrogeologically insulated territories will account for a small part of the cost of proofed earth area in industrially developed regions (excluding cases of very deep natural watertight layer location). However so far as after mentioned works execution an earth cost will rise in the insulated territories, such expenses can be considered justified.

In spite of expressed modification of a climate and an ecological situation change for the worse, we still have a possibility to avoid the fate of helpless victims of an element and of our own industrial technologies imperfections.

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Landfill liners and covers – Development and practical application of sealing systems in Germany

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ABSTRACT: Liners at the base of solid waste landfills prevent leachate from migrating towards the ground water. Covers keep snow and rainwater away from the waste deposit and help to minimize the generation of leachate in the long term. The sealing layers consist of soils of low hydraulic conductivity and of geomembranes or asphalt. Extensive research and development work aiming at an appropriate assessment of the effectiveness of different sealing systems has been exercised in Germany during the past three decades. The practice of constructing composite basal liners is well established. But the standard solutions for cover systems are being questioned at the present time and supposedly will be updated. The paper presents a brief review of several liner and cover systems.

1. Introduction

In Germany and in some other European countries strategies to reduce, reuse and recycle residues have been effective in minimising the amount of solid waste to be disposed of. The demand for storage space for solid waste has declined drastically as compared to conditions 10 to 15 years ago, the time when the development of technical rules for safe waste disposal was a major issue to the geotechnical profession. The political commitment of the German Federal Ministry of the Environment aims at further reducing the amount of solid waste by promoting the development of waste processing techniques. However, the need to design and construct new and to rehabilitate old landfills for solid waste still exists and calls for the attention of geotechnical engineers.

In order to achieve a comparable high level of safety with respect to the protection of the environment at all waste disposal sites, technical instructions for hazardous and for domestic waste landfills have been issued by the German Federal Government, TA-Abfall (1991) and TA-Siedlungsabfall (1993). These instructions are supplemented by regulations of the German States in order to account for regional particularities. Recently a group of experts from all German State Administrations, LAGA-Arbeitsgruppe (2000) reviewed the Federal instructions for cover systems and prepared an update accounting for recent technical and scientific developments.

Independent of the Federal Government regulations but in accordance with them, since 1985 the German Geotechnical Society (Deutsche Gesellschaft für Geotechnik, DGGT) has edited Geotechnical Recommendations for the design and construction of landfills annually in the journal Bautechnik. They have been elaborated by the technical committee on Geotechnics of Landfills (Arbeitskreis Geotechnik der Deponiebauwerke, AK 6.1). The state of the art was compiled and put down in the 3rd edition of GDA-Empfehlungen, DGGT (1997). The series of recommendations is updated and extended by new issues every year Gartung & Neff (1997, 1998, 1999, 2000).

2. Solid waste landfills – engineered structures

Solid waste may contain substances which are harmful to the environment. So the engineering problem to be solved consists of designing and constructing a containment which safely prevents hazardous and harmful substances from migrating into the environment and endangering the nature. The philosophy to achieve this follows the concept of the multibarrier sytem, Stief (1986). The first barrier is the waste itself. It should be deposited in such a condition that no substantial chemical and biological reactions will take place and that harmful components are not present or at least are not mobile. The second barrier is the basal lining system for the prevention of leachate from contaminating the ground and the ground water. The next barrier is the natural ground on which the landfill rests. It should possess a low permeability and a high adsorption capacity and thus act as an efficient geological barrier. Finally the landfill body will be provided with a cover when the landfilling operation ceases. The capping barrier acts in two ways, it retains dust, odours and gas developed within the waste and it keeps precipitation water outside the waste body thus minimising the generation of contaminated leachate.

The natural and the technical barriers of solid waste landfills interact. They are influenced by the geology of the site, the climatic conditions, the type of waste and the technical means by which they are constructed. So each landfill project requires careful studies of the natural site conditions and must be designed individually in such a way that all relevant aspects are encompassed.

3. Basal liners

3.1 General aspects

The technical barrier at the base of a landfill has to prevent seepage out of the waste body. Since any repair of the basal liner of an operating or of a closed landfill would be practically impossible, the basal liner must serve its function reliably and permanently. The basal liner system consists of a mineral liner of low hydraulic conductivity, in most cases a synthetic geomembrane, a protector for the sensitive geomembrane and leachate collection facilities.

These consist of a coarse grained drainage blanket inclined at an angle of at least 3 to 5 degrees, sufficient to facilitate gravitational flow of the leachate towards perforated pipes which conduct it to maintenance shafts and further out of the landfill containment for treatment in a purification plant.

The basal liner system rests directly on the natural ground, that is at the surface of the geological barrier. There should be no drainage layer or capillary block below the mineral liner, in order to prevent the loss of moisture. The hydraulic conductivity of mineral liners is lowest, when they are well compacted at a water content slightly above the Proctor-optimum and keep this moisture content. If the mineral liner would lose water, it might develop desiccation cracks and the sealing function could be impeded.

3.2 Compacted clay liners

A major component of standard basal seal consists of a well compacted layer of natural clay. By the selection of suitable clayey soil, thorough homogenisation, adequate compaction at the correct water content, it is possible to obtain hydraulic conductivity values of the mineral liner of less than $5*10^{-10}$ m/s. This is the highest accepted permeability of mineral basal liners according to German technical standards. For the preparation of each individual job suitability testing in a soil mechanics laboratory and at site compaction tests in a test field for the optimisation of the applied construction technology and equipment are required. It is further of great importance to have well trained and quality minded personnel at the construction site who perform the earthwork reliably under a rigorously exercised quality management. Finally it is relevant to the quality of the mineral liner to protect the finished surface against desiccation, rain, snow and frost action. The achievement of the desired low hydraulic conductivity and efficient permanent sealing function in the field depends largely on the execution of the job. So great emphasis is placed on quality-management and -testing.

The scientific basis for the assessment of the efficiency of mineral liners to act as seals with respect to seepage and to diffusion is well established by soil mechanics fundamentals and by specific research. If alternative mineral liners are proposed, their equivalency with the standard compacted clay liner is demonstrated in accordance with the rules of the German Institute of Construction Technique, DIBt (1995). They include experiments for the determination of the properties of the liner material, in particular the hydraulic conductivity and the diffusion coefficient under specified boundary conditions and the calculation of leakage and diffusion rates for specified assumed actions.

Gartung et al. (1999) exhumed a compacted clay liner at the base of a domestic waste landfill after more than 12 years of operation. Samples were taken and analysed by scientists from the disciplines: soil mechanics, mineralogy-geochemistry and microbiology. In summary the results lead to the conclusion, that under the pertinent favourable conditions the sealing function of the compacted clay liner improved with time and that the barrier performed better than expected on the basis of permeation calculations. It seems that phenomena of coupled flow due to hydraulic, electrical, chemical concentration and thermal gradients as described by Mitchell (1976) and microbial life at the surface of the compacted clay liner contribute considerably to the barrier function and almost eliminate hydraulic and diffusive migration of pollutants. This result is of great interest for the evaluation of the contamination potential of many older landfills which are equipped with compacted clay liners only without geomembranes. It is also noticeable for predictions of the long term behaviour of landfills with composite basal liners for time periods beyond degradation of the polyolefine geomembranes.

3.3 Alternative mineral liners

In areas where natural clays, clayey sands or silts are not available as construction materials for basal liners, coarser soils are blended with a sufficient amount of imported clay powder (between 3 to 15%), such as bentonite, kaolinitic or illitic clays. Well composed gradations of this type mixed in plant and compacted to high values of dry density can reach a lower hydraulic conductivity than typical natural clays. Systematic research into the behaviour and performance of the blended mineral liner materials has lead to products called BENTOKIES, DYWIDAG Trockengemisch, and CHEMOTON. The latter one with improved performance and high resistivity against aggressive chemicals due to additives, silicates and DYNAGROUT, Lauf & Müllner (1993).

The thickness of compacted clay liners which comply with the hydraulic conductivity requirements mentioned above amounts to 50 cm for landfills of category I, containing harmless waste such as inert construction residues, 75 cm for domestic waste and for their incineration residues landfill category II, and 150 cm for hazardous waste landfill category

III. If mineral liners with superior sealing performance are used such as CHEMOTON, the thickness of the basal liner can be reduced according to their improved lower hydraulic conductivity as compared to standard requirements.

3.4 Composite liners

Landfills of categories II (domestic) and III (hazardous) are provided with composite liners at the base. Composite liners consist of a low permeability mineral layer, either compacted clay or blended minerals as described in previous chapters and a 2.5 mm thick geomembrane on top of it. This combination is an especially effective barrier when both components are placed in intimate contact. Geomembranes of high density polyethylene PEHD consist of nonpolar molecules. They completely retain harmful polar substances such as e.g. heavy metal ions, but they are somewhat pervious to nonpolar liquids such as chlorinated hydrocarbons. If hydrocarbons permeate through the PEHD geomembrane they encounter the surface of the mineral liner which is composed of polar molecules restricting further migration. When there is no lateral flow at the interface of the geomembrane and the compacted clay liner, because both components are in intimate contact, there will be an increase of the concentration of hydrocarbons at the lower side of and within the geomembrane causing a reduction of the concentration gradient and thus the diffusion of hydrocarbons through the geomembrane ceases, August et al. (1992).

To achieve this beneficial performance of the composite liner, intimate contact between the geomembrane and the mineral liner must be reached in construction. This means that the spread geomembrane is not allowed to have any waves or wrinkles. Very careful planning and sequential execution of the construction work is asked for, taking the physical properties, in particular the thermal expansion of the geomembrane and the daily temperature cycle at the site, into account.

In order to warrant a high quality of the geomembranes, German standards request geomembranes used in landfill construction to be approved by the Federal Institution for Material Research and Testing (BAM). The criteria which geomembranes have to meet for the application in landfill construction with respect to manufacturing as well as with respect to installation at the construction site are very strict, they are well established and during the past 10 years have proved to be reliable and efficient, BAM (1992). Quality management in the production, transportation, placement and fusion welding of geomembrane sheets is exercised with great emphasis.

Geomembranes are sensitive against damage. To prevent puncturing caused by coarse grained drainage gravel or crushed rock, special protection layers are placed between the geomembrane and the drainage blanket. These protectors formerly consisted of 10 cm thick sand layers. Nowadays geosynthetics or geocomposites like sand filled geotextile mats are used. Cushioning geosynthetic products without mineral filling have also been applied successfully Zanzinger & Gartung (1999).

Asphalt is sometimes used instead of polyolefine geomembranes. The sealing performance and the resistance of asphalt to aggressive chemical substances has been demonstrated by long term testing, Arand et al. (1992). Rules for the design and execution of asphalt liners at the base of solid waste landfills were put down by the German Institute of Construction Technique and the German Geotechnical Society, GDA (1997).

4. Cover systems

4.1 General aspects

When the filling process of a solid waste landfill or of a larger portion of it is completed, the surface of the waste body is covered by an upper barrier to close the waste confinement to the atmosphere. Many older waste dumps, deposited before the time of engineered landfills and thus neither equipped with a basal liner nor with an impervious cap have to be retrofitted with cover systems which are essentially designed along the same lines as covers for modern engineered landfills. The cover system prevents the infiltration of rain water, the emission of odours, dust and gas, and it facilitates the growth of vegetation and landscaping. The cover should be impervious or of low hydraulic conductivity, it ties the waste landfill into the environment, into the nature and thus has to be designed for the pertinent local climatic conditions.

The main components of the cover are: a regulating soil layer immediately above the waste body, a gas venting system, sealing layers, a drainage system and the restoration profile. Depending on the requirements for different landfill categories and different stages of landfill age, these layers may vary to some extent. The properties and the behaviour of the waste influence the performance of the cap. They are evaluated according to methods of waste mechanics and taken into account in stability analyses and settlement predictions, Jessberger (1993). For waste bodies which contain mineral solids that do not undergo chemical or biological reactions, no major long term settlements are expected.

Most solid wastes are not suited for finish profiling. So in general a regulating soil layer of about 30 to 50 cm thickness is needed for this purpose. If gas is generated in the landfill body a gas venting system has to be installed below the seal. The functions of the regulating layer and the gas venting layer are most often served in combination by a single sandy soil layer, typically recycled material. It must be sufficiently pervious and it has to be compacted to a degree that facilitates qualified earth work, in particular adequate compaction of the overlying mineral sealing layers. The gas is collected by pipes and either used for energy production or it is processed and released in a harmless state.

4.2 Mineral sealing layers

For landfills without long term differential settlements, the placement of the final cover can be carried out as soon as the design height is reached. However common municipal waste bodies are very compressible and in addition to that are essentially bio-reactors, where degradation processes take place in the waste body, associated with significant gas production and volume changes. The surfaces of domestic waste landfills experience large settlements for quite some time, substantial settlement differences may occur locally, impeding the integrity of mineral seals and straining geomembranes. So it is advisable to provide municipal landfills with an interim cover and to install the final impervious capping system after the cease of major settlements. To determine the right time for this action, the deformation of the landfill surface is monitored.

Since bio-reactors need a certain amount of water for the degradation processes, some leakage of the interim cover is probably of no concern. In a few German landfills which were provided with impervious geomembranes at an early stage, gas production slowed down to such a degree, that technical means had to be provided for the supply of water below the seal in order to keep the microbiology alive and the degradation of organic waste ongoing. So the former practice to cover every landfill with a mineral sealing layer and a geomembrane as soon as the waste body had reached the design height, is presently changing towards the application of interim mineral sealing layers which are not absolutely water tight and which can be integrated into the final cover systems at a later stage.

The Federal instructions of TA-Siedlungsabfall (1993) specify a compacted clay layer placed in two lifts of 0.25 m thickness each with a coefficient of hydraulic conductivity of no more than $5*10^{-9}$ m/s. This type of mineral sealing layer has been constructed at many landfill sites. However, often the side slopes of waste bodies are steeper than the long term shear strength of natural clays permit. Blended mineral sealing materials with a high content of coarse grained soils such as BENTOKIES or CHEMOTON, mentioned earlier, have large angles of internal friction and provide sufficient stability. They can be used at slopes which could not be covered with natural clays. The coarse grained mixed in plant mineral seals further have the advantage that lower coefficients of hydraulic conductivity can be achieved, so the thickness of the mineral seal can be reduced accordingly.

The use of capillary barriers in landfill cover systems is gaining the recognition of supervising authorities, LAGA (2000). The system is based on the physical phenomenon that water flows laterally in an inclined partially saturated layer of fine sand placed above a layer of coarse sand/gravel, provided the difference between the two layers in void size and in the associated degree of saturation is large enough to prevent the water from breaking through the interface into the coarser soil. Research and pilot applications have lead to rules for the design, construction and quality management of capillary barrier systems, e.g. von der Hude et al. (1999), Gartung & Neff (2000). To date this method has reached a degree of maturity to be regarded as competitive with conventional mineral sealing layers.

Another alternative mineral seal is the geosynthetic clay liner GCL. The criteria of equivalency of GCLs with compacted clay liners have been discussed in the international literature. In Germany they were elaborated by a technical committee on the basis of the guidelines of DIBt (1995). The advantages and shortcomings of GCLs as members of landfill cover systems have been presented by Gartung & Zanzinger (1998) among others.

Practical experience shows, that GCLs have some advantages over compacted mineral liners. Handling and installation are easier, less time is needed for placement, waste storage space can be saved due to the smaller thickness. However, GCLs are thin and sensitive against mechanical damage. Most of the GCLs on the market use sodium bentonite with a very high swelling capacity and extremely low hydraulic conductivity. Observations at many sites indicate, that the hydrated bentonite undergoes cation exchange with time. By the replacement of sodium with calcium ions which takes place in nature, the swelling capacity of the bentonite is reduced by one half and the hydraulic conductivity increases by one order of magnitude. GCLs may lose their sealing function completely if the protection against desiccation is insufficient. Once desiccation cracks have occurred, it is unlikely that they will fully self heal, because of the simultaneous effects of drying, wetting cycles and cation exchange Melchior (1999).

Like briefly discussed for thin GCLs, the thicker mineral liners in capping systems are exposed to fluctuations in their water content as well. Their larger thickness and the greater amount of water stored makes them less prone to complete failure due to desiccation than GCLs, but under Central European climatic conditions they may also experience desiccation cracking after a few years of seasonal drying – wetting cycles, if the soil cover above does not prevent them from drying out.

The evapo-transpiration rate is high during the growing season from about April until late September, at the same time precipitation may be low. During this time the water content of the mineral landfill cover layers is reduced. In autumn and in winter, evapo-transpiration is decreasing, precipitation may be high and the cover is re-wetted. Observations at large test fields indicate, that desiccation may cause the formation of micro-fissures and cracks in cohesive cover soils in summer. These defects are preferably utilised by the plants for root paths, and the detrimental effect of the desiccation due to thermal gradients is further increased by suction of the roots. As a result, within a few climatic cycles the mineral liner may experience fissuring to a considerable extent, the overall hydraulic conductivity may increase, and the sealing function may be impeded. Blended mineral seals with a coarse grained skeleton such as CHEMOTON are less sensitive to desiccation cracking than compacted clay liners and GCLs. Among the clays the more active species like the bentonites are more prone to cracking than the less active clay minerals.

Nowadays it is well understood among geotechnical engineers, that the performance of the soil cover above the sealing layer and the vegetation combined are crucial with respect to water storage and release in the cover system and thus control the moisture content and the sealing function of the mineral sealing layer. The thickness of cover soils of 1 m as specified in the Federal instructions TA-Siedlungsabfall, is insufficient in most cases, 1.5 to 3 meters are considered more appropriate for German climatic conditions. Guidelines have been developed for the design, placement and quality management of cover soils by a team of geotechnical engineers and soil scientists of the German Geotechnical Society DGGT, Gartung & Neff (2000).

4.3 Geomembranes as members of cover systems

Fissuring and growth of roots in mineral seals of landfill capping systems is prevented by the placement of a geomembrane. A geomembrane intercepts the migration of moisture from the underlying mineral seal upwards into the cover soil and vice versa. Final cover systems of landfills commonly consist of the combination of compacted mineral liners or GCLs with geomembranes.

Since geomembranes of covers are not exposed to a corrosive chemical environment, they must not be made of HDPE and their thickness must not be 2.5 mm as for the BAM-approved basal liner geomembranes and as often often used in German cover systems until now. The installation of thinner geomembranes or of softer polymers such as VLDPE are more favourable with respect to the anticipated deformations of the landfill surface and are preferred nowadays.

The construction requirements and installation techniques are essentially the same for geomembranes of the cover as of the basal liner. The seaming technique and all details of manufacturing and construction quality assurance apply to covers as well. The surface of the landfill or of the regulating layer has to be modelled to a shape, which allows plane geomembranes to be spread without distortions. This design requirement is especially important, when HDPE geomembranes of 2.5 mm thickness are used, because it is impossible to place them on three dimensionally curved surfaces with small diameters of curvature.

Usually landfills are hills with sloping surfaces. Slope stability is an important issue. In order to mobilise enough shear resistance geomembranes with rough structured surfaces are used in cover construction. Particular attention is paid to their long term tensile strength and stress cracking resistance. In order to avoid tensile forces in the geomembrane, the mobilised friction at the lower surface of the geomembrane should be greater than at the upper surface.

5. Summary and conclusions

During the past 10 to 15 years, the activities in design and construction of solid waste landfills have seen a steady development. Based on observations in the field and on research into the performance of the components of the landfill structure, technical instructions have been issued. They specify minimum requirements for sealing and for dewatering systems on a high technical level. Great emphasis is placed on quality assurance in manufacturing and in construction in order to achieve the efficient performance of the sealing and the dewatering elements that have been established theoretically and experimentally by numerical and physical modelling. The components of liners and covers consist of mineral materials and of geosynthetic products, in most cases in combination. The design-, manufacturing- and construction practice for composite basal liners are well established in Germany. The technical rules for cover systems are being revised at the present time, taking positive and negative experience and recent scientific research results into account.

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Permeable reactive barrier systems for ground water clean-up

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ABSTRACT: Permeable Reactive Barriers (PRBs) represent a new in-situ method for remediation of contaminated ground water. The paper comprises a short specification of variant designs as well as the description of a current research project at ETH Zurich, concerning the development of novel filling media to apply with this promising technology.

1. Introduction

Increasingly it is realised that, under economical and ecological aspects, conventional pump-and-treat systems for remediation of contaminant plumes do not lead to satisfying results. This is particularly true if remediation periods of several decades are anticipated, which means a continuous and, ultimately, high input of energy for pumping water from extraction wells and operating water treatment systems, as well as periodic maintenance and monitoring.

In the early 90s the method of "Permeable Reactive Barriers" (PRBs) was suggested in Canada and USA. PRBs are a passive in-situ technique that runs without any need of permanent and cost-intensive operations. Once installed in the subsurface, geochemical or geophysical reactions between the material in the PRB and ground water contaminants take place without any further external interference.

Research efforts at the Institute of Geotechnical Engineering (IGT) include the development of an adsorptive barrier material containing different reactive media to treat a wide range of contaminants and contaminant classes. The research programme will comprise both laboratory and full scale geochemical and geotechnical tests.

2. Specification of the Permeable Reactive Barrier (PRB) -proceedings

Permeable Reactive Barriers are installed in the aquifer across the flow path of a contaminant plume. As the contaminated groundwater moves through the PRB due to the natural gradient, the contaminants are removed by physical, chemical and/or biological processes. Depending on what processes take place, the reactive barrier material can remain permanently in the subsurface, or replaceable units can be provided. As the reactions that occur in such systems are affected by many parameters, successful application of this technology requires a sufficient characterisation of contaminants, ground water flow regime and subsurface geology. In case of instability of the subsoil or if great depths are to be reached, techniques of specialised heavy construction are essential for the implementation (i.e. sheetpiling, contiguous bored cased piles).

Important for the decision on the feasibility of a PRB is, apart from a financial point of view, the examination of:

- Installation facility and permeability ($k_{f,\ PRB} > k_{f,\ Aquifer}$)
- Efficiency and clean-up performance
- Reliability and potentiality to monitor the performance of the geochemical / geophysical processes
- Hydraulic and mineralogical long-term stability
- Environmental compatibility

Currently, two basic designs are being used in full-scale implementations of PRBs. A continuous trench, filled with the reactive media, is called *"reactive wall"* or *"treatment wall"*. The combination of cut-off walls and permeable in-situ reactor(s) is known as the *"funnel-and-gate"* system (EPA (1998), Gavaskar et al. (1998), NATO/CCMS (1998), Starr and Cherry (1994), Teutsch et al. (1996)).

2.1. Reactive walls

Ground water remediation with continuous reactive walls represent an especially environmentally friendly way. The disturbance of ground water flow by the constructional interference is minimal. The permeability of the filling material must at least be as high as that of the natural aquifer. By this, the ground water flow is prevented from changing its direction and passing around instead of through the wall. The horizontal thickness must be designed in a way that, concerning the chemical and physical processes, a sufficient residence time of the polluted ground water is provided within the wall to achieve the required effluent concentration.

2.2. Funnel-and-gate systems

To remedy polluted ground water in-situ successfully, a continuous reactive wall must be big enough to cover the whole range of the contaminant plume. If the latter is wide and reaches great depths, the extent of the reactive wall would become very large. To avoid this problem and to increase the efficiency of the flow-through, "funnel-and-gate" systems can be conceived alternatively. Herewith, the contaminated ground water flow is enclosed and directed towards the permeable reactive zone (gate) by cut-off walls (funnel). The cut-off walls typically consist of interlocking sheet pilings or slurry walls. It is important to note that, by this method, backwater upstream of the system emerges which causes an in-creased gradient and hence higher flow velocity. This must be taken into account with re-spect to the contact time of the contaminants with the reactive material and the thickness of the gate, respectively.

Some variant designs of PRBs are shown in Figure 1. The capture zone of a funnel-and-gate system is related directly with the flow through the gate.

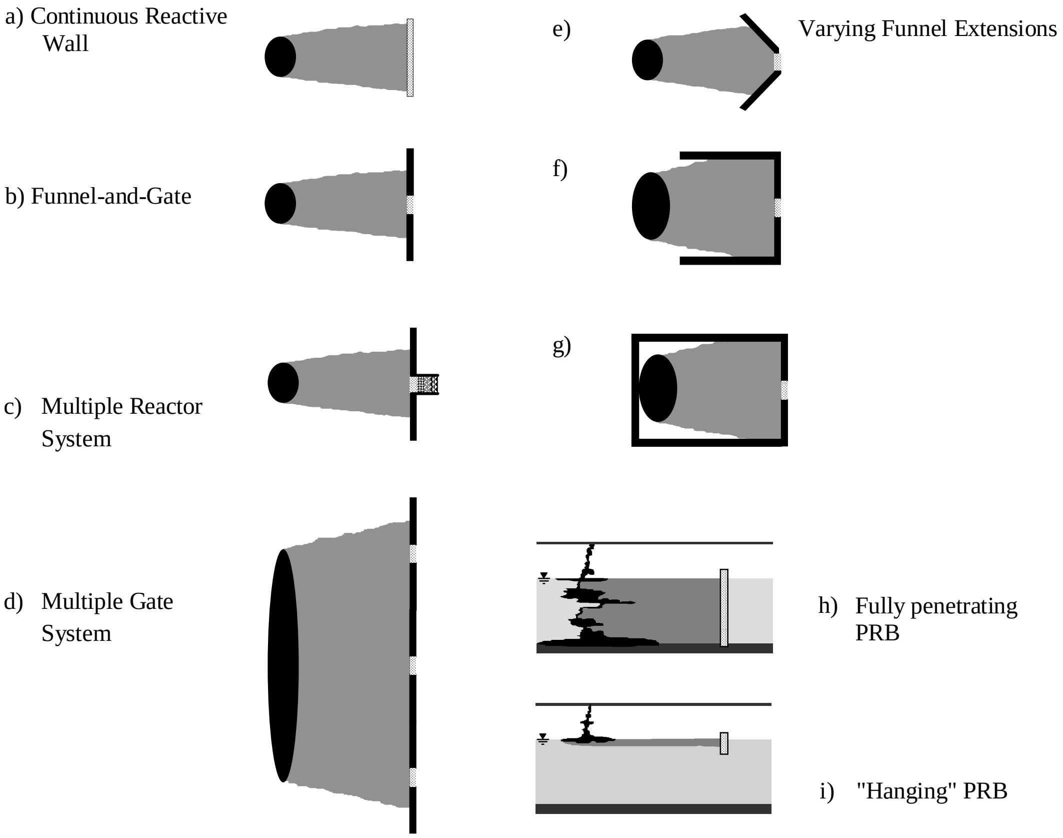
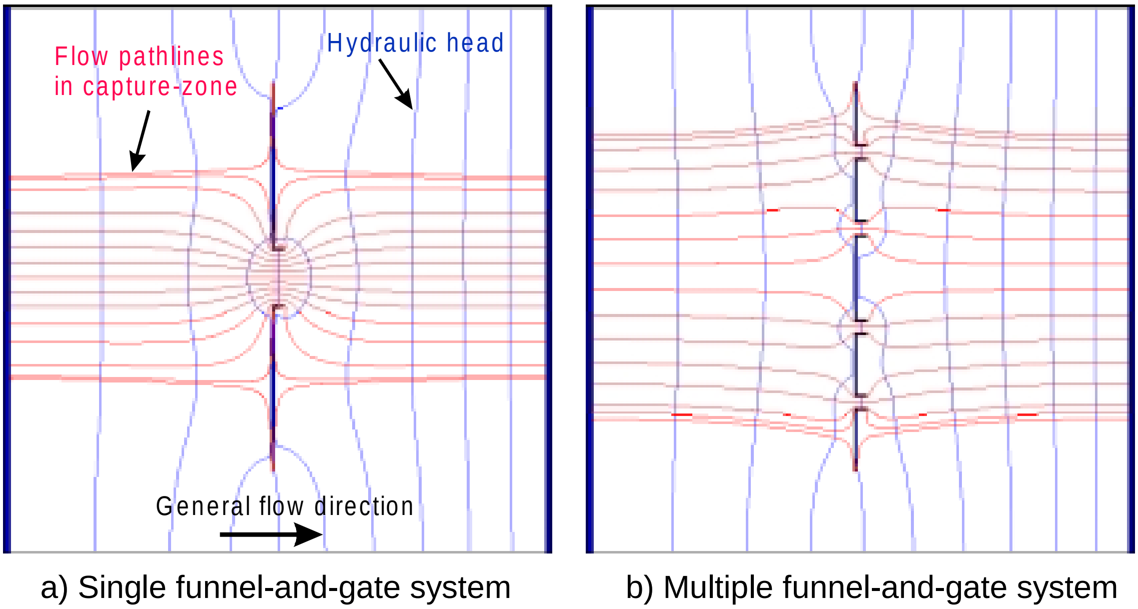


Figure 1. Variant configurations of Permeable Reactive Barriers (PRBs) (after Starr and Cherry (1994)).

Plumes with a mixture of contaminants that require more than one type of in-situ reactor can be controlled using multiple gates *in series* (Figure 1c). On the other hand, multiple gates *in parallel* can be used for controlling wide plumes (Figure 1 d). Generally speaking, the capture zone of a funnel-and-gate system with several (small) gates is larger than that of a system with the same overall extent and only one single reactive zone. This is due to the fact, that the water stream flows around each half of a funnel-segment (Figure 2).

An in-situ PRB should function until either the reactive capacity is consumed or it is clogged by precipitants or micro-organisms. As a consideration, a reactor enclosed in a relatively small gate offers better possibility to remove and replace the reactive material than a continuous reactive wall. If the extent of a plume is relatively large, the latter should be designed for a longevity exceeding the calculated remediation durance.

Another advantage of funnel-and-gate systems is the feature, that they offer a better and uniform exploitation of the reactive filling material in heterogeneous underground, particularly in combination with drainage trenches.



a) Single funnel-and-gate system b) Multiple funnel-and-gate system

Figure 2. Capture zone of different tunnel-and-gate configurations (exemplary demonstration of a numerical flow model).

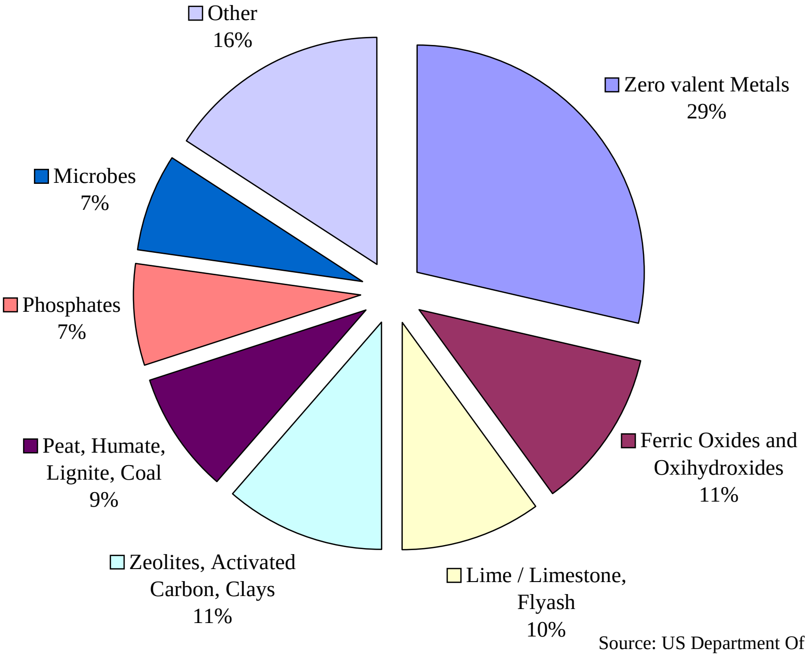
3. Reactive materials

The interest in PRBs has increased eminently over the past years, whereas implementations of full-scale projects have been realised especially in North America. So far, the predominant filling material has been *zero-valent iron* (Fe^0) in form of chips, jet blasting media, ironfoam or Fe-filler material for concrete etc. These materials can often be found as by-products in metalworking industry. Additionally, some highly reactive metals and metal alloys are being developed and modified with complex and expensive procedures. Fe^0 is very suitable for degrading chlorinated organic compounds (Dahmke (1997), Dahmke et al. (1999), Gillham et al. (1994), Gillham and O'Hannesin (1994), Johnson and Tratnyek (1994)). Hereby, an abiotic, heterogeneous surface process occurs, which involves adsorption of the contaminant and hereafter a progressing, normally complete reductive dehalo-genation of the chlorinated compound. In the end, essential degradation products are eth-ene or ethane, respectively. In small quantities, also some problematic low-grade chlorinated compounds, such as cis-dichloro-ethylene (cDCE) and vinylchloride (VC) occur as metabolic products. Generally speaking, Fe^0-reactive barriers represent an important tool for remediation of ground water contaminated with halogenated compounds. Nevertheless, from scientific point of view, there are still several unsettled questions (e.g. degradation processes; influence of further substances in the ground water; performance of contaminant mixtures with diverse degradation- or sorption-characteristics; processes occurring down-gradient of the PRB, concerning subsequent reactors and, not to forget, water protection rights). Recent research studies show that using this degradation method, serious problems, such as clogging effects and/or inhibition of the chemical processes might occur in presence of HCO_3^-, SO_4^{2-}, PO_4^{3-} or NO_3^- or other competing oxidants (Dahmke et al., 1999). Furthermore, the influence of microbiological activities on the degradation process is widely unknown.

Zero-valent metals are suitable for a series of heavy metals as well (Cr^{VI}, As^{VI}, As^{III}, Se^{VI} and TC). Soluble forms of these metals are transferred into insoluble forms by the reduction process, which then precipitate as hydroxide, for example (Blowes et al., 1996).

Significantly less distributed is the application of *adsorptive PRBs*. That is to achieve an immobilisation of the pollutants by chemically attaching them to mineral surfaces. With drinking water, treatment by adsorption of organic components on solid surfaces is established. For this, activated carbon is used predominantly. Activated carbon has also been used as filling material in first applications of adsorptive PRBs (Grathwohl and Peschik (1997), Teutsch et al. (1996)). The tendency of a solvent to leave the fluid phase and to adsorb on a certain solid surface, is quantified by sorptionisothermes. This process provides just a retardation of the contaminant transport. With the reactive material showing a finite capacity, in most cases frequent replacement of the adsorptive medium must be considered.

Beside these commercially applied technologies, further ones are being developed, in order to optimise known processes as well as to develop novel methods. Figure 3 gives an overview of diverse research activities.



Source: US Department Of Energy
"Research and Application of
Permeable Reactive Barriers"
April 1998

Figure 3. Present laboratory research projects on the development of reactive materials.

4. Development of adsorptive filling materials for Permeable Reactive Barriers

Development of novel adsorptive media to apply with Permeable Reactive Barriers (PRBs) is the object of a present research project at the Institute of Geotechnical Engineering at ETH Zurich. Materials and material mixtures are being generated that can be utilised for adsorption of a wide range of contaminants, as typically occur at hazardous waste disposal sites. One goal is in particular, to achieve the immobilisation of pollutants which have proven to be difficult to manage with other remediation methods. Exceedingly, environmental impact is heeded, and economical aspects are given prime importance. It is hoped to find suitable media among those which typically occur as by-products in industry.

Adsorptive processes are based on physical-chemical properties for separation of certain components from mixtures. Hereby, the detached substances affiliate on the interface between solid and fluid. Adsorption is more intensive the larger the area surface per unit mass is (specific surface). It is increasing rapidly with decreasing grain size. Furthermore, an effective detachment of contaminants from water can only be expected if specific affinities between the compounds and the adsorptive medium exist. Additionally, surface tension of the fluid is relevant, since it affects the wetting capability of the solid.

For application in PRBs, relatively coarse grained materials are eligible, categorically, which guarantee high hydraulic permeability. To be able to use the adsorptive properties of clay minerals, for example, they must show several soil mechanical and mineralogical characteristics that are unusual and even undesirable in many conventional geotechnical fields which deal with clays. Primarily only such minerals are suitable, which are available in fractured form without any fine grained material or in granulated form (so called pellets). Moreover, the following characteristics have to be fulfilled:

- Hydraulic and mineralogical long term stability
- Small deformations
- Erosion stability of the pellets
- Uniformly graded grain sizes

With certain materials, like zeolites, clays / bentonites, silicon oxides, alumina clays, hydrotalcite etc., geotechnical tests are carried out with respect to the feasibility in PRBs on one hand. First of all, oedometer tests are performed on the reactive materials to relate permeability to in-situ stress conditions. Additionally, swelling tests can be performed to check out if effective pore volume remains stable. On the other hand, one-dimensional flow tests in columns are carried out to quantify the adsorptive kinetics. The design of a typical column set-up is shown in Figure 4.

For volatile compounds, a collapsible Tedlar bag (a material similar to Teflon) is used as repository, so that no head space emerges while outpouring. The column flow is from bottom to top with a pump providing a constant rate. The flow velocity should comply with that of a typical ground water flow. Sampling ports are equipped with gastight and watertight fittings. Sampling syringe cannulae are left permanently inserted into the column, with the tip at the centre of the column. Concentration profiles can be generated periodically for the distribution of the solute compounds by collecting and analysing samples systematically.

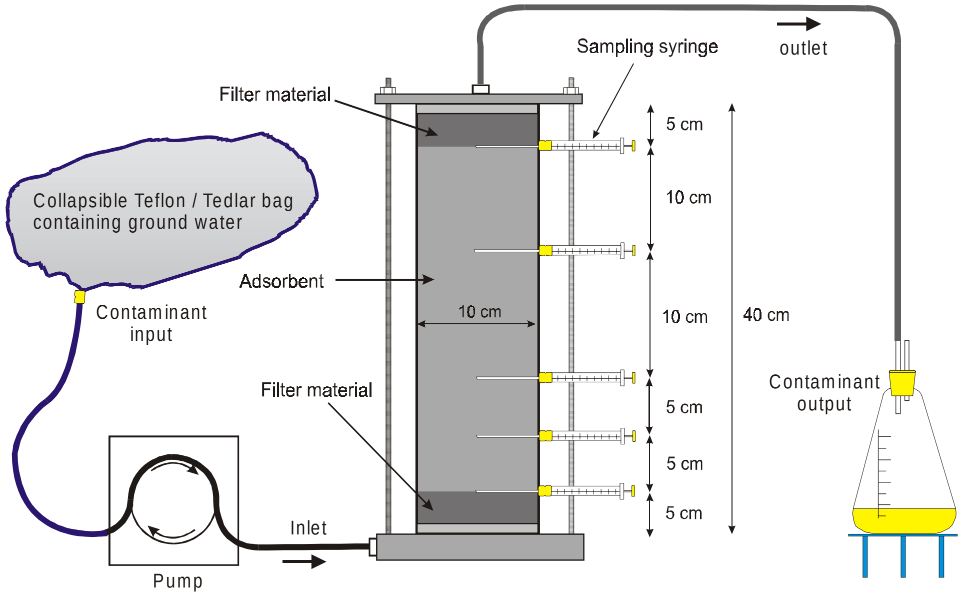


Figure 4. Schematic of a column test used to quantify the adsorptive properties of the reactive materials.

Column tests are not only used for basic research to find out about eligible filling materials, but they are indispensable in view of definite applications and designs of PRBs with selected reactive materials. To comply with all relevant boundary conditions on laboratory scale, it is essential to use original site ground water. The flowrate through the column should be set to approximate site conditions to adjust the relevant reaction kinetics. Therefore, it is desirable to have reliable ground water velocity data from the site at the location of the proposed barrier. Especially with designing a funnel-and-gate system, considerably higher ground water velocities than in the surrounding aquifer must be taken into account. Furthermore, the significant influence of temperature has to be considered. Sorption processes (exothermal) normally run faster in cool underground than at normal room temperature in the laboratory.

5. Outlook

Column testing for basic research is currently being undertaken at the Institute of Geotechnical Engineering of ETH Zurich. Simultaneously, data from different hazardous sites are collected. As soon as suitable reactive materials can be confirmed, it is aspired to apply and verify the results gained on laboratory scale by implementing a field test or even rendering a contribution within a full scale remediation project.

Research and development of Permeable Reactive Barriers and of appropriate filling materials in particular, as well as on-site applications, are being promoted continuously at many places, but especially in North America (EPA (1998), EPA (1999)). It would be desirable if this innovative and comparatively economical long-term remediation method could obtain global acceptance.

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Applying mathematical models to determine the efficiency of the protection measures for waste disposal sites

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ABSTRACT: Sanitation of old waste dumps and polluted areas, which are a threat to the natural environment, is a relatively young discipline, whose importance is still increasing due to progressive environmental degradation.

This paper summarises and describes shortly the methods developed and applied for decontamination and protection of the contaminated land. Constructed and operated without an appropriate design, old dumps frequently endanger the environment and the ground water. Along with the contamination of the groundwater/soil biological damages and air pollution occur. All these factors have a direct influence upon the neighbouring areas by degrading them. Among the endangered natural ressources – ground water and estuaries are the most sensitive to the pollution and important to protect. The thorough investigation of soil-water conditions and determination of pollutants' migration variations and directions have the basic meaning while estimating the impact of ground water filtration to the environment. These analyses, supported by computer simulations, which allow for faster observations of parameter variations, bring the experts in the position to be able to assess correctly the encountered situation and forecast future development. Effective ways to prevent the consequences of the uncontrolled run-off migration can be designed. In the article numerical simulations of filtration applied for an old municipal waste landfill are presented.

1. Introduction

The rapid and intense development of civilisation during our century poses a constant threat to the natural environment in which we live. This is reflected in the catastrophes that are becoming more common, accidents threatening the biosphere and quickly increasing numbers of communal and industrial wastes.

Incorrectly used and constructed dumps are creating a huge danger to the environment of underground water systems and the soil. This could cause biological hazards (epidemics, the development of insects and rodents) and pollute the air. All these factors have a direct influence on the surrounding areas, causing their degradation. However, among the most dangerous is the hazard to the environment of underground and surface waters.

Sanitation of old disposal sites and contaminated areas is still a very young field, whose importance started to increase in 1980/1990. The old disposal sites and regions of intense industrial work can be considered contaminated areas when they pose a threat, or could pose a threat, to the environment and particularly human health. Considering any given area of potential hazard (e.g. old industries) or disposal site (e.g. old waste disposal dumps) as a dangerously contaminated area (a degraded area of an ecological disaster) depends on whether it in fact poses a threat to the natural environment. To answer these questions it is usually essential to complete many tests to precisely identify the given area and the potential it possesses to pose a threat to the environment. Without these detailed tests such an area can only be considered an area of potential (hypothetical) hazard.

If, after the completion of identification tests, a given area or object is classified as contaminated and hazardous to the environment (especially human health) it is essential to take up the work of liquidation or, in some cases, minimisation of the hazard. There are many ways of sanitation a contaminated site (object), Gartung (1990), GDA (1997) and Holzlöhner et al. (1994).

2. Technical solutions to the securing of contaminated areas

The main aim of the sanitation of contaminated areas should be to reach a state, which does not threaten humans, the environment and ecology. To reach this goal one can choose different ways and systems of solutions, depending on the specifics of the given problem.

One can consider all engineering solutions, which make the further migration of pollutants impossible, technical solutions.

If one takes the huge costs of complete sanitation (healing) of contaminated areas and the difficult economic situation in Europe into account, technical solutions, being the least expensive ones, are becoming more and more important.

Among the technical security solutions are:

a) passive hydraulic and pneumatic procedures (lowering the level of ground water, pumping out contaminated water or air),
b) alternative passive systems like reactive walls and funnel and gate systems (it is important to note that alternative passive systems contain some aspects of decontamination,
c) engineering security constructions (sealing the surface, cut-off walls completed with basal liner),
d) decontamination (solidification, stabilisation, vitrification).

Usually different security methods are used in combination to attain the optimal solution, i.e. the minimisation of pollutant migration. It is possible that in many cases it is essential to also combine security with decontamination methods.

Because the aim of the article is to analyse the hydraulic conditions of ground water filtration in the area of the disposal site, as well as the evaluation of technical security construction efficiency, the author concentrates on ground water as the main factor that allows for the movement of pollutants in the ground, as well as on analysis of the efficiency of technical security constructions and passive hydraulic methods, that aim at decreasing migration.

3. Types and descriptions of basic security constructions

The application of present engineering security constructions in the form of hydrological procedures, cut-off walls and horizontal liners is part of the conventional technical state. The hydrological procedures (groups of wells) are to lower the water level in the body of the disposal site, or to cut off the influx of water by directing it away from the disposal site. The contaminated water is usually pumped into purification devices (the so-called pump-and-treat method). The purification is most often done through chemical and physical procedures.

After closing off (sealing) of contaminated area through the security constructions, the further emission of pollutants is greatly reduced, or totally eliminated. Technical security constructions are usually used to close off (cut off) the source of migration. Elements of security constructions are:

- sealing of the surface,
- cut-off walls,
- additional basal liner.

The securing functions of the sealing of the surfaces and vertical screens are normally supported by hydrological procedures (groups of wells).

4. Examples of the influences of old disposal site, on the ground water environment. The situation in the region of the communal waste disposal site in Szczecin

The old, closed down waste disposal site at Szczecin is among the sites that pose a potential threat to the natural environment. The studies that have been completed to this date confirm this, Kowalów (1996, 1997). When considering the influence of ground water flow on the environment, it is important to identify the ground water conditions and determine the changes and direction of the migration of pollutants.

The waste disposal site in Szczecin is located in the southern part of the city (Fig. 1) This disposal site was used from 1957–59 till 1974. During the seventeen years of use a dump of about 650000 m^3 was created Kowalów (1997). The total area of the disposal site is about 7ha and the maximum height is about 12 m above the ground. The dump is located in the river valley about 150 m from the river Odra and the base of the dump is below the ground water level. The hydro-geological conditions cause the body of the dump to be constantly in contact with the ground water.

The measurement of electrical conductivity and part of a chemical test were conducted on the ground and surface water. The results of the tests show the migration of leachate from the disposal site into the ground water (a high factor of electrical conductivity and the presence of compounds characteristic to leachate from disposal sites e.g. sulphur, chrome, metals).

Due to the possibility of further emissions of pollutants into the ground water, more hydro-geological and chemical tests should be carried out in the region of the disposal site. Bedsides this, the influence of the disposal site on the environment, particularly the pollution of the river Odra, should be determined. The present state of technology allows for the application of many effective methods to counteract the negative influence on the environment, like sealing off the surface, vertical cut-off walls, geomembranes, drainage systems, etc.

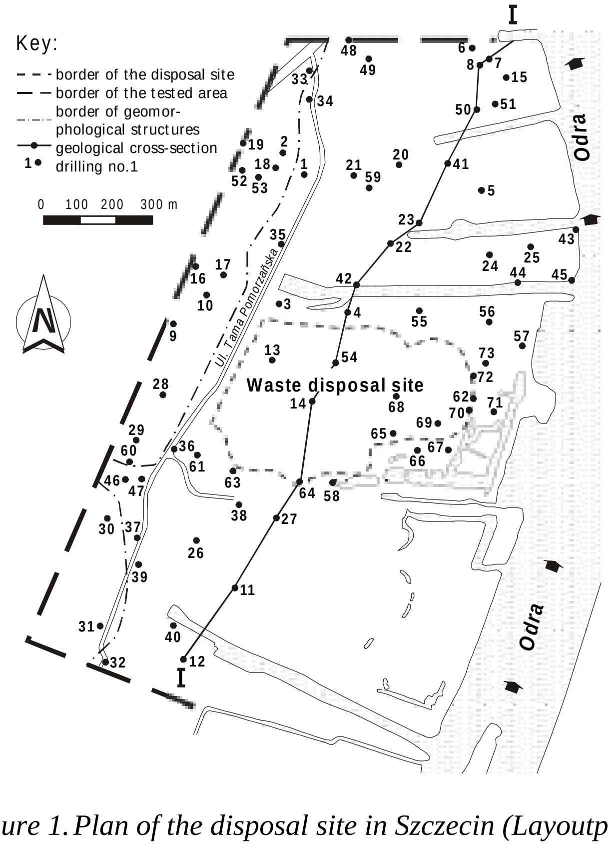

Figure 1. Plan of the disposal site in Szczecin (Layoutplan).

5. Applying mathematical models to determine the efficiency of safety measures against further migration of pollutants to the ground water of communal waste disposal sites in Szczecin

When determining the influence of ground water flow on the environment it is important to determine the ground water conditions in detail, as well as the description of changes and direction of pollutant migration. These analyses, combined with computer simulations, allow for the quicker observation of the changes in parameters, makes the evaluation of the situation and prognosis on the most effective ways to counteract the results of the migration of the outflowing waters easier. Computer models using the program package SPRING (old name SICK100) were used to carry out a full analysis of the influence of the different methods that reduce the leakage of pollutants in disposal sites, SPRING (1999), Kowalów (1996, 1997, 1998)

To grasp the whole water balance of the region being tested a, previously agreed upon, horizontal 2D model was used. The choice of two-dimensional horizontal model was dictated by the ground water conditions (small dickness of aquifere, constant coefficient of permeability in vertical direction and an impervious layer below the aquifer). A model made up of 1066 nodes and 1127 elements was created for the inductory calculations.

The eastern boundary of model is the Odra, on the north and south there are channels of the Odra. The western boundary is between two geomorphic structures of this area, in other words on the boundary between alluvial strata and glacial till..

With the calibrated model the direction and velocity of water flow through the area was determined. The flow field of ground water in the region of the disposal site was calculated under consideration of boundary conditions. Figure 2 shows the distribution of ground water potential and (through vectors) the directions and velocity of flow for each element of the area. In the case of the disposal site, lying next to a channel we are considering, that is in hydraulic contact with the ground water, the main direction of flow is towards the river. The flow in the region of the disposal site is a lot greater than in the area around the disposal site. This is due to the fact that the permeability in the disposal site is much larger than in the surrounding area.

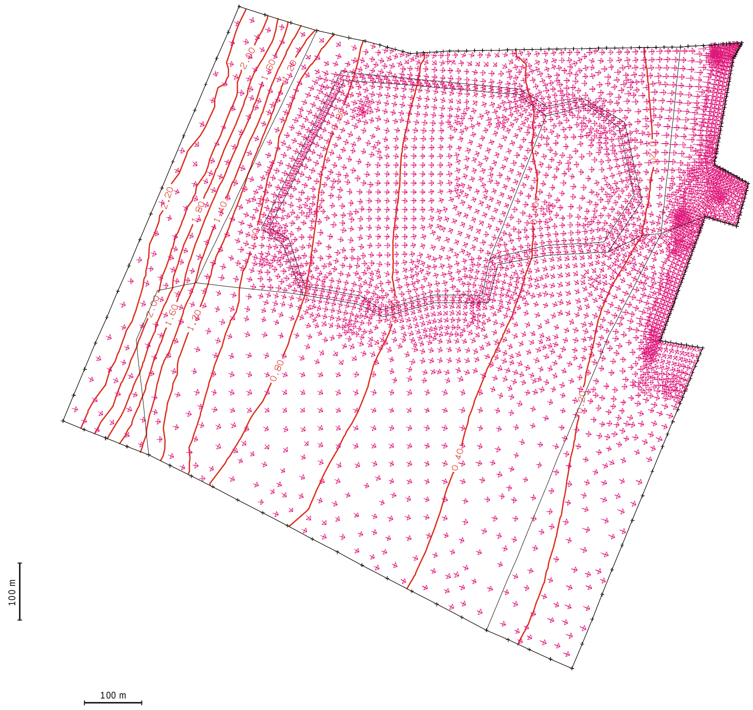

Figure 2. Groundwater flow in the calibrated model.

6. Rehabilitation methods considered in the numerical calculations

Using the calibrated flow model of the local hydrogeological situation, a calculation of the efficiency of the different rehabilitation methods proposed to use in the tested areas was done.

The following methods were chosen for the numerical calculations:

- hydraulic procedures (groups of wells),
- sealing off the surface of the disposal site,
- vertical cut-off wall round the disposal site,
- deep drainage around the disposal site,
- combination of hydraulic procedures and sealing off the surface,
- vertical cut-off wall and sealing off the surface,
- deep drainage and sealing off of the surface,
- vertical cut-off wall and deep drainage,
- vertical cut-off wall, deep drainage and sealing off of the surface.

Hydraulic procedures - used to secure the area around the disposal site against further emissions were represented in the calculations by groups of wells in the in- and out-flow areas. Through their placement and specific water collection, these wells cause the water table inside the disposal site to be lowered. Hydraulic procedures (groups of wells) reducing the migration from the body of the disposal site and reducing the water flowing into the site (reducing the flow and migration).

Sealing off of the surface- cuts off the influx of rainwater into the disposal site (reduces the infiltration of rainwater into the disposal site body to zero). Calculations take a watertight cover of the disposal site area into consideration by taking the infiltration water in the site as zero.

The calculation considered the influence of the vertical cut-off wall, keyed into a deeper watertight layer. This cut-off wall is located around the perimeter of the disposal site. The permeability of the wall was taken to be 10^{-9} m/s.

Deep drainage. The influence of ring drainage on the filtration area in the disposal site was considered in the calculation. The location of the drainage corresponded with the location of the vertical cut-off wall discussed earlier. The calculations took the permeability of the drainage as 10^{-2} m/s. The function of the drainage is the collection and redirection of ground water in the inflow area and pumping it into the water carrying layer of the outflow area. Due to the deep ring drainage the water is directed around the disposal site, cutting off its water supply.

Combining the different methods. To consider the effects of all the methods simultaneously, simulations of the above mentioned methods were created.

7. Results of the calculations

Because the aim of the calculations is to analyse the effects of different types of security constructions on hydraulic conditions of the flow of pollutants out of waste disposal sites into ground water, two criteria of effectiveness were decided upon:

- the reduction of water output flowing out of the disposal site into the outflow area in relation to the situation before the security constructions
- the difference in the state of water around the disposal site in relation to the flow of water before the security constructions.

The results of the numerical calculations, according to both criteria of effectiveness, were compiled for the variations under consideration in calculation table 1. Fig. 3 shows for example the difference of groundwater level for interaction of cut-off wall, drainage and surface sealing.

Figure 3. Difference of groundwater level – combination of cut-off wall, drainage and surface sealing.

Table 1. A summary of the results obtained in the calculations for the ground water flow at the disposal site area in Szczecin, taking security constructions into account.

VAR.	TYPE OF CONSTRUCTION	SIZES TAKES UNDER CONSIDERATION IN CALCULATIONS	QUANTITY OF WATER FLOWING OUT OF DISPOSAL SITE (1/min)	REDUCTION OF QUANTITY ACCORDING TO THE BEGINNING SITUATION (%)
0	Without security construction	-	112,7	-
1	Hydraulic procedures	6 wells in inflowing area 6 wells in outflowing area	27,0	76,0
2	Surface sealing	Infiltration of precipitation water = 0	51,4	45,6
3	Vertical cut-off wall	$k_{pp} = 10^{-9}$ m/s	2,0	98,2
4	Deep drainage	$k_{dg} = 10^{-2}$ m/s	108,10	4,1
5	Hydraulic procedures and surface sealing	6 wells in inflowing area 6 wells in outflowing area Infiltration of precipitation water = 0	23,4	79,2
6	Vertical cut-off wall and surface sealing	$k_{pp} = 10^{-9}$ m/s, Infiltration of precipitation water = 0	0,1	99,9
7	Deep drainage and surface sealing	$k_{dg} = 10^{-2}$ m/s, Infiltration of precipitation water = 0	46,5	41,1
8	Vertical cut-off wall and drainage	$k_{pp} = 10^{-9}$ m/s, $k_{dg} = 10^{-2}$ m/s	0,4	99,6
9	Vertical cut-off wall, deep drainage and surface sealing	$k_{pp} = 10^{-9}$ m/s,$k_{dg} = 10^{-2}$ m/s, Infiltration of precipitation water = 0	0,02	100

Source: own calculations

8. Conclusion

To determine the effectiveness of the security methods for old disposal sites regarding the migration of pollutants into the ground water, a complete model of ground water flow in the region of the disposal site was created. Using the calibrated model calculations, of the influence of different security methods on the reduction of pollutants migrating along with the ground water into the outflow area, were studied. The seepage model presented allows one to check the effectiveness of different disposal sites security methods, taking into account their local hydrologic conditions. These models should be complemented with transport models based on supplementary field tests and lab analyses.

When analysing the results calculated in table 1, one has to conclude that the most effective solutions, leading to the maximum reduction of the outflow from the disposal site, are the vertical cut-off walls and sealing off of the surface, or totally cutting off of the disposal site through sealing off the surface, vertical walls and deep drainage. Taking economic aspects into account, the last solution is the most expensive and most technically complicated solution. The simplest and most effective methods are: vertical cut-off walls, groups of wells, as well as groups of wells in connection with sealing off the surface.

Executing the required security measures reduces, or even totally stops, the out flow of contaminated water from the disposal site region and assures long term protection of ground water and the surface of the region.

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Improving degree of environmental protection in case of hazardous, toxic and radioactive wastes disposal

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ABSTRACT: The paper introduces theoretical principles of synthesis of a mineral-like artificial stone, in which the most harmful substances- heavy metal elements, toxic, nuclear and other wastes are fixed within alkaline aluminosilicate compounds, analogous in composition to natural zeolites of sodalite, analcime, feld spars type, characteristic of high stability to chemical weathering and durability. Chemical composition of the above wastes, from one side, and an ability of zeolites to serve as casing-like crystals, from other side, in which harmful elements are "locked" in energetically nonsaturated cavities of a zeolite framework have been taken as prerequisites of conceptual design. Despite the fact that hazardous, toxic and radioactive wastes vary within a wide range of chemical forms and sources of origin, some of them contain large quantities of alkaline elements to provide under certain conditions a synthesis of mineral- like compounds. When alkaline compounds are not present in the wastes, f.e. electroplating sludges, these should be incorporated from outside. The validity of this approach has been proved on model systems and real wastes. The study's results indicate the enhanced reliability of disposal at less energy consumption compared to the known-in-the art processing techniques and considerably lower rates of leaching into surrounding environments.

1. Introduction

Ecological danger caused by collection of huge amounts of hazardous, toxic and radioactive wastes, especially in industrialised and urbanised regions, more strict environmental regulations put forward the problem of environmentally safety and reliable long-term disposal of hazardous wastes and made this problem a first priority one.

First of all, to these toxic wastes may be referred to the non-recycled wastes from chemical industry, wastes containing heavy metal elements (for example, electroplating sludges) and radioactive ones. As was established by numerous works of the scientists from the Scientific Research Institute for Binders and Materials, the alkaline cements that had been first proposed by Professor V.D.Glukhovsky in 1957, were found to be the most efficient to solve the problem of their localisation. Depending upon chemical and mineralogical composition of wastes, it is possible to select for mineralization the most appropriate composition of the alkaline cement according to their classification developed by Glukhovsky and Krivenko (1979), Krivenko (1995), Krivenko (1997).

2. Experimental and discussion of results

The developed approach was supported by the experience of use of the alkaline cements for localisation of different waste such as electroplating sludges reported by Krivenko, Skurchinskaya and Samoilenko (1991), as sodium sulphate- a waste of chemical industry reported by Krivenko, Skurchinskaya and Lavrinenko (1993), as liquid radioactive wastes of nuclear power plants reported by Krivenko, Skurchinskaya and Lavrinenko (1993), as contaminated soils (Krivenko, 1997).

2.1 Heavy metals-containing wastes

The ions of heavy metal are found, as a rule, in electroplating sludges, ashes from garbage incineration, contaminated soils, etc. Heavy metals are the most widely present in the electroplating sludges making the problem of their immobilisation of great importance

By the experiments held it was established that the introduction of an additive of the electroplating sludge (chemical composition is given in Table 1) in quantities of 5–15% by mass it is possible to produce an artificial stone performing compressive strength 25–35 MPa depending on type of alkaline component used. During following hardening in water conditions the strength characteristics increase and by 90 days reach 27.5 and 37.5 MPa, respectively.

Table 1. The contents of elements in the electroplating sludge.

Content of elements (% by mass)								
Si	Al	Fe	Ca	Mg	S	Mn	Cr	Ni
1.61	0.69	5.59	17.75	0.72	0.61	0.06	2.4	9.7

Continuation of Table 1.

Zn	Pb+As	Cu	Sn	Cd	Sr	Co	LOI
1.84	0.028	0.015	0.0017	0.0007	0.38	0.005	54

To evaluate degree of reliability of heavy metals immobilisation within a slag alkaline stone the methods of nuclear-emission, atom-absorption and neutron-activation analyses were applied. The samples before testing were ground and studied before and after boiling during 50 hr. in distilled water (water was changed repeatedly after every 10 hours of boiling). The study's results (Figure 1) testify that when up to 10% by mass of electroplating sludge was incorporated into a slag alkaline binder, such metals as Sr, Cu, Sn, Co do not leach, the only explaination of which is their full binding within the artificial stone formed. Insignificant washing-out (leachate) is observed of such elements as Ni and Pb+As; the leach rates are 0.01 and 0.0007% by mass, respectively.

While incorporating into a binder composition up to 15% by mass of electroplating sludge, the content of heavy metals, present in a free state, is within 0.002–0.02% by mass, and is significantly lower the allowable limits of hazardous substances concentration in water basins/reservoirs. These data are proved by the results of sanitary-hygienic expertise, according to which the binder comprising up to 15% by mass of electroplating sludge is considered non-toxic one and may be recommended for residential and civil engineering except reservoirs for drinking water.

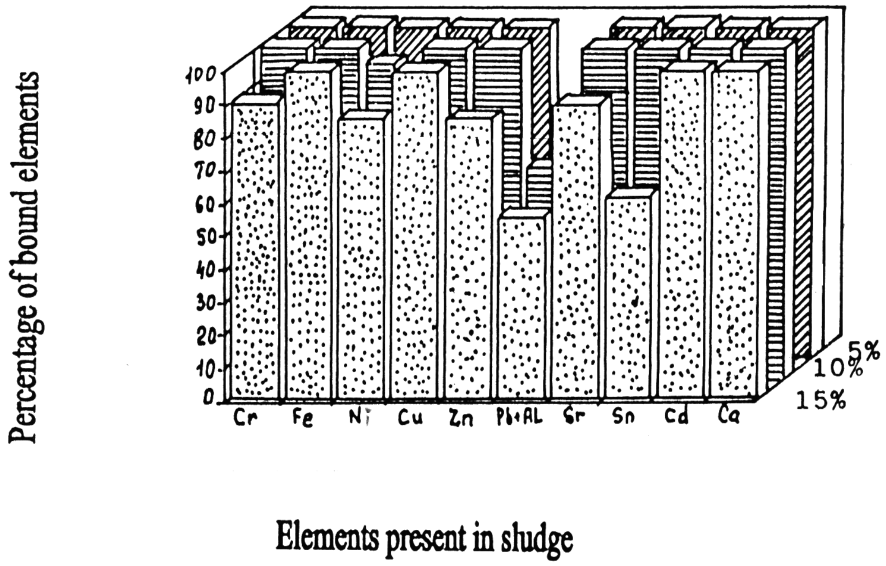

Figure 1. The influence of electroplating sludge content (5, 10, 15% by mass) in the slag alkaline binder on heavy metals leach rate, % by mass.

2.2 Na_2SO_4-containing wastes

These wastes are generated in great quantities, for example, in the production of barium salts, isopropyl alcohol, alumina and other products and are collected and disposed in sludge settling tanks.

Because of great amounts of SO_4^{2-}-ions present in them, it is impossible to dispose them safety within, f.e. of portland cement stone.

The possibility of immobilisation of these wastes within an alkaline cement stone is based on regulation of the acidic – basic equilibrium in a binding system Na_2O-CaO-Al_2O_3-SiO_2-H_2O due to introduction of a mixture “Na_2SO_4+ zeolite”.

The ion-exchanging abilities of zeolites provide the process of replacement of a zeolitic water in an intermolecular space of the zeolite with the Na_2SO_4-molecules. This results in the increase of alkalinity of the liquid medium and formation of a zeolite-like phase analogous to natural nosean $Na_8(AlO_2)_6(SiO_2)_6SO_4$. The SO_4^{2-}-ions turn out to be firmly fixed in the cavities of this zeolite by structural bonds what is confirmed by data obtained with the use of NMR method (Figure 2). So, the changes in the spectrum of lines by Al testify to formation of bonds Al-O-S.

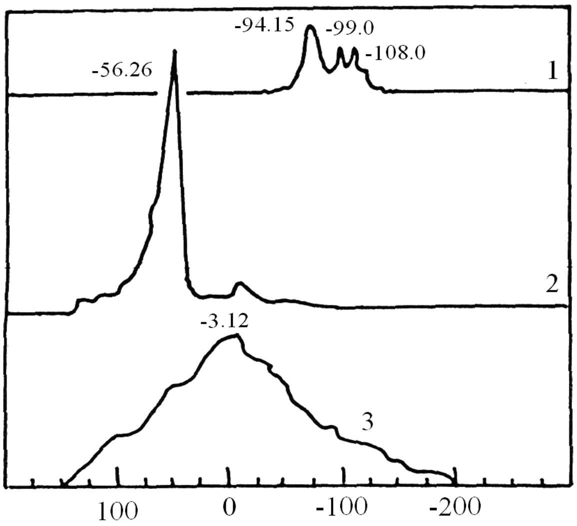

Figure 2. NMR spectrum lines.
1 – yielded zeolite NaY by Si
2 – yielded zeolite NaY by Al
3 – system “Na_2SO_4 + zeolite” by Al

The elaborated principles of directed regulation of structure formation processes in the process of hardening of the slag alkaline cements allowed not only safety localise the toxic SO_4^{2-} - containing wastes but to produce slag alkaline cements with compressive strength 30-40 MPa for general purposes.

2.3 Radioactive wastes

The most advantageous feature of the alkaline cements with regard to radioactive waste immobilisation is that the majority of these wastes contain alkali metals such as Li, K, Na, Cs, or their compounds which are at the same part an obligatory constituent of these cements.

A high content of alkalis creates significant difficulties in immobilising these wastes with the use of traditional processing techniques and cementitious materials. So, the solidification of radioactive wastes using cement, which is the most commonly used worldwide, is characteristic of not satisfactory content of bound alkali metal and not satisfactory water stability of resulting cement stone.

The use of alkaline cements, in particular, their variety– geocements, increases considerably the efficiency of radioactive nuclides immobilisation.

With regard to low and intermediate-level radioactive wastes a synthesis of the compounds may be carried out under normal conditions. The resulting compounds are characterised by rather high strength and high content of bound alkali metal and water stability as a results of the formation of zeolite-like compounds of analcime type.

Used in the experiments were concentrates of liquid radioactive wastes of the Ukrainian nuclear power plants, namely: the Khmelnitsk Nuclear Power Plant (WWER type reactors) and the Chernobyl Plant (RBMK type reactors) (Table 2).

Table 2. Characterisation of liquid radioactive waste.

Characteristics	Khmelnitsk NPP	Chernobyl NPP
Density of concentrate (kg/l)	1.32	1.225
pH	11.92	13.6
Salt content (g/l)	453	356
BO_3 content (g/l)	142	-
NO_3 content (g/l)	1.70	180.0
Cl^- content (g/l)	2.00	-
SO_4 content (g/l)	-	5.9
Specific activity (Bq/kg)		
Cs- 134	1.77·E+06	3.33·E+05
Cs- 137	3.38·E+06	1.96·E+07
Na- 24	6.30·E+06	-
Co- 60	1.52·E+06	1.92·E+04
Total activity of radionuclides (Bq/kg)	5.37·E+06	

Cementing, that is, the inclusion of liquid radioactive wastes in the mineral cementitious materials, is recognised now by the specialists worldwide as the most perspective conditioning technology in terms of simplicity and cost.

However, when it is applied to wastes with a salt content up to 200 g/l, only 5 to 7% by mass of them are bound within a compound produced. That’s why to increase a salt content in the compounds formed the use was made of evaporation technique was applied to the concentrate in laboratory conditions and also the water to cement ratio was increased up to 0.6. As a result, the Khmelnitsk nuclear power plant’s radioactive waste dry residue concentrations increased to 49–51% by mass and up to 47–65% by mass (those of the Chernobyl nuclear power plant). These degrees of evaporation correspond to salt concentrations for the Khmelnitsk nuclear power plant- about 600–700 g/l and for the Chernobyl nuclear power plant- 646–991.9 g/l.

To enhance the isolating/barrier effect, the modifying additives of natural origin have been introduced into geocements. Their action is based on their own sorption properties and is also provided by their direct participation in the synthesis of zeolite- like neo-formations.

The evaporated concentrate was mixed with other constituents to produce a flowable mixture and the prism- specimens (2 x 2 x 8 cm) have been prepared, then, after 1 day before testing, they were allowed to harden in normal conditions (T= 20^{o}C, RH= 95–100^{o}C).

To determine the degree of reliability of isolation, the leach rate was examined. After 56 days starting from the preparation the specimens have been tested for compliance with the IAEA (International Atomic Energy Agency) and ISO 6961-1982 standards (E).

Test results of leach rate of radionuclides held at the Khmelnitsk and Chernobyl nuclear power plants under the IAEA (International Atomic Energy Agency) testing procedure are shown in Figure 3.

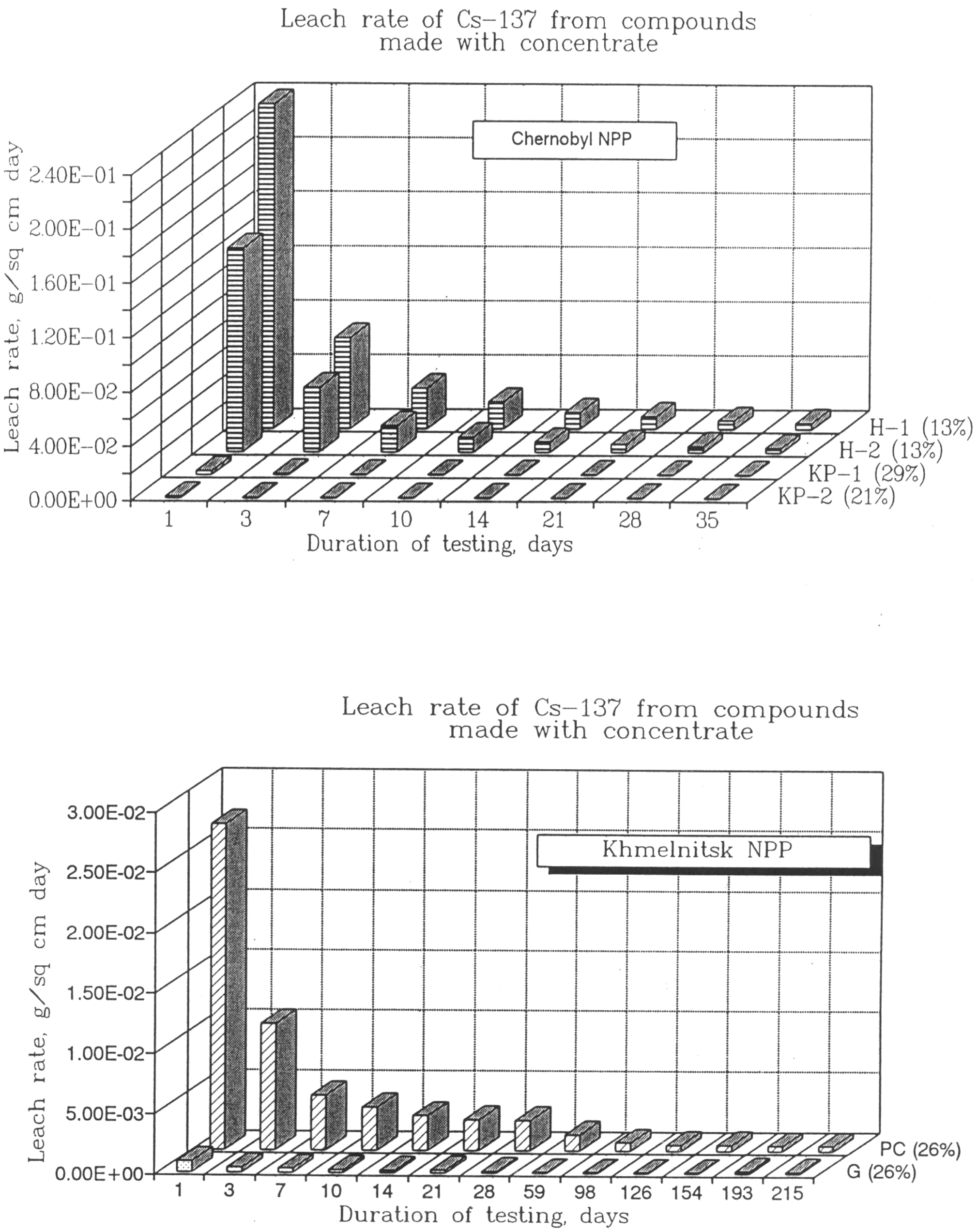

Figure 3. Leach rate of Cs-137 from compounds made with concentrate.

Definitions: *H–1, H–2 – reference compounds made with portland cement;*
• • –1, • • –2 – compounds made with geocement
NOTE: *Salt content in the compound H–1, H–2 – 13% by mass;*
Salt content in the compound • • –1, • • –2 – 21–29% by mass.

As it follows from the data obtained, strength of the specimens made with geocements, in which the concentrate from the Khmelnitsk nuclear power plant was used as a geocement constituent, was at an age of 28 days (just this age corresponds to a cement strength class)- 12.7–17.3 MPa, thus exceeding considerably the minimum allowable value of 10 MPa, and of the specimens made with portland cements- 9–11 MPa. The salt content in all the resulted compounds was of about 26.5% by mass. Strength of the specimens made with geocements, in which the concentrate from the Chernobyl nuclear power plant was used as a geocement constituent, was at an age of 28 days 11.4–18.8 MPa at salt content in the resulted compounds- 28.6 and 21.1% by mass, respectively.

According to conclusion made by the commission of the Khmelnitsk nuclear power plant, the leach rate of Cs- 137 from the resulted compounds made with geocements after 28 days was 1.62.E-04…9.43·• -05 g/sq cm day, being considerable lower the allowable limit- 1·• -03 g/sq cm day, whereas those from the resulted compounds made with portland cement were 1.56·• -03... 2.47·• -03 g/sq cm day. Worthy mentioning is that in the resulted compounds made with geocements the leach rate stabilised by 28 days starting from the moment of its determination, whereas in those made with portland cement- by 98–154 days.

When using the concentrate from the Chernobyl nuclear power plant, the leach rate of Cs- 137 from the resulted compound made with geocement was by 1 day- 2.69 • -03–9.62 • -04 g/sq cm day, by 10 days age from the time of determination declined to 2.14 • -04 end 8.83 • -05 g/sq cm day. In the compounds made with portland cement and slag portland cement- the stabilisation of leaching took place by 28–35 days from the time of determination and was 4.48 • -03–5.95 • -03 g/sq cm day.

The developed approach to immobilisation of liquid radioactive wastes suggested to demonstrate that the use of a new class of mineral hydraulic cementitious materials- *geocements*- gives rise to environmentally responsible long- term storage by ensuring a strong chemical fixation of radionuclides within the mineral-like cement stone matrix.

The technology is advantageous in terms of simplicity and cost. These advantages come from low cost of geocement constituents, since a wide range of industrial wastes and by-products as well as widely available natural raw materials are used, and the facilities that are commonly used now can be also involved. The results of feasibility study show that a manufacturing cost of the compounds is by 15–30% lower (the comparison was based on raw materials cost). Of great advantage in terms of minimising environmental risk and cost of maintenance, is the greater durability of the compounds made with geocements which can be predicted and this prediction is supported by the knowledge about zeolite-like formations formed in the resulted compounds, because zeolites themselves are recognised among other natural rocks as the best for their excellent properties (stability and strength).

3. Conclusions

The developed approach provides not only the higher degree of mechanical adsorptive binding, but on the contrary to traditional approaches, the chemical binding due to synthesis of a mineral like artificial stone resulting in more safety, environmentally friendly and reliable long-term disposal of hazardous, toxic and radioactive wastes.

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Closing landfill sites with low-technology

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ABSTRACT: One of the results of the unification of eastern and western Germany was the need to close many of the smaller landfill sites in the east. As these closures had to be effected with some haste, it was often impossible to install base liners and otherwise implement the stringent specifications of the Technische Anleitung Siedlungsabfall (Specifications for Disposal of Household Wastes), the regulation governing the procedures for an orderly closing of landfill sites. The main problem in the construction of covers is quality assurance. Individual samples are no indication of the integity of the system as a whole. There is a need of a great deal of more work in this area, an area that will increasingly occupy engineers in the next years.

1. Introduction

In the final analysis, closing a landfill means that the contents of the site are to be kept permanently and safely isolated from the biosphere. If this is not assured, the ground water path is threatened. Methods for closing landfills have been developed that pay particular attention to covering their surface. Several of these have been put into practice. Experience has shown, however, that the methods employed are not appropriate for all sites, and that the use of layers of mineral sealant is questionable at best. Along with two surface sealing designs suggested in the Specifications for Disposal of Household Wastes, figure 1 illustrates simpler „low-tech“ possibilities to cover a site.

At present, we have no practical experience with long-term security of closed sites. Due to the multiplicity of old hazardous waste sites and the paucity of public funds, available security measures are limited.

Whereas only a few years ago we were concerned with responding to a predicted waste crisis in Germany, so that landfill sites were to be developed as quickly as possible, events have changed course dramatically. Since TASI incorporates deadlines, we are faced with an oversupply of disposal sites at present, a fact which places the profitability of modern, state-of-the-art sites in jeopardy.

Along with those sites deemed ecologically sound, i.e. sites whose orderly closing is financially assured, there are a number of smaller dumps which, for a variety of reasons, do not (cannot) benefit from a cover built up in accord with stringent TASI guidelines.

2. What is to be protected?

In general, it is primarily the water path that is endangered by old dumps and waste sites. In Germany ca. 2/3 of the public water supply comes from ground water sources. Any contamination of the ground water is accompanied by considerable purification costs over indefinite time periods.

Contamination of the ground water can be reduced by suitable employment of covers and sealant layers that interrupt the flow patterns. Reconfiguring landfill sites can reduce the area of surface affected by the percolation of rain water, in turn reducing the costs for a cover.

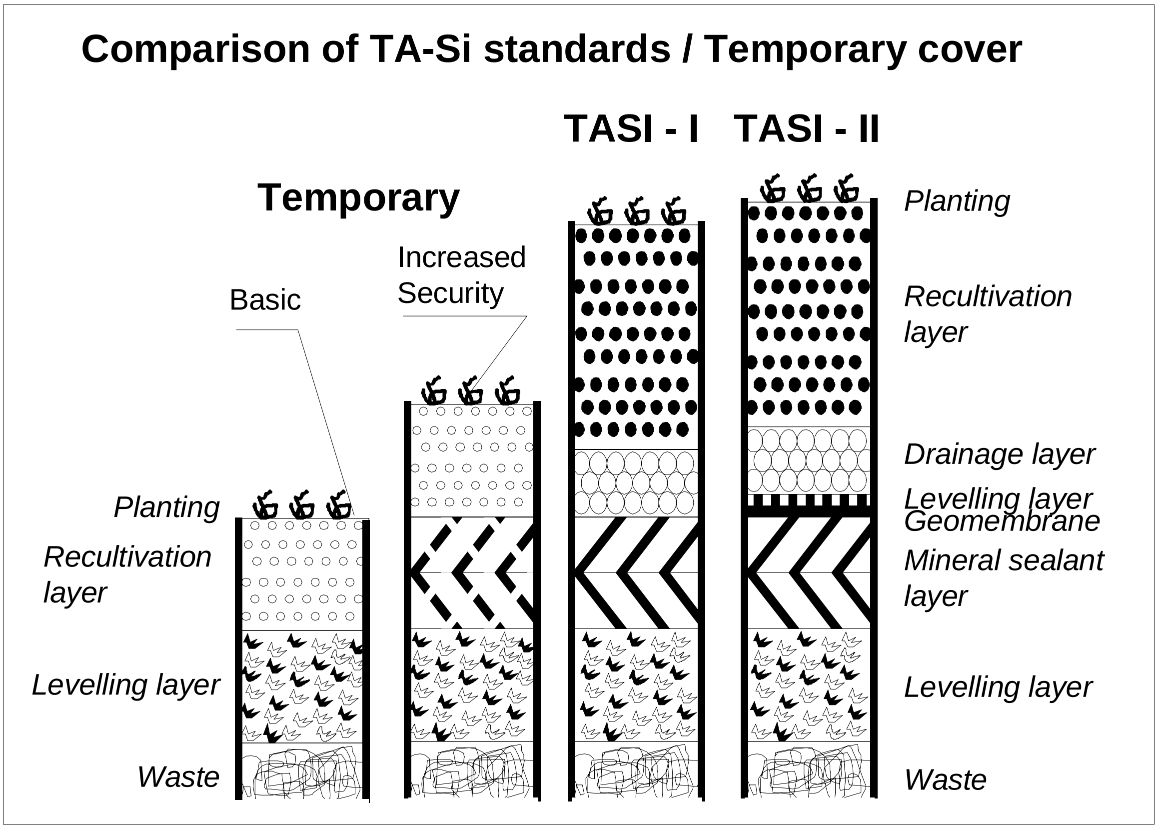

Figure 1. Comparison of the basic stucture of a cover: Basic solution (left), Increased security, covers according to TASI-I / TASI-II (right).

3. Catagories and criteria for evaluation

What should we be looking for when considering contamination due to dumps? Along with types of waste (household, construction, hazardous), the location of the site relative to areas which should be protected (drinking water) needs to be taken into account. If the geology and hydrology of the area are known (setbacks, is the old dump in contact with ground water?), one may investigate a bit further and arrive at a fair assessment of the risk.

An analysis of a body of information such as the statements of eyewitnesses, chemical analyses of the wastes and the like can suggest whether simple methods such as grading and recultivation suffice to effect an adequate closure, or if special conditions warrant further safety measures.

Such factors might include volume, content (household and construction wastes), proximity to protected areas (including the position of the base of the dump relative to the ground water level). If there is no protective layer between the landfill and gound water and/or volume approaches 50,000 m3, the area is classified Drinking Water Protective Area II and/or there is an insufficiently protected aquifer, only high-quality safety measures as outlined in TASI may be considered (combination sealant according to TASI). Of course all hazardous waste dumps require a special risk assessment.

4. Safety measures

All measures outlined here incorporate the following components of the basic level:

a) Old landfill sites must be fenced to preclude further dumping.
b) Surface treatment guards against precipitation percolating into the body of the landfill, dissolving substances there and carrying them into the ground water.

This involves a conturing of the old dump. Figure 2 shows the original condition in profile and from above.

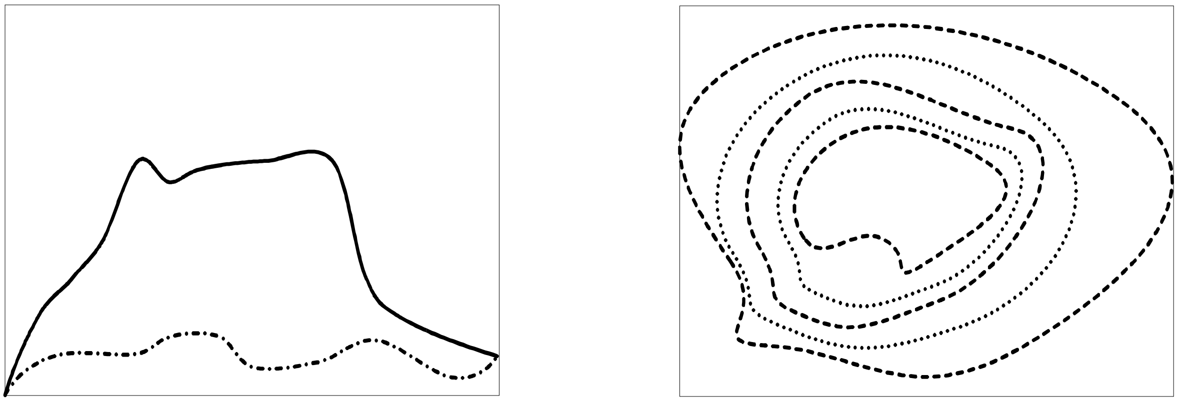

Figure 2. Original condition: Left: Section through the landfill; dotted line is original ground level. Right: Contour line.

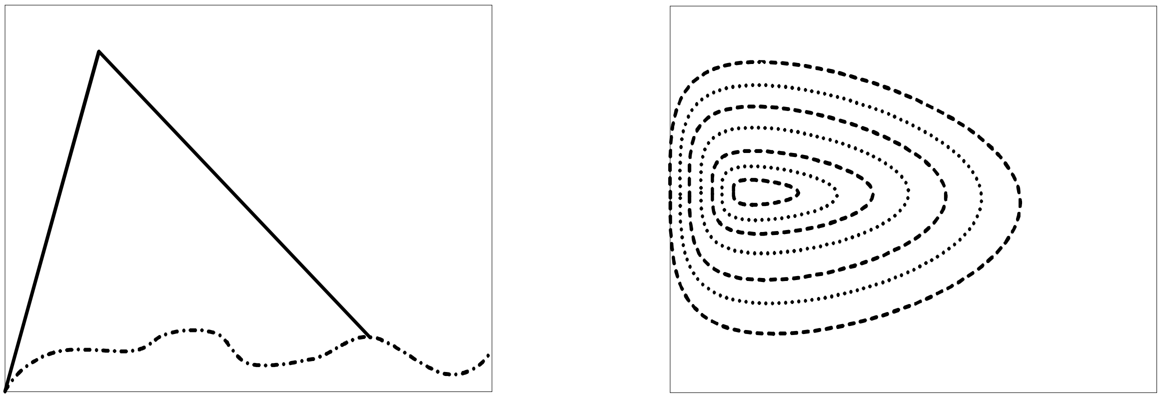

Figure 3. New condition: Left: Section through the newly-contured landfill; dotted line is original ground level. Right: Contour line.

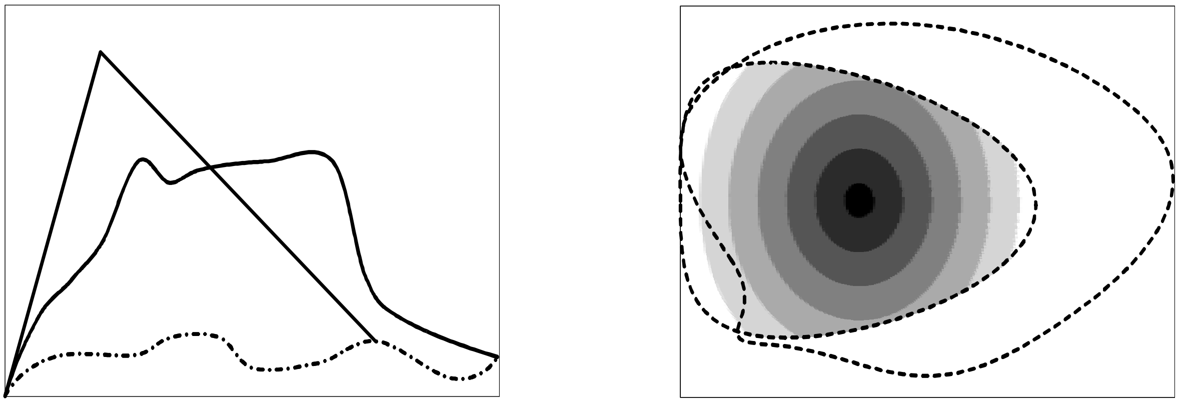

Figure 4. Superimposed views: Left: Section through the landfill; Right: Surface area.

Figure 3 shows the newly-contured mass. Figure 4 superimposes the views, showing that footprint and surface area have been reduced, so that much less water can enter the body of the landfill.

One of the low-tech variations occasionally proposed and –unfortunately –installed is the so-called Bentonite Mat. Monitoring of test sites incorporating Bentonite Mats have shown initial impermeability followed by higher and higher rates of percolation. Drying and shrinkage turns the Bentonite into agregate; the gaps thus formed provide excellent water pathways, and the mats were full of roots. A large number of questions such as long-term integrity, suceptibility to invasion by roots, moisture dependency etc. are as yet unanswered.

A complete enclosure of the waste mass would be the most desirable solution for long-term security.

Financial reasons dictate simple surface sealing for most basic situations, and preclude locating leaks. This can be partially compensated for by regular inspections (at least twice a year).

4.1 Basic systems

In all cases, the first step is collecting all scrap and bulky objects from the surface. These are either recycled or deposited in a state-of-the-art landfill. Grading and compacting to provide a surface for a levelling layer is the next step. A recultivation layer is placed on top of this, forming an environment for new plantings. This layer should be > 0.5 m, if possible. If necessitated by the volume of fill, groundwater observation shafts should be installed to insure that groundwater quality can be monitored over time. Damage to sealing layers is possible in all cover systems.

4.2 More secure systems

When simple grading and covering with a recultivation layer are deemed insufficient protection due to the risk evaluation, more secure systems must be used. First of all, the area must be surveyed. This gives the engineer a basis for planning the necessary construction process. The planner can design the contouring of the landfill mass along with its embankments and borders, observing a minimum surface inclination of 5%.

In the case of more secure systems, the levelling layer mentioned in 4.1 is followed by a mineral layer > 0.5 m thick and a permeability coefficient of $k_f < 5 \cdot 10^{-7}$ m/s. This sealant layer is intended to keep precipitation that has percolated down through the recultivation layer from reaching the landfill mass. The recultivation layer caps the sealant layer. Careful grading of the surface with attention to shedding surface water guarantees erosion-free diversion of precipitation.

Seepage can also be kept away from the sealant layer through the incorporation of an integrated drainage layer in the surface layer.

Gasses that may be present in the landfill should be collected and treated. In simple cases, biofilters serving as outlets for the gas will suffice.

A sufficient number of monitoring wells should be incorporated as well.

4.3 High-security measures

When the risk assessment indicates high-security measures must be taken, surface sealing according to TASI can be planned. This may call for a combination with a well gallery and/or encapsulation. Where small volumes of waste are involved, relocation is to be preferred for cost reasons.

5. Costs

What does a cover cost? Depending on the demands made by planning and construction, costs vary between ca. 40 Euro/m^2 for basic and 80 Euro/m^2 for more secure installations, including anciliary costs. If high-security measures according to TASI are called for, one may assume costs of 150 Euro/m^2. Lower prices are quoted for normal sealing, perhaps this is due to much larger surfaces. Local conditions such as road construction etc. increase costs accordingly.

It is obvious that costs vary with the system used, as can be seen in Fig. 1. The options „Basic“ and „Increased security“ are less demanding in their materials specifications, and do not incorporate a drainage layer.

Depending on the sampling program involved, maintenance activities must be carried out, passive gas filters serviced and ditches kept free. Anciliary tasks such as maintaining leach fields for surface water must be planned in as well.

6. Outlook

A good deal has already been accomplished in closing old landfill sites in eastern Germany. Unfortunately, geosynthetic coverings proven to be ineffective have been preferred by several Federal States for cost reasons. Even if the use of mineral sealing layers continues to be justly criticised, this method will be a part of landfill technology for some time to come. It is imperative, however, to introduce quality control to assure that the covers can safely shed precipitation.

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Full-scale landfill bottom liner test structures at Ämmässuo landfill, Espoo

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ABSTRACT: Full scale tests structures were constructed in summer 1996 to the Ämmässuo landfill to gather experience on quality control during the construction and long term behaviour of mineral liners and combination liners. Actual leachate was used to create the chemical loading and a hydraulic pressure of one meter. The structures were monitored for two years. The leachate seeping through the liner structures was collected to the lysimeter basins and further to the lysimeter wells, in which the amount of the water was measured automatically by pressure sensors and water samples were taken for chemical analyses. The structures were pulled down under control in November 1998, and material samples were taken to evaluate the effects of leachate.

1. Introduction

At summer 1996, full-scale landfill bottom liner test structures were constructed to Ämmässuo landfill. The purpose of the project was to:

- verify the importance of new, strict requirements and necessity of the artificial liner
- gather practical experience during the construction
- test available field quality measuring equipments
- monitor the behaviour of the liners, and especially combined liners, under chemical loading caused by the landfill leachate
- collect information about the effects of frost.

The project was funded by Ministry of Environment, Finnish Environment Institute, Helsinki Metropolitan Area Council, Technology Development Centre and private companies.

2. Structure and materials

2.1 Materials

Three different mineral liners and two artificial liners were used; natural clay from the vicinity of the landfill, mixture of bentonite and crushed stone from the landfill area, and fly ash with desulphurating agent as a mineral liner, and HDPE geomembrane and dense asphalt concrete as a artificial liner. Actually seven different combinations were investigated (the number and letter are referring to the specific part, see Figure 1):

1) natural clay (1B),
2) natural clay with geomembrane (1A),
3) bentonite soil mixture (2B),
4) bentonite soil mixture with geomembrane (2A),
5) fly ash and desulphurating agent 50%:50% (3B),
6) fly ash and desulphurating agent with dense asphalt concrete on the top (3A), and
7) dense asphalt concrete alone (4A).

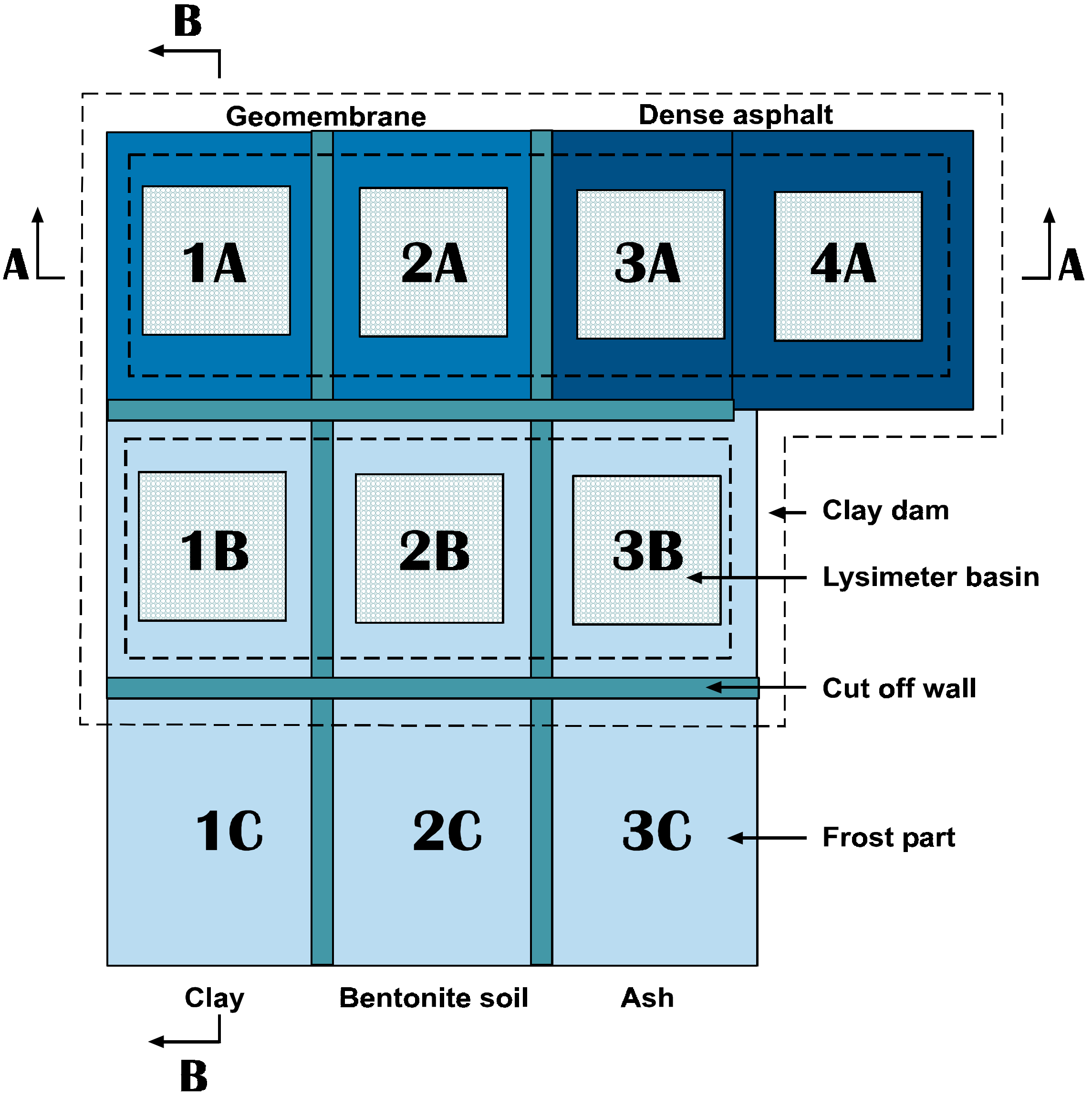

Figure 1. Schematic layout of the test structure.

2.2 Structural principles

The test structure was based on 0,5 m layer of crushed rock compacted on the bedrock, thus no settlements were to occur. Lysimeter basins, which collected the leachate seeping through the liners into the collection wells, were constructed under the liners (see Figure 2). The average area of the lysimeter basin was 80 m^2.

Liner materials were separated by vertical cut off walls made from special bentonite soil mixture containing 10% of bentonite. The walls were extended below the liners to prevent horizontal water movements between the materials.

The surface of all the liners were at the same level. The landfill conditions were simulated by 1 m layer of actual leachate from the Ämmässuo landfill pumped to the drainage layer on the liners. The level of the water was monitored from pipes and wells, and additional leachate was pumped automatically to sustain this level. The whole structure was covered by a thick clay layer to prevent infiltration of rainwater.

One third of the mineral liner was covered by the artificial sealing line (A-part) and one third was left unprotected, directly exposed to the leachate (B-part). The third part of the mineral liner was left without the leachate layer and soil cover, and exposed to the frost and other climate effects (so called frost parts or C-parts).

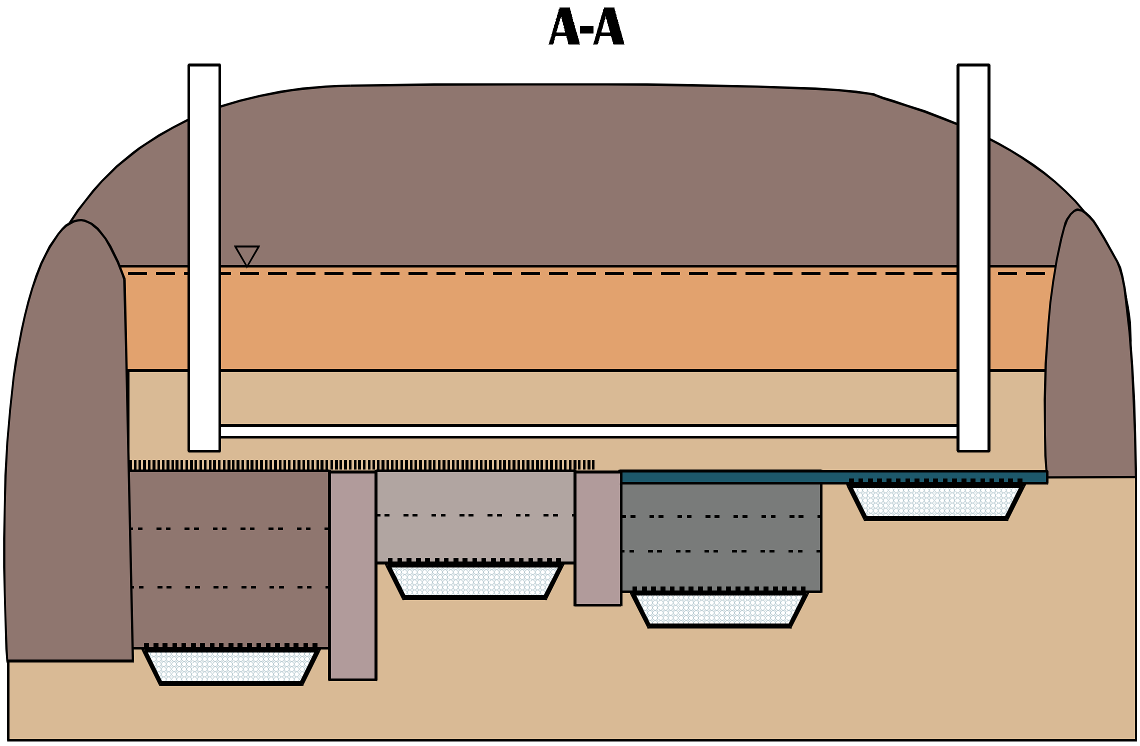

Figure 2. Schematic cross section of the test structure.

3. Results and discussion

The results of laboratory and field permeability, frost and temperature measurements are discussed in the paper published in Proceedings Sardinia 99, 7th International Waste Management and Landfill Symposium. In this paper, the emphasis is on results of chemical analyses of water and material samples.

The quality of the leachate seeping through the liner structures was frequently followed by pH and conductivity measurements, and water samples were taken from lysimeter wells and leachate storage for laboratory analyses.

3.1 Quality of the leachate

The loading water used in test structures was pumped from the settling pond of Ämmässuo landfill. The quality of leachate in the pond is regularly monitored as a part of landfill observation.

During the monitoring period from March 1995 to August 1997, the pH-value of the leachate has been between 6,7–7,7 and the solid contents between 60–550 mg/l, and the corresponding average 185 mg/l. The electrical conductivity and chloride content of the leachate have a good correlation, shown in figure 3.

The leachate quality monitoring includes, in addition to wastewater parameters, following substances: Ca, Mg, Al, Co, Ni, Fe, Mn, Cd, Cu, Pb, Zn, Cr, Hg and As.

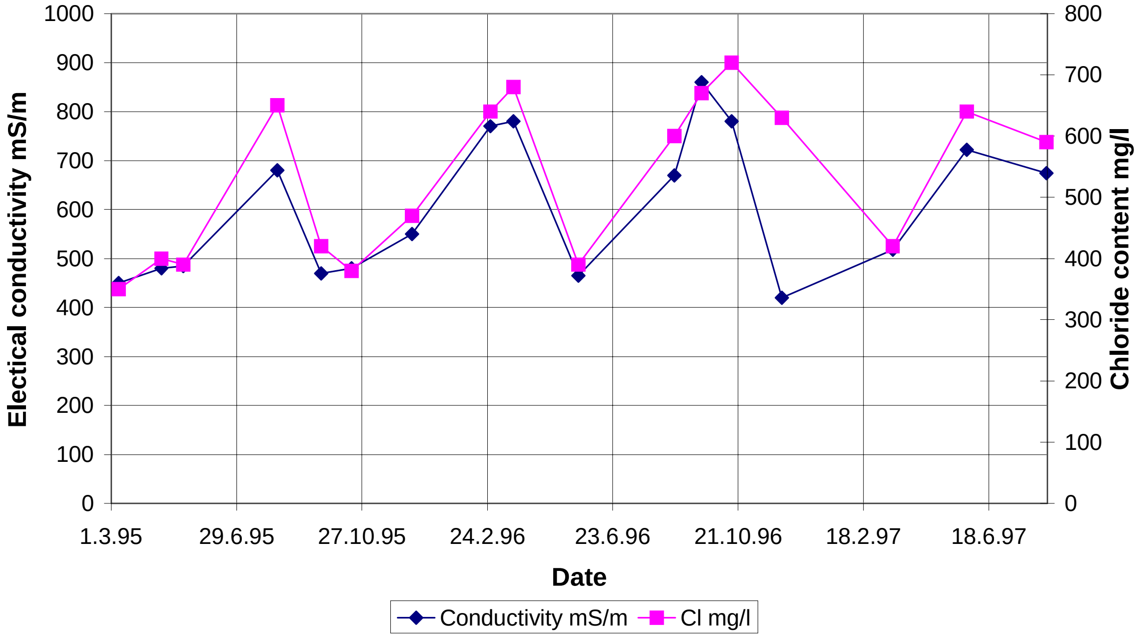

Figure 3. pH-values of leachate samples and seeping water samples from lysimeter wells.

The pond gathers leachate form all filling areas, both old and new. Therefore, the quality of the leachate has a large range of variations. In the comparison, the maximum and minimum values of the leachate have been plotted to describe the variations of the leachate.

3.2 pH and electrical conductivity

The pH-value and electrical conductivity of the water samples were measured immediately after sampling at laboratory of Finnish Environment Institute using glass electrodes. The conductivity was also measured in the laboratory of Vesihydro, Ltd. Results are presented in figures 4 and 5.

The electrical conductivity of the water seeping through the ash structure (3B) differs clearly from the other two. At first, it increases rather quickly to the maximum value, about 3000 mS/m. Then is slowly decreases to the same level as the leachate. Thus, the chloride is diluting from the material.

The electrical conductivity of the water seeping through the bentonite structure (2B) reaches the level of leachate soon after the implementation of the leachate. A small peak can be noticed at the moment of increasing flow rate, in January 1997.

In the samples taken from the lysimeter well of clay structure (1B), the level of conductivity remains almost the same throughout the monitoring period. Values are clearly below the conductivity of leachate. For this reason, the clay liner provides the best ground water protection from these three structures.

Different from conductivity, there are no clear trends in the pH-values. Results from ash structure display a slight decrease. In soil bentonite structure, there is the minimum value at the moment of increasing flow rate. The pH-values of clay remain close to the neutral.

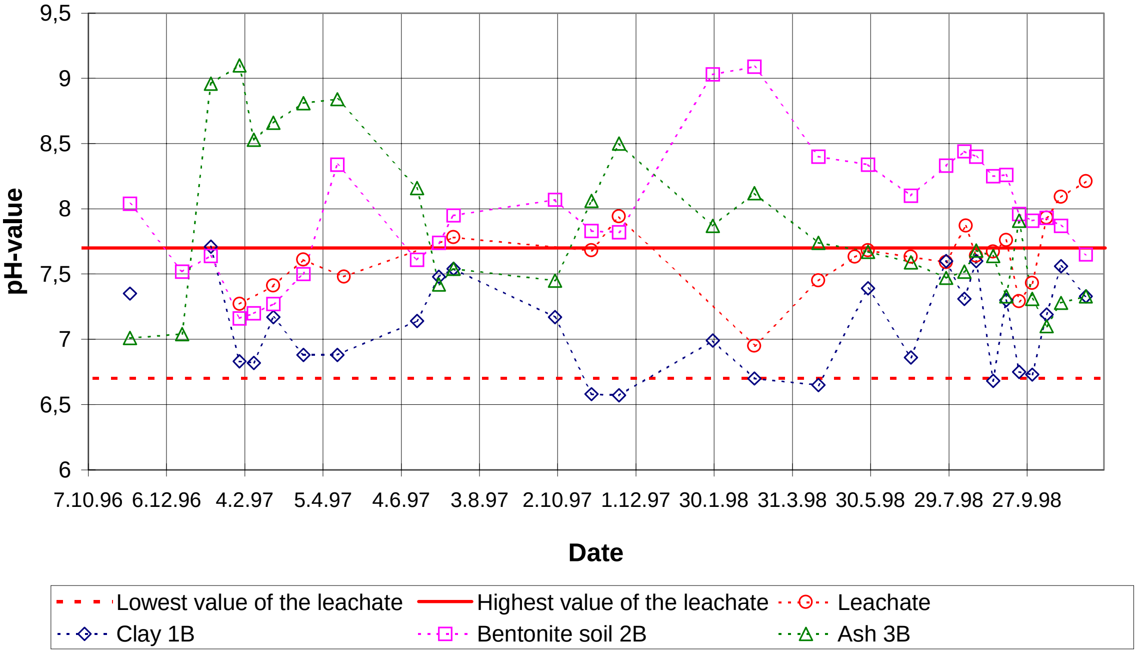

Figure 4. pH-values of leachate samples and seeping water samples from lysimeter wells.

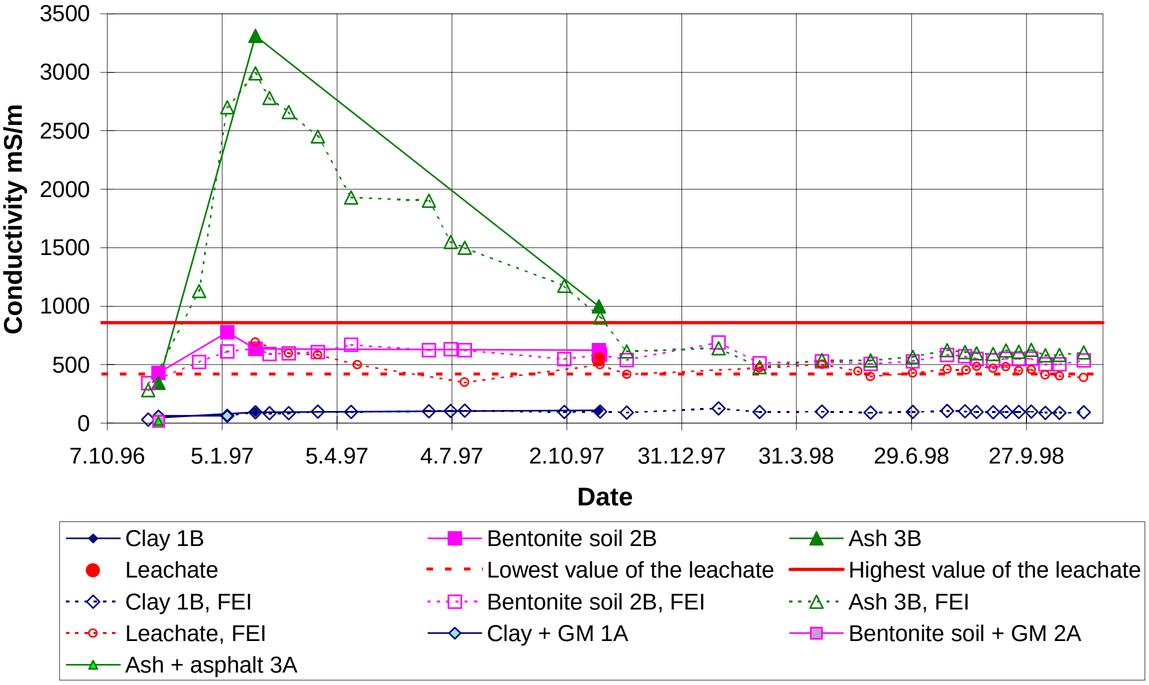

Figure 5. Electrical conductivity values of leachate samples and seeping water samples from lysimeter wells. Results are from two laboratories, Vesihydro Ltd. and Finnish Environment Institute (FEI). There is only one set of samples from A-parts.

3.3 Results of chemical analyses

In order to evaluate the propagation of the contaminants through the liner, and effects of sorption and ion exchange, and possible occurrence of chemical reactions, the chemical analyses were made of water samples taken from lysimeter wells and leachate storage. The content of Ca, Na, Cl, Cr, Mg, Al, Ba and SO_4^- were measured. The analyses were made in the laboratory of Vesihydro, Ltd. and Geological Survey of Finland (GSF).

Figures 6, 7 and 8 illustrate the trends of three different materials. The first results describe the water used in lysimeter well calibration, and therefore should be neglected or considered with caution. The assessment of results should be done taking into the consideration the amount of water seeping through the liner.

In clay structure, the even results of chemical analyses support the conclusion that the clay acts as a filter and provides a good protection.

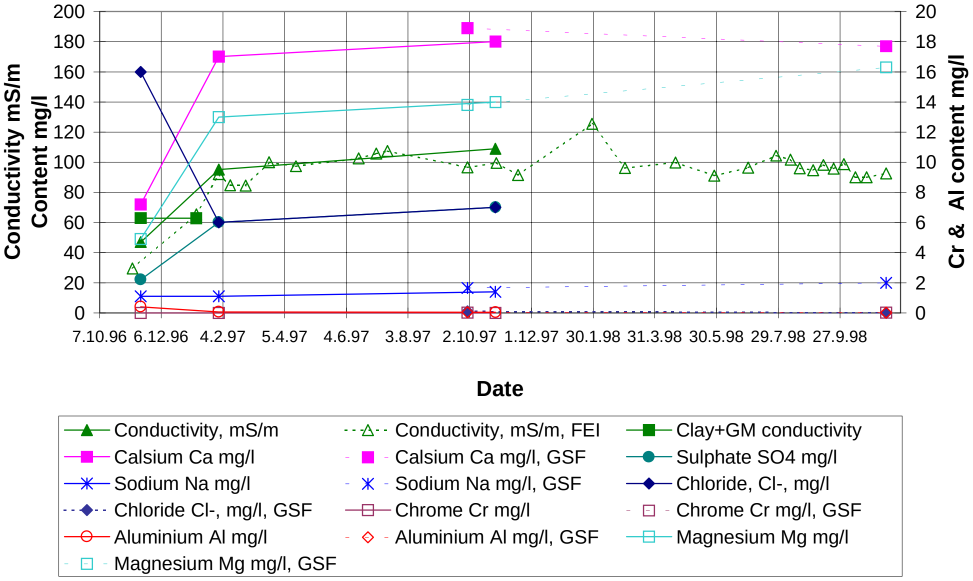

Figure 6. Results of chemical analyses of seeping water collected from lysimeter of clay liner.

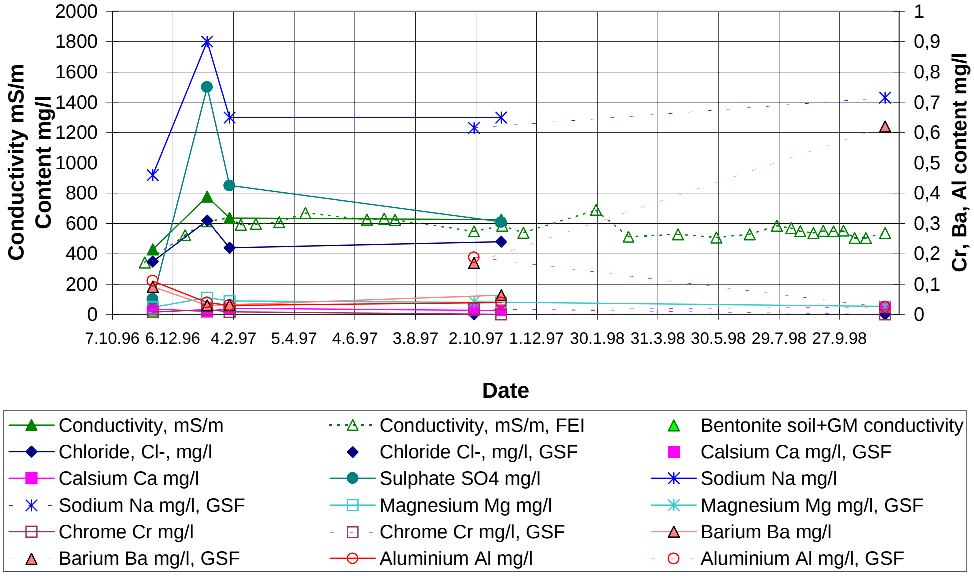

Figure 7. Results of chemical analyses of seeping water collected from lysimeter of soil bentonite liner.

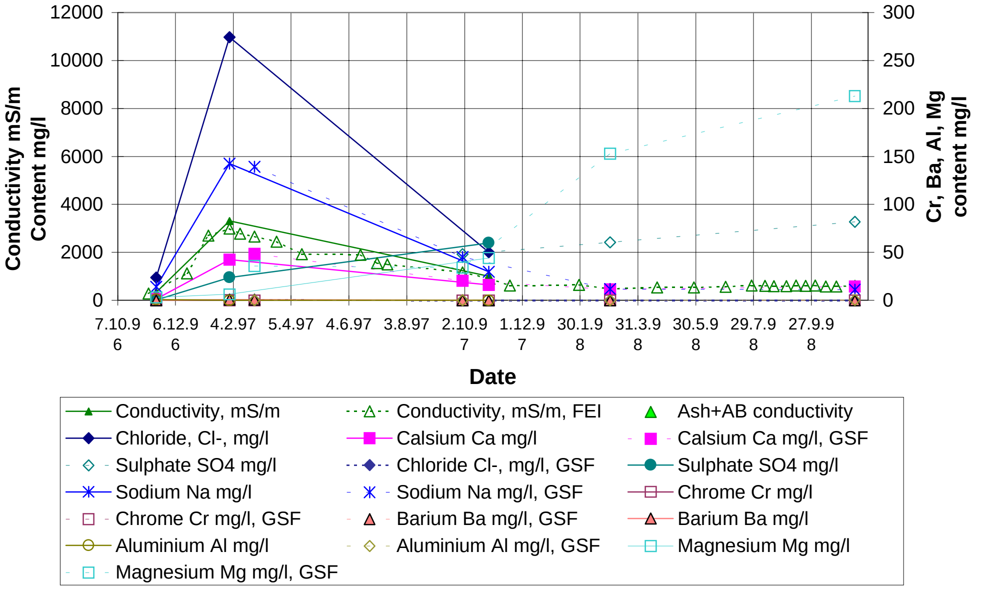

Figure 8. Results of chemical analyses of seeping water collected from lysimeter of ash liner.

3.4 Chemical analyses of the materials

The test structures were demolished in November 1998 and material samples were taken for laboratory analyses.

In order to evaluate the propagation of the contaminants through the liner, and effects of sorption and ion exchange, and possible occurrence of chemical reactions, the chemical analyses were made of material samples. The concentrations of 25 substances, including heavy metals, were measured. The analyses were made in the laboratory of Geological Survey of Finland (GSF). A selected part of the results are presented in table 1. The concentrations are compared to the Finnish guiding and limiting values used in assessing of soil contamination. Similar to the water analyses, the assessment of these results should be done taking into the consideration the amount of water seeping through the liner.

In clay, the natural concentrations of some contaminants, such as vanadium and chrome, exceed the guiding values. No clear sign of effects of leachate can be noticed.

The guiding values are exceeded in fly ash and desulphurating agent, too. Typically the concentrations decreases due to the presence of leachate. It follows that the sorption processes aren’t significant, whereas diluting is.

The chloride content of ash is high at the A-part, where the structure has been protected by the asphalt layer and hasn’t been in a contact with the leachate. At the B-part, where the leachate can infiltrate to the ash layer and seep through it, the chloride content is significantly lower, only percents of the original values. The smallest values are from the surface of the liner structure, where the effect of the water is largest. On the contrary, the concentration of arsenic is rather even at all ash parts, due to the poor solubility in water of the arsenic.

In bentonite soil the amount of sodium is diminishing due to the presence of leachate. The effect can be noticed from the sample taken from the surface of B-part and from the sample taken under a geomembrane failure point found at the A-part during the demolition. Results don’t show signs of accumulation of contaminants.

Based on these results, the leachate has a detrimental effect on both ash and bentonite soil liners investigated in this study. The effects on clay liner are undetectable.

Table 1. The concentration (mg/l) of selected substances in liner material samples. Samples taken before the leachate implementation are marked with text “before”. n.d. – not detected, DSA – desulpurating agent, BE-soil – soil bentonite.

Location	**Cl mg/kg**	**As mg/kg**	**B mg/kg**	**Ca mg/kg**	**Co mg/kg**	**Cr mg/kg**	**Mg mg/kg**	**Mo mg/kg**	**Na mg/kg**	**Ni mg/kg**	**P mg/kg**	**V mg/kg**
Clay BEFORE	n.d.	< 10	n.d.	5400	22,0	**106**	15000	< 5	540	50,0	597	**117**
Clay 1A surface	n.d.	< 10	**5**	3730	18,7	73,9	11300	< 0,3	417	41,1	357	**90,4**
Clay 1A bottom	n.d.	< 10	**7**	6260	28,3	**110**	18200	< 0,3	672	**61,3**	566	**134**
Clay 1B surface	n.d.	< 10	**12**	4660	21,6	87,5	13500	< 0,3	816	48,0	499	**108**
Clay 1B bottom	n.d.	< 10	**8**	5610	24,8	**102**	16500	< 0,3	611	55,8	531	**125**
Clay 1C	n.d.	< 10	**9**	5490	22,3	99,0	15400	< 0,3	580	53,9	553	**116**
Fly ash BEFORE	n.d.	**31**	n.d.	9800	10,0	22,0	2900	**6**	550	26,0	1740	45
Fly ash&DSA BF	n.d.	**14**	n.d.	104000	12,0	17,0	4400	< 5	11000	23,0	1380	37
Ash 3A 0 m	10400	**26**	**113**	10400	9,5	11,9	2650	**7**	4890	22,9	1720	39,2
Ash 3A 0,2 m	13100	**25**	**116**	9460	7,9	11,4	2350	**6**	5170	20,2	1490	35,9
Ash 3A 0,6 m	20900	**16**	**197**	56600	6,6	7,9	3020	4	6700	16,0	1020	22,7
Ash 3B 0,2 m	529	**38**	**128**	82900	9,8	15,4	3900	< 0,3	973	23,8	1480	40,9
Ash 3B 0,6 m	716	**22**	**473**	103000	10,5	12,9	5660	**6**	746	24,8	1390	35,7
Fly ash 3B surface	125	**20**	**42**	10400	10,0	14,4	2530	< 0,3	416	25,3	1890	37,2
Fly ash 3C	2,7	**28**	**61**	8840	9,9	11,6	2700	< 0,3	230	24,0	1790	39,3
BE-soil BEFORE	n.d.	< 10	n.d.	9600	8,0	36,0	6000	< 5	2270	15,0	337	42
BE-soil 2A surface	n.d.	< 10	< 5	7010	6,2	19,1	4390	< 0,3	2100	9,2	240	28,8
BE-soil 2A bottom	n.d.	< 10	< 5	9110	5,6	17,7	4250	**10**	3000	9,2	234	25,4
BE-soil 2A defect 0 m	n.d.	< 10	< 5	6450	5,6	17,5	4240	< 0,3	986	9,6	228	27,8
BE-soil 2A defect 0,2 m	n.d.	< 10	< 5	7170	4,7	13,6	3620	< 0,3	2210	6,0	205	21,7
BE-soil 2B surface	n.d.	< 10	**8**	11100	5,7	17,9	4280	< 0,3	541	9,2	318	27
BE-soil 2B bottom	n.d.	< 10	< 5	9350	5,2	15,6	4260	< 0,3	3000	7,1	252	25,7
BE-soil 2C	n.d.	< 10	< 5	8630	5,8	17,0	4320	< 0,3	2460	8,1	223	25,4
Guiding value		**10**	**5**		**50**	**100**		**5**		**60**		**50**
Limiting value		**50**	**50**		**200**	**400**		**200**		**200**		**500**

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Lining permeability of store of contaminated soil

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ABSTRACT: An old cement store has been built store for contaminated soil. The store has been built in two phases and the lining structure is different in each phase. The lining structure in both cases has been built as a double lining structure where under pavement there is a drainage layer and under that there is another lining layer. At first phase the second lining layer is construct of either Bentonite soil or Trisoplast. At second phase the second lining layer was construct of Geomembrane and Trisoplast as a double lining layer. The aim was to construct the pavement so that its permeability should be at first phase $k< 10^{-9}$ m/s and at second phase $k<10^{-11}$m/s. There have been observed leaks through pavement in operating conditions after contaminated soils have been placed on pavement.

1. Introduction

An old cement store at Virkkala has been built store for contaminated soil. The store has been built in two phases and the lining structure is different in each phase. The lining structure in both cases has been built as a double lining structure where under pavement there is a drainage layer and under that there is another lining layer. At first phase the second lining layer is construct of either Bentonite soil or Trisoplast. At second phase the second lining layer was construct of Geomembrane and Trisoplast as a double lining layer. The store fields have been moulded to form of clamps. In that form their permeability is measurable even in operating conditions. The aim was to construct the pavement so that its permeability should be at first phase $k< 10^{-9}$ m/s and at second phase $k<10^{-11}$ m/s.

At design phase there was permeability measurements in laboratory with each material. As field-tests there have been infiltrometer tests. From complete pavement have been taken samples and their permeability have been tested in laboratory.

There have been notified leaks through pavement in operating conditions after contaminated soils have been build up on pavement. Groundwater pressure in clamps and quantity of passed water through pavement have been determined with measurements in winter 1999 … 2000.

2. Permeability measurements

2.1 Measurements of first phase structure

There was notified leaks to the under drain inspection wells at the area built in 1998. After this there were measured the quantity of infiltrating water. According to these measurements there was leak of 0,25 m^3/d from one clamp which area was 400 m^2. This infiltrated water quantity conforms to permeability rate of $k = 10^{-9}$ m/s (Table 1). Water infiltrated through layers was on the average 0,060 m^3/d which conforms to permeability value of $k = 10^{-10}$ m/s.

In addition permeability was measured with 455-mm cone as a transient pressure test. Permeability was in three different measured places 7,9 … 0,57*10^{-9} m/s.

Pavement structure in most areas could be found to meet with the required permeability $k < 10^{-9}$ m/s.

Table 1. Approximation of permeability of first phase pavement structure.

Measured biggest value [m^3/d]	0,25
Measured average [m^3/d]	0,055
$k = 10^{-8}$, h = 0,5 … 2 m	1,9 … 11,5
$k = 10^{-9}$, h = 0,5 … 2 m	0,19 … 1,15
$k = 10^{-10}$, h = 0,5 … 2 m	0,019 … 0,115
$k = 10^{-11}$, h = 0,5 … 2 m	0,0019 … 0,0115

2.2 Measurements of second phase structure

For this structure the permeability requirements were $k < 10^{-11}$ m/s. In the area of two clamps there had been stored contaminated soil. They cover 210 m^2 at the clamp area 1 and 630 m^2 at the clamp area 2. To the inspection wells of the clamps there has been measured infiltration water 0,12 m^3/d and 0,094 m^3/d. According to these measurement the permeability is much bigger than required $k < 10^{-11}$ (Table 2). Compared with the theoretical calculations the permeability of first clamp area is bigger than 10^{-10} m/s and the permeability of second clamp area is app. 5*10^{-10}.

Table 2. Approximation of permeability of second phase pavement structure.

	Clamp 1 [m^3/d]	Clamp 2 [m^3/d]
Measured	0,12	0,094
$k = 10^{-9}$, h = 0,5 … 6 m	0,10 … 1,21	0,30 … 3,63
$k = 10^{-10}$, h = 0,5 … 6 m	0,010 … 0,121	0,030 … 0,363
$k = 10^{-11}$, h = 0,5 … 6 m	0,0010 … 0,0121	0,0030 … 0,0363

3. Additional investigations

During spring 2000 there were installed standpipes into clamps to measure the water pressure against the pavement. After installation of standpipes the clamps were irritated. Through the standpipes there could not be measured any water pressure even there were measured leaks through the pavement. Conclusion was that the water pressure against pavement in low permeable clamps is only the pore water pressure. This pore water pressure is strongly related to the mass of clamps. Therefore the pressure can become several meters high.

During summer 2000 the pavement permeability should be investigated more precisely. At this time there should investigated two different situations. The first one is to investigate the permeability when there is a permeable layer under the clamp. This permeable layer should decrease the pore water pressure under the clamp. The second investigation is the normal clamp where the clamp should be built directly on pavement.

To calculate permeability more precisely there should be installed pore water pressure gauges into pavement. With gauges and measurements of water content, dry unit weight, wet unit weight and with measurements of clamp profile the permeability of pavement could be calculated.

4. Conclusions

According to the measurements the first phase pavement of which $k < 10^{-9}$ m/s met with the requirements. Requirements of second phase structure $k < 10^{-11}$ m/s could not be met. The underground of the pavement was not dense enough for the compaction and that is why the pavement didn’t meet with the requirements. In both cases with this study the pavement behaves like a mineral lining.

In low permeable clamps the water pressure against pavement is mostly the effect of pore water pressure. Therefore the water pressure is related to the mass of clamp and that is why the fall head could become several meters high. This fall head could be easily reduced with permeable layer under the clamps.

The possibilities for observing settling in a base sealing system for maintaining the effect of a barrier on dumps of the central German lignite areas using the Cröbern Centralised Landfill as an example

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ABSTRACT: The Cröbern Centralised Deposit Site is on a 70 meter high dump. We forecasted that the centralised deposit site would settle up to 2.40 meters in accordance with the technogenous ground. The results of measurements will then form the basis for the security and further subsequent construction work.

1. Introduction

Lignite mining in Germany has a long tradition. It was only when mines were put into operation that it was possible to excavate lignite on a high-performance basis. However, the more lignite was excavated, the greater was the accumulation of overburden. This overburden had to be deposited somewhere, which in the beginning phases of mines was usually done on stockpiles or in already existing mining voids. When operations began running, they changed over to internal dumping. Depending upon the technology applied, various types of equipment were used for dumping the overburden masses.

In the Espenhain Mine, overburden above the seams was excavated and dumped by means of an overburden conveying bridge and a belt conveyor that was capable of selectively excavating arable soil for reclaiming the dump areas. The medium overburden and the floor overburden was dumped by means of a tension spreader. In addition, the spreader dumped ashes from the power stations in the surrounding area. Depending upon the type of excavation, transportation and dumping of the overburden, the earth materials were more or less well mixed. Therefore, we can say that the mine’s interior dump consists of two dumped slabs. Figure 1 shows the existing situation for the interior dump of the Espenhain mine. At a thickness up to 70 m, this technogenous material of the two dumps possesses a high potential for cavities and pore spaces. This means that after dumping there is a high degree of settling potential contained in the dumped slabs that could contain an element of risk for later engineering structures.

The lower slab forms the overburden conveying bridge slab with a thickness of approximately 45 meters. The structure of the AFB dump is homogenous in accordance with its development, which is confirmed by the existence of a granulation belt in the sediments. Masses of overburden in the partings, the floor and to a certain extent also ashes from the power stations were dumped in the spreader dump (the upper dump slab). These masses were built into the spreader dump both separate and mixed so that there is a large number of earth material mixtures in the individual dump lamellas (refer to Figure 1).

Settling of up to 2.4 meters was forecast for the base of the Cröbern Landfill. Therefore, the magnitude of settling includes the possibility of increased stress on individual structural components of the multibarrier system. We took this into consideration when planning these systems and we installed the appropriate design solutions making it possible to reliably record the forecasted values. We also set increased expenditures for the control mechanisms for building and operating the landfill to check whether the permissible values were being met as well as for ensuring the workability of important structural components of the base sealing system and the seepage water catchment. The observation plan for the Cröbern Centralised Landfill forms the basis for making measurements, evaluating them and establishing our conclusions. This plan for the Cröbern Centralised Landfill is based upon the observation method pursuant to DIN 1054 (a draft). When planning and building individual system components, observation elements were assigned depending upon the design form and the specific geotechnical situation of the location. We also made measurements parallel to building the base systems and subjected the results to constant evaluation and interpretation. If necessary, it was also possible to verify the forecasted values using the results of the observations. The observation plan for the centralised landfill establishes the structures to be observed so that there is constant control of the interrelation between bringing loads from on-going construction and landfilling as well as the deformations of decisive structural components of the landfill.

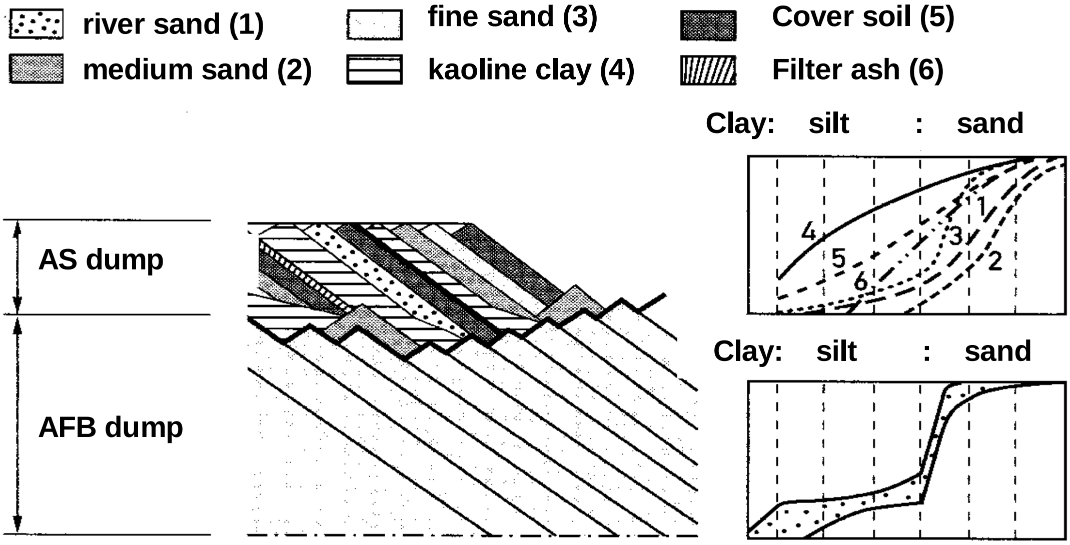

Figure 1. The geotechnical situation under the Cröbern Centralised Landfill.

2. The multibarrier plan for the Centralised Landfill

Landfill planning is based upon the valid conditions of Technische Anleitung Abfall (the Technical Instruction for Refuse). The reason for this may be found in the geotechnical situation in the dump as a landfill contact surface. The individual elements of the multibarrier system in the base of the landfill consist of the following:

- a solid dump massif at a thickness of approximately 70 m in the form of an overburden conveying bridge slab and a spreader dump. The two dump slabs possess ground permeabilities of $k_f \leq 1 \times 10^{-6}$ to 1×10^{-5} m/s.
- creating a roof profile base relief with an exaggeration for safely taking on the forecasted settling hollow. The thickness is 0 to 8 m. The base relief is set in a ring dam approximately 11 m high.
- installing a geotechnical barrier as a replacement for the geological barrier at a thickness of 3 m. The geotechnical barrier consists of 10 layers of compressed built

in material from the AFB dump that has to comply with the requirements of the geological barrier.

degree of compression $D_{Pr} \geq 95\%$
$k_f \leq 1 \times 10^{-7}$ m/s
clay mineral content ≥ 10%

- creating a mineral seal made of clay at a thickness of 1.5 m in 6 layers, whereby at least the uppermost layer is grogged for increasing the frictional interlocking with the plastic sealing layer by means of kaolinic sand. The requirements made of the mineral seal can be found in the determinations of Technische Anleitung Abfall (the Technical Instruction for Refuse)

degree of compression $D_{Pr} \geq 95\%$ with $w_n > w_{Pr}$
$k_f \leq 5 \times 10^{-10}$ m/s
clay granulation content ≥ 20%

The grogged material clay / kaolinic sand complies with the required values.

- plastic sealing layer made of PEHD at a thickness of 2.5 mm
- protective layer consisting of a sand layer
- drainage layer made of 16/32 washed gravel where the drainage elements are laid.

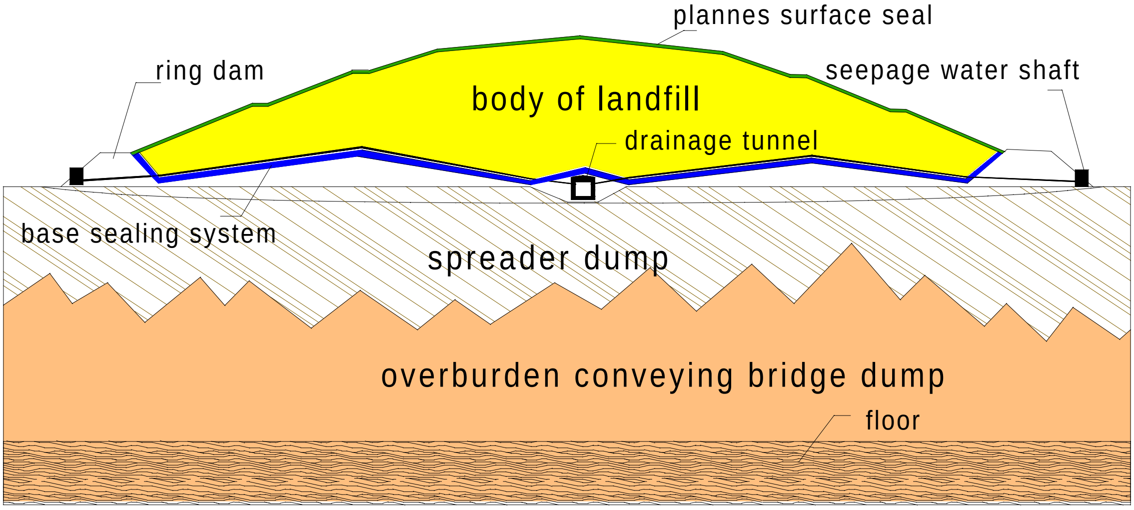

Figure 2. The north/south cross-section of the Cröbern Centralised Landfill.

The multibarrier system used for the Cröbern Centralised Landfill consists of a combination of the individual elements of the base sealing system. We dumped sample loads for assessing the loads of the individual components of the base system with whose aid it was possible to make measurements. At the same time, it was necessary to make suitability studies on the dump masses as well as their geological prospecting.

3. The possibilities for investigating the dump’s properties

We applied various methods for assessing the properties of the materials in the underground of the landfill. Evaluating the existing substrata on the operations provided us with information on the technological processes in the mine and the material flows linked to that when the coal was being excavated. This makes it possible to divide it up into individual annual slabs as well as the storage time of the dump areas resulting from that. Furthermore, we stationed measuring points in the planned area of the landfill with whose help it was possible to observe the process of settlement on the dump surface.

It was necessary to drill, make pressure explorations, ram explorations and do prospecting work for investigating the dump and to work out the properties of the soil physics of the dump masses. Beyond this, we made a geophysical survey in selected areas and subjected the samples extracted to detailed laboratory analyses. Parameters such as grain distribution, consistency limits, Proctor values, permeabilities, shearing parameters and stiffness modules were of special interest for the assessment. Furthermore, we determined the lime content, ignition loss and the proportion of organic components and made clay mineral investigations.

4. Laboratory methods of investigation for determining strength parameters

It is necessary to have a knowledge of the stiffness modules of the individual materials in the dumps and the construction materials for the base sealing system for determining the settling behaviour of the dump masses. We determined them based upon a variety of methods. First of all, we evaluated the settlement under sample load dumps in order to assign an integral stiffness module to the dump material. Furthermore, it was possible to generally classify the material by co-relating the peak pressure conditions from the pressure explorations. It was also possible to determine parameters specific to selected materials in the dump as well as the construction materials by means of laboratory experiments. The following investigations were used:

- small-scale oedometer experiments
- pressure experiments in a large-scale pot
- triaxial experiments.

Finally, we carried out experiments in soil physics on the mineral sealing material for deformation behaviour.

5. The observation strategy and its elements

Several measuring techniques were used for checking the development of settling in the Cröbern Centralised Landfill and the parameters to be derived from that such as expansion and curvature. The measuring elements for the individual techniques were arranged in the individual construction layers. The following were used:

- geodetic measurements, the classical as well as the GPS technique (satellite-related measurements);
- inclinometer measurements in profile tubes (inclination measurement using a probe);
- hydrostatic measurements in stainless steel tubes (the hose weigh scale principle);
- constant measurement electrical system using a displacement transducer in the drainage tunnel.

The geodetic measurements are specifically used to check individual construction elements such as buildings, shafts, fixed points and taking stock of finished structural components. GPS is used to survey areas and surface profiles. The profile tubes of the inclinometer measuring system are the lowest measuring layer and reflect the former surface of the dump. This system consists of three measuring lanes. One measuring lane is below the high point of the landfill levelled ground of fields 1–3 in landfill area I. A second measuring lane runs under the high points between fields I/3 to I/4. The third inclinometer measuring lane has been laid on the floor of the pit for the drainage tunnel that divides up the landfill surface into two landfill areas and runs under the base seal. The hydrostatic measuring tubes in the last layer of the technical barrier are the second measuring layer. They run parallel to the drainage pipes in the fields. These pipes end at the ring dam on the seepage water shafts and come together in the middle of the drainage tunnel as with the drainage system. There is also a measuring tube for the hydrostatic system under this tunnel in accordance with the project. This distribution guarantees a parallel arrangement for the drainage systems under the Cröbern Centralised Landfill.

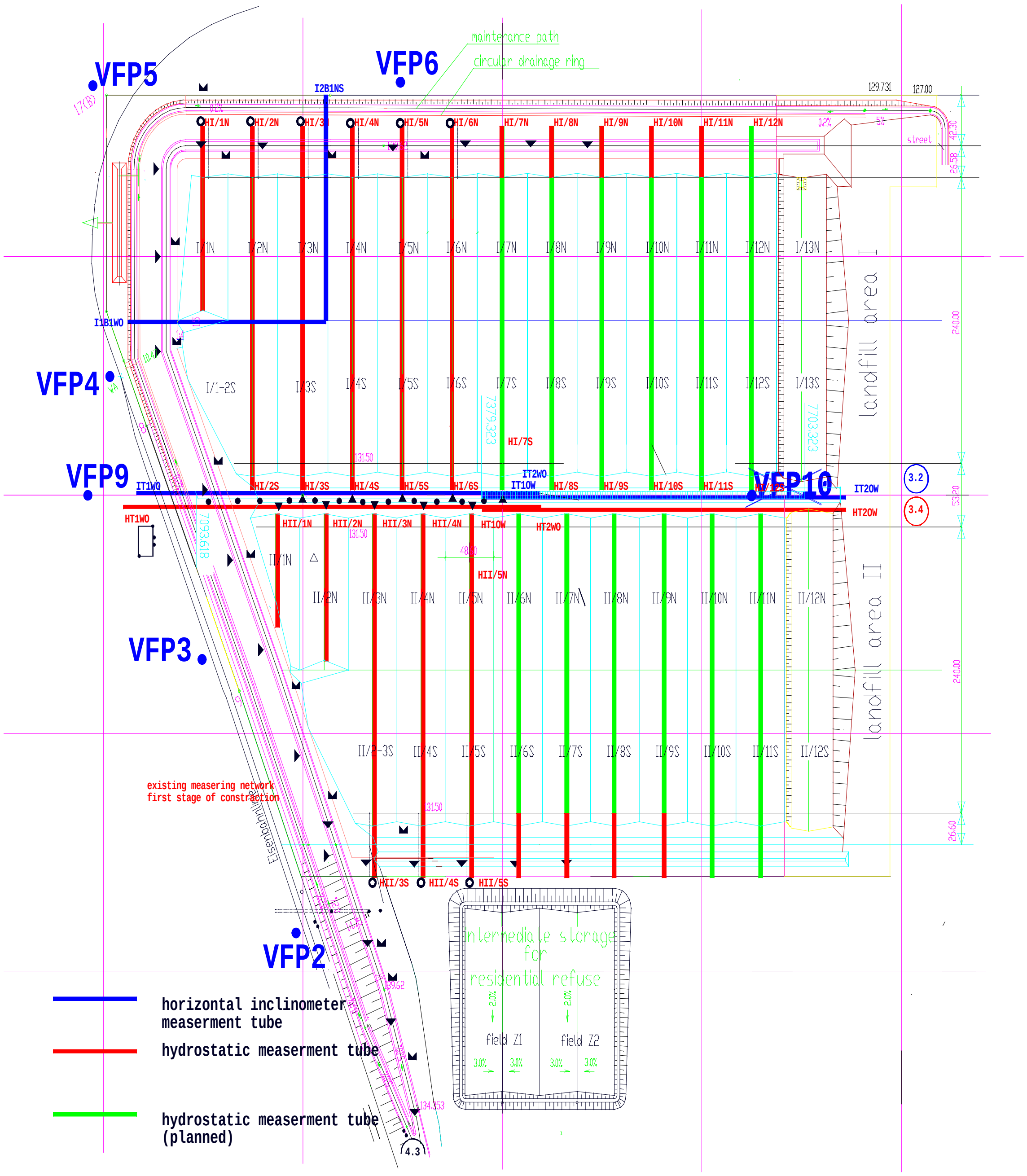

Figure 3. The layers of the settling masuring systems.

A constant measurement system in the drainage tunnel forms the third measuring layer. Joints are arranged in the tunnel at intervals of eight meters that break down the building structure into individual blocks. These joints make a variety of movements possible as a result of settlement. Furthermore, it is at these joints that the transmitters of the constant measurement system are located. Computer programs re-calculate the registered movements of the transmitters into a description of the layers of the tunnel elements, thereby allowing a precise description of the development of movements as well as the absolute values. The construction site co-ordinate system is used for spatially linking all of the measuring data.

6. Assessing the results received

We have been measuring the individual components of the observation system for different periods of time. This is done because of the process of construction and also to arrange the individual elements at varying heights under the landfill. In general, we may state that the development of settling was harmonious. Settling is in accordance with the way that the height of placing refuse develops. We did not notice any acute jumps. On the other hand, bringing in a concentrated load in locally limited areas expresses in the form of a quicker development of settling in the immediately surrounding area. The process of construction and placing refuse should be adjusted to that and they therefore should be made plane and without greater jumps in loads. Beyond this, further construction and the placing technology have to be monitored by geotechnical expertise in order to protect the multibarrier system from any damage.

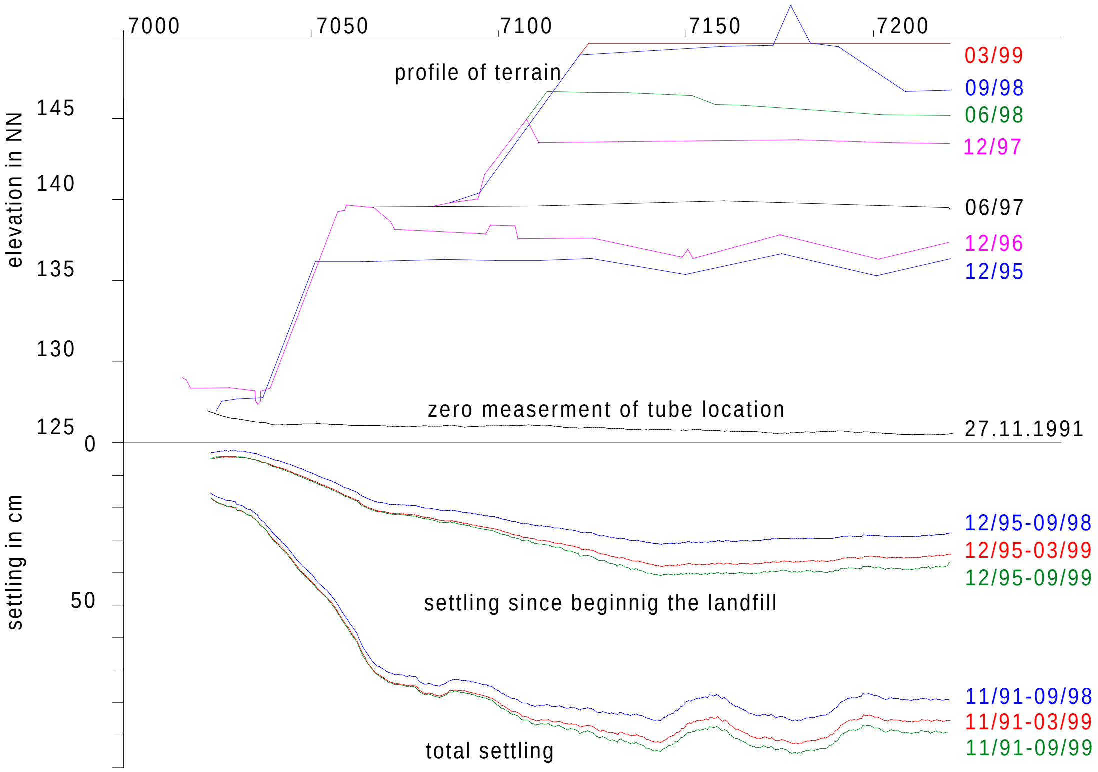

Figure 4.Settling in the Inclinometer Lane I1B1WO.

Figure 4 shows a visualisation of the settling measured with reference to the development of the terrain. Since the measuring tube was installed, we measured settling of up to 96 cm by September of 1999. The change in the curve does not show any conspicuous settling jumps and therefore corresponds to the load contour. The even curvature of settling since the beginning of the landfill also represents the balancing effect of the structural components of the multibarrier systems built using earth such as the relief design, the geotechnical barrier and the mineral seal. These structural components bring various settling potentials in the upper dump masses into harmony.

Figure 5 shows the measured settling in the drainage tunnel. The profile above the diagram shows a cross-section along the tunnels in the first stage of construction, making it possible to recognise the tunnel blocks. It also makes it possible to reconstruct the development of placing refuse from the profiles of the surface in relation to the periods of time shown. We measured settling in the tunnel of up to 85 cm. The experience that we have gathered from these measurements are continuously integrated into the further process of construction and placing refuse. Here, we have evaluated the weak points we have recognised, drawn our conclusions and undertaken the appropriate modifications when instrumenting measuring elements, in the process of building the multibarrier system and in continuing to build the base sealing system. The installed observation system for the Cröbern Centralised Landfill as well as the measuring techniques used have proved their reliability and have supplied meaningful results within the framework of the individual system preciseness. Furthermore, the geotechnical control of the multibarrier system has made it possible to operate the landfill in a trouble-free fashion up to now. At the same time, we were not able to discover any negative effects that could not be kept under control for continuing the operation of the landfill.

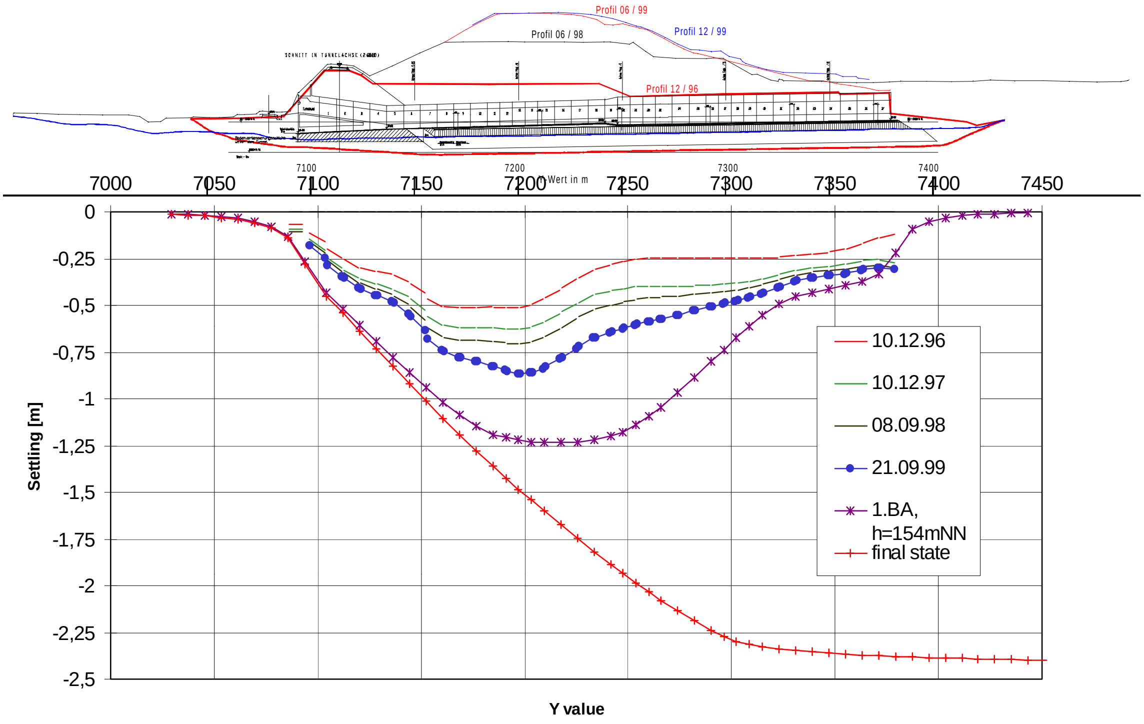

Figure 5. Settling in the first stage of construction of the drainage tunnel.

Landfill bottom sealing with Trisoplast®

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ABSTRACT: Trisoplast® is a innovative mineral sealing material for soil and ground water protection at landfills, industrial areas, sewage plants, container areas and any other site where harmful substances may cause threat. Trisoplast® is a mixture of medium grained sand, bentonite clay powder, certain polymer and water. When compacted, Trisoplast® forms a very flexible mineral sealing with high-class protection properties. Low permeability allows very thin sealing layers, which give more space for waste and lower protection costs and less material consumption.

1. Mineral barrier requirements

Planning a landfill barrier construction is partly a search for an inexpensive solution, which also fulfills the quality requirements set by the government officials. The quality level is defined by landfill regulation based on EU directive. According to it, bottom construction shall consist of a mineral sealing and an artificial sealing on top of it. Costs for making bottom sealing can, for example, be reduced by constructing the landfill on natural soil layer. However, this is seldom possible, because landfill areas are not normally situated by prevailing soils, but other more important factors like distances and population. In addition, homogenous natural soil layers with low permeability, adequate strength and dimension are seldom found in Finland.

1.1. Two-layer construction

Environmentally safe and cost effective solution can be achieved by dividing functions of the mineral sealing into two layers: lower layer with thickness of 0.41 m prevents consolidation and diffusion and upper layer – 90 mm of Trisoplast® - keeps off the leaching waters together with artificial sealing – 2 mm of HDPE membrane. Lohja Envirotec Ltd has gained knowledge of constructing two-layer structure with Trisoplast®. This solution has been tested and given clearance for use by Finnish Technical Reseach Centre.

Functional demands of landfill barrier construction are stated in Finnish Governmental decisions. According to it, a landfill for municipal waste requires one meter mineral sealing with k-value < 1 x 10^{-9} m/s and an artificial sealing, normally a plastic membrane (thickness > 2mm) as a protective structure on top of it. If natural soil layer do not fulfill these requirements, a 0.5 metre of mineral layer must be constructed. The level of protective properties may not be reduced, which means that the k-value of the layer must be decreased. In most cases, new landfill bottom constructions have included a 0.5 metre layer of compacted soil bentonite with permeability coefficient of $6.7*10^{-10}$ m/s. Nevertheless, the thickness of mineral layer can still be reduced while improving permeability together with other relevant technical properties like chemical stability, transformation capability, erosion resistance and plasticity.

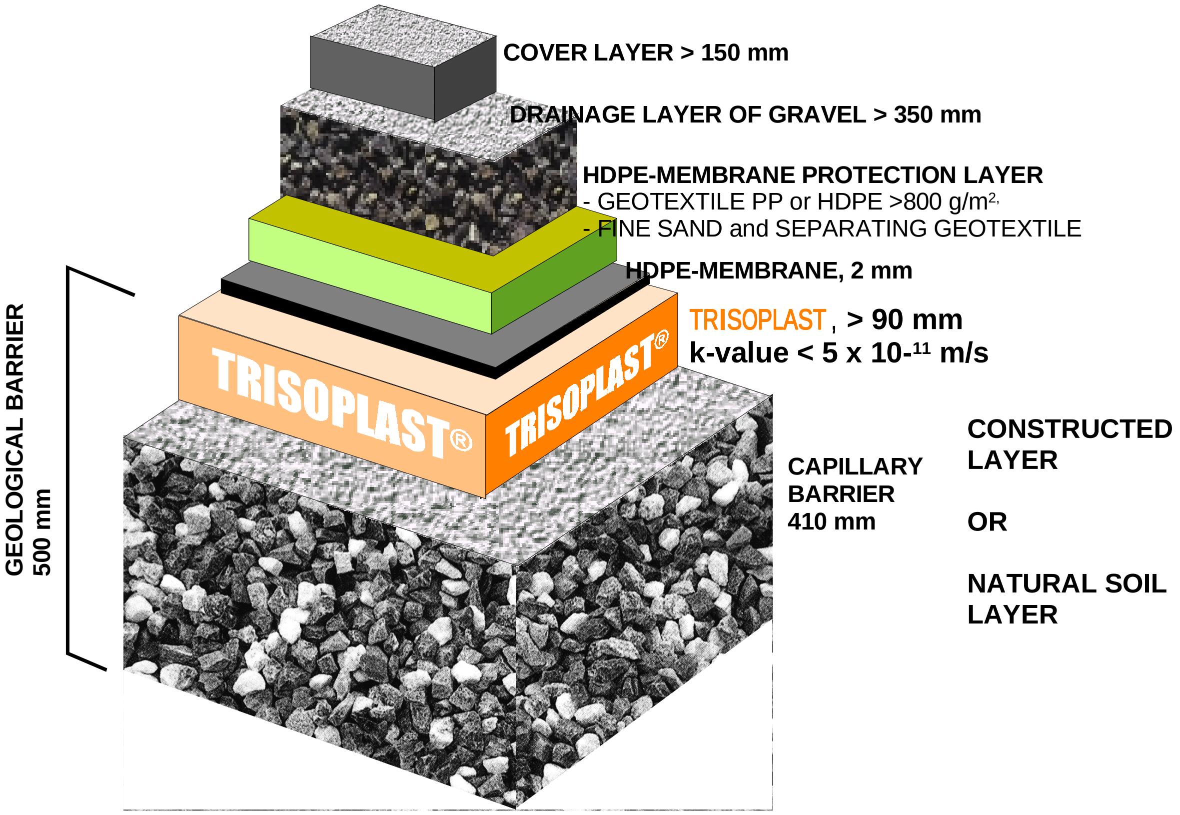

Figure 1. Typical landfill bottom liner construction. Mineral barrier is constructed with 90 mm Trisoplast®- layer and 410 of other mineral material.

2. Properties of Trisoplast®

Developed in Holland by GID, Trisoplast® is used in landfill top and bottom sealings, to other environmental structures protecting ground water at industrial sites and also on sealing of contaminated soil. Trisoplast is done by mixing together four components: even grainend sand, polymer, bentonite clay and water. The consistence is always nearly the same mixture being only fine tuned with sands from different locations.

Water permeability efficient of Trisoplast® is always smaller than $5*10^{-11}$ m/s. This figure is the minimum quality level guaranteed by the constructor and the basis for the calculations related to functional applications. In fact, k-values of samples taken from constructed sites have varied between 10^{-12}– $3*10^{-11}$ m/s meaning that sealing properties have been several times better than the promised minimum quality level. Thus, Trisoplast® forms, even loosely compacted, nearly impermeable layer in respect to water. Studies have shown, that k-value stays in a level below $5*10^{-11}$ m/s with compaction degree even as low as 70 per cent. In practice, Trisoplast® is always compacted to at least the level 90 per cent and so still improving the excellent quality.

The excellent properties of Trisoplast® are based on the joint effect of the four components. Water causes swelling of the bentonite particles mixed with sand grains and this mixture fills pores tightly. The polymer forms streching fiber bridges around sand grains, which are chemically bonded to bentonite clay. These polymer fibers strengthen the structure and make it remarkably flexible enabling Trisoplast® to keep its sealing properties unchanged in heavy transformations. In addition, these polymer fibers reduce water permeability and prevent ion exchange in bentonite clay. This has a notable effect on product’s good long term stability. Trisoplast® ‘s stability in severe chemical conditions has also been studied. It does not loose its sealing properties in constant strain, for example in contact with phenol, petroleum or salt water. Strong acidic or basic solutions (pH 1,2–10) or oxidizing conditions have no effect on it, either. In Holland and Belgium, technical and chemical properties of Trisoplast® have led to its approval for use in dump sites as bottom sealing, alone as a 9 cm layer. Environmental Ministry of Holland has stated that Trisoplast® protects environment better than 0,5 meter clay or sand bentonite layer with k-value 6,7*10–10 m/s.

3. Trisoplast® as a landfill sealing

Surfaces of old dump sites can be sealed with 7 cm thick Trisoplast® which works not only as a water sealant, but also prevents gases entering into air. This is why no other plastic foil is required. Due to irregular consolidation of waste, the surface of old dump site will be uneven, thus, the barrier construction will be under heavy transformations. This particular characteristic of landfills and variable climate conditions – repetitive drying, soaking and freezing/thawing – cause strict requirements for the surface barrier. Trisoplast® is not affected from repetitive freezing/thawing processes, it is flexible without loosing its sealing properties and it also tolerates drying. Good technical properties, experiences in practice and saved money are reasons for its wide – and still rising - usage in dump site construction.

3.1. Salo-project, first Trisoplast® application in Finland

In Finland, the first application of Trisoplast® has been the first phase of constructing the bottom sealing of landfill at Salo, in southern Finland (Salon Seudun Jätehuolto Oy, Korvenmäki). The whole area of bottom sealing was 17000 m2. Because there was no previous experiments of the product’s use in Finland, the construction was done by applying 10 cm Trisoplast® on top of 40 cm moraine layer. The quality control during the process and after it shows that required quality level was reached and the degree of compaction was actually remarkably better than the objectives. Water permeability tests have been done in five different laboratories and results prove the k-value to be 10–11 m/s or better.

4. Advantages of Trisoplast®

According to a new statement from Finnish Technical Research Centre, Trisoplast® fullfills the EU Directive requirements (and also Finnish regulations VNp 1049/99) for landfill, if the mineral sealing is built in two layers: lower layer with 410 mm and 90 mm Trisoplast® on top of it (picture 1.) In addition, statement notifies that Trisoplast® does not cause any such harm to environment that thickness could not be reduced. The Directive specifies only the permeability and thickness, with a combined effect, of the mineral sealing layer.

Common fact is that dump site forms a risk to the environment if leachate waters gets through the barrier structure. In Trisoplast® solution, this risk is many times smaller than in the standard solution.

As a barrier layer, Trisoplast® saves precious natural materials. Into the lower layer can be put, for example industrial by-products if proven harmless. Trisoplast® is an inexpensive solution and with it can be achieved a far more better protection level than required in the directive.

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Published by

VTT
Vuorimiehentie 5, P.O.Box 2000, FIN-02044 VTT, Finland
Phone internat. +358 9 4561
Fax +358 9 456 4374

Series title and number

VTT Symposium 204

Author(s)

Tammirinne, Markku (ed.)

Title

International Conference on Practical Applications in Environmental Geotechnology. ECOGEO 2000

Abstract

The publication contains the papers of the International Conference on Practical Applications in Environmental Geotechnology, ECOGEO 2000, held on 4–6 September 2000 in Helsinki, Finland. ECOGEO 2000 provided a forum for transferring knowledge on practical applications concerning the technical and environmental aspects of industrial by-product utilisation, remediation of contaminated soils, and barrier structures for groundwater protection. Environmental risks connected to the use of industrial by-products were dealt with very thoroughly. Remediation of contaminated soils was presented in lectures, as well as excursion sites. Results of the Ecogeotechnology R&D-programme, funded by Tekes, the National Technology Agency of Finland, were presented.

Keywords

environment, environmental protection, geotechnology, water pollution, air pollution, soil pollution, decision making, landfills, refuce disposal, remediation, groundwater

Activity unit

VTT Communities and Infrastructure, Infrastructure and Environment,
Lämpömiehenkuja 2, P.O.Box 19031, FIN–02044 VTT, Finland

ISBN	Project number
951–38–5701–8 (soft back ed.) 951–38–5702–6 (URL: http://www.inf.vtt.fi/pdf/)	

Date	Language	Pages	Price
August 2000	English	477 p. + app. 2 p.	J

Name of project	Commissioned by
ECOGEO 2000	The National Technology Agency (Tekes), private Finnish enterprises and R&D organisations

Series title and ISSN	Sold by
VTT Symposium 0357–9387 (soft back ed.) 1455–0873 (URL: http://www.inf.vtt.fi/pdf/)	VTT Information Service P.O.Box 2000, FIN-02044 VTT, Finland Phone internat. +358 9 456 4404 Fax +358 9 456 4374