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Environmental adaption of concrete
Environmental impact of concrete and asphalt pavements

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ABSTRACT

The object of the study has been to assess the environmental impact of concrete and asphalt road pavements. The assessment is based on the estimation of service life of road pavements and the environmental burdens caused by their production, use and disposal. Also taken into account is the influence of the pavement on fuel consumption by traffic, noise, lighting requirements and dust formation. The functional unit studied is 1 km of pavement of the Tampere motor way assuming passage of 20 000 vehicles per day. The time scale is 50 years.

On the basis of the results the environmental burdens of concrete pavements significantly depend on the cement content of concrete. Consequently, the environmental profile of concrete pavement also significantly depends on the depth of the concrete layer. The environmental burdens from paving and maintenance are rather low compared with those caused by production processes of high-strength concrete. On the contrary, the significance of lighting during 50 years is high. The dust emissions of the concrete pavement studied are mainly induced by abrasion and salting of the pavement.

The significance of pavement materials, paving, maintenance and lighting is low compared with the environmental burdens caused by traffic during 50 years. With respect to the effect of material properties of pavement on fuel consumption, it was assumed that the influence on fuel consumption related to the surface texture is the same for both pavements, the difference in E-modulus does not influence the fuel consumption for the heavy vehicles and that the measured differences in rolling resistance have no influence on fuel consumption. However, any difference in fuel consumption of traffic due to pavement materials would significantly affect the result. For example, a roughly 0.1 - 0.5% decrease in fuel consumption of traffic due properties of concrete pavement would bring "savings" in emissions of the same order of magnitude than those from all the other parts of the life cycle of concrete roads.

On the basis of the results the environmental burdens of asphalt significantly depend on the bitumen content of asphalt. In addition, the manufacture of asphalt including

drying of aggregate materials significantly accounts for the environmental burdens of asphalt pavement. The result also significantly depends on the maintenance operations presumed.

The result was assessed using different valuation methods. The differences between asphalt and concrete scenarios are rather low according to the Swiss, Dutch and Norwegian ecoscarcity methods. According to the Swedish ecoscarcity method the scenario based on concrete is environmentally more negative than scenarios based on asphalt. In contrast, according to the eco-category methods and EPS system, the scenarios based on asphalt are more disadvantageous than those based on concrete. The determining environmental burdens of asphalt pavement are carbon dioxide, sulphur dioxide and nitrogen oxide emissions, dust and energy consumption. The same is true with respect to concrete pavement. The negative impact for concrete is partly due to the high valuation factors for mercury and cadmium according to the Swedish political targets.

CONTENTS

FOREWORD

Nordic Project on Environmental Adaption of Concrete

The Nordic project on sustainable concrete technology has been initiated by the Nordic cement industry represented by Finncement AB (Finland), Cementa AB (Sweden) and Norcem A/B (Norway). The project is financed by Nordisk Industrifond, TEKES and the participating companies.

The main purposes of the project are:

- To increase our knowledge of the product systems of cement and concrete
- To compare the environmental and health effects of concrete products with different competing product systems
- To generate options for product system improvement within a life cycle context.

The project is divided into three main parts:

1. Case studies of the cement production plants in Finland, Sweden and Norway. This part of the project included the development of software for the analysis and presentation of LCA data of cement.

2a. Comparison of concrete and asphalt roads from a life cycle perspective.

2b. Comparison of concrete and steel building frames from a life cycle perspective.

3. Evaluation of potential improvments to the product systems of cement and concrete with respect to environmental aspects.

This report describes the results from the second (2a) part of the project.

The project is organised by a steering committee:
Kurt Lundström, Finncement AB, Project co-ordinator
Bo-Erik Eriksson, Finncement AB, Leader of the steering committee
Christer Ljungkrantz, Cementa AB
Erik Stotenberg-Hansson, Norcem AS.

Part 2a of the project was carried out at the Technical Research Centre of Finland (VTT) by:

Tarja Häkkinen	project manager
Kari Mäkelä	project co-worker.

The report was written by Tarja Häkkinen (VTT Building Technology). The indirect environmental burdens of pavements were assessed by VTT Communities and Infrastructure. The subreport was written by Kari Mäkelä (Appendix 3).

A support group for part 2a was formed of representatives from the national road administrations and the cement, concrete and bitumen and asphalt industries from all participating countries:

Kurt Lundström	Finncement, Finland
Timo Blomberg	Neste, Finland
Kauko Linna	Lohja Rudus, Finland
Pauli Velhonoja	Finnish National Road Administration, Finland
Seppo Lundgren	Asphalt Association, Finland

Ronny Andersson	Cementa, Sweden
Svante Johansson	Swedish National Road Administration, Sweden
Åke Knutz	Swedish National Road Administration, Sweden
Erik Stoltenberg-Hansson	Norcem, Norway
Halvard Mageröy	Mur- og betongsentret, Norway
Åsmund Knutson	Public Roads Administration, Norway
Hans Peter Lorenzen	Asphalt Entr. Association, Norway.

The linguistic revision of the text was done by Adeleide Lönnberg, B.Sc.

NOTATION

ABK	Asphalt concrete
As	Arsenic
Cd	Cadmium
CH_4	Methane
CML	Centre of environmental science in Leiden
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
Cr	Chromium
ELU	Environmental loading unit
EPS	Environmental priority strategies in product design
HC	Hydro carbons
Hg	Mercury
HHV	Higher heating value
HTP	Concentration that has been observed to be harmful
IFO	Industrial fuel oil
LCA	Life cycle assessment
LHO	Light heating oil
Ni	Nickel
NMVOC	Non-methan volatile organic compounds
NO_x	Nitrous gases
PAH	Polycyclic aromatic hydrocarbons
Pb	Lead
SMA	Split mastic asphalt
SO_2	Sulphur dioxide
Tl	Thallium
TRP	Transportation
SETAC	Society of environmental toxicology and chemistry
Zn	Zinc
VOC	Volatile organic compounds
VTT	Technical Research Centre of Finland

1 INTRODUCTION

Construction affects the environment to such an extent that determining its overall impacts requires dividing them into sub-categories for closer scrutiny. These include the impact of urban planning and zoning as well as of buildings and other constructions and associated products and systems. The potential environmental effects of buildings and other constructions include the impact caused by their use, for example, with respect to buildings particularly heating, water supply and waste management. The environmental impact of a product is often expressed in terms of an environmental index or "profile" indicating how the product potentially contributes to changes in the environment, such as global warming or acidification.

Methods used for assessing the environmental impact of products consist of "life-cycle assessments" (LCAs) designed to provide information on all the significant environmental effects of products from raw-material extraction and manufacture to end-use and final disposal. A procedure for assessing the environmental impact of products (Anon. 1993a) suggested by SETAC has won international acceptance. The Nordic Council of Ministers has supported the development of Nordic guidelines on LCA (Anon. 1995a,b,c).

Research into the environmental impact of building materials and methods for its evaluation has been carried out by VTT's Building Technology Institute with the support of the Finnish Ministry of the Environment (Häkkinen and Ruohomäki 1992, Häkkinen and Kronlöf 1994, Häkkinen 1994a,b). The work has been continued in the framework of Nordic (Anon. 1995d) and European (Brite-EuRam 1994) cooperation.

This report discusses the environmental impact of road pavements. Environmental burdens of concrete and asphalt pavements were assessed and compared. In addition, the environmental burdens from production processes of pavement materials were compared with those induced by the use of roads.

2 THE BASIS OF LCA

According to the Nordic guidelines, and based on the definition given by Consoli et al. (Anon. 1995a), the LCA process is understood as a process of evaluating the environmental burdens associated with a product system, or activity by identifying and quantitatively or qualitatively describing the energy and materials used, and wastes released into the environment, and of assessing the impacts of these energy and material uses and releases into the environment. The assessment includes the entire life cycle of the product or activity, encompassing extracting and processing raw materials; manufacturing; distribution; use; re-use; maintenance; recycling and final disposal; and all transportation involved. LCA addresses environmental impacts of the system under study in the areas of ecological systems, human health and resource depletion. It does not address economical or social effects.

General application areas in the private sector (manufacturers) includes (Anon. 1995a):

- Identifying processes, ingredients, and systems that are major contributors to environmental impacts,
- comparing different options within a particular process with the objective of minimising environmental impacts,
- providing guidance in long-term strategic planning concerning trends in product design and materials,
- evaluating resource effects associated with particular products, including new products,
- helping to train product designers in the use of environmentally sound product materials or
- comparing functionally equivalent product.

The methodological framework recommended by the Nordic guidelines (Anon. 1995a) divides the LCA of products into the following steps:

- Goal and scope definition,
  where the goal and scope of the study are defined,
- Inventory analysis,
  which comprises the materials and energy flow analysis of the studied system within defined system boundaries, resulting in an inventory and
- Impact assessment,
  (classification, characterisation and valuation).

In classification, materials and energy inputs and outputs are classified into impact categories. Characterisation is a stage where the contributions to each impact category are assessed by quantitative or qualitative methods. In valuation, the impact of each impact category is addressed and related to the others, and the total impact is assessed. The goal for all the valuation models is to set a one-dimensional value on resource use and emissions in order to calculate the total environmental impact of a product or system. Life-cycle studies do not always use impact assessment, but in many cases inventory data alone are sufficient for evaluation. In this report (section 8) the results of inventory assessment are valuated according to different valuation models.

In this report the results were evaluated based on the following models:
- Ecoscarcity method in Swizerland (Reference Ahbe et la. 1990 in Anon. 1995a)
- Ecoscarcity method in the Netherlands (Reference SIMA-PRO, 1993 in Anon. 1995a)
- Ecoscarcity method in Norway (Reference Baumann, 1992 in Anon. 1995a)
- Ecoscarcity method in Sweden (Reference Baumann et al., 1993 in Anon. 1995a)
- Effect-category method (CML Sweden)
  (Reference Baumann et al., 1993 in Anon. 1995a)
  According to the short term goals and long term goals
- EPS-system, version 2.0 (References Steen and Ryding, 1992 and Boström and Steen, 1994, in Anon. 1995a).

The weighting factors of the Norwegian and Swedish ecoscarcity methods and those of the effect-catregory method (short term goals) and EPS-system are the same as those used to cements (Vold and Rønning 1995). These methods are described in Appendix 1 (Vold and Rønning 1995). The weighting factors are listed in Appendix 2.

3 GOAL AND SCOPE OF THE STUDY

The environmental impact caused by roads falls into the following categories:

- Environmental impact due to materials in the course of the whole life cycle (raw material extraction, production, transportation, use, deposition, final disposal or reuse). These potential effects are induced by use of energy and material resources and by emissions from combustion and procurement of energy and other process emissions.

- Environmental impact induced by land use of road constructions.

- Environmental impact caused by traffic.

The object of the study is to assess the environmental impact of road pavements. The aim is to assess the environmental impact of concrete roads and to compare this with the environmental impact of asphalt roads.

The project also aims at creating information from the environmental point of view regarding the significance of various factors connected with road construction and use of roads.

The assessment of the environmental impact of road pavements is based on the estimation of service life of road pavements and environmental burdens caused by production, use and disposal of road pavements. Also taken into account is the influence of the pavement on

- fuel consumption by traffic

- noise

- lighting requirements and

- dust formation.

Of importance may also be but not observed in this study

- traffic safety and health impacts,
- solubility of pavement materials during use and final disposal and
- demolition and final disposal of pavement materials.

4 FUNCTIONAL UNIT

The environmental impact of road pavements is examined in a case study.

The functional unit studied is

- **1 km of pavement in Tampere motor way**
- **time scale 50 years**
- **20 000 vehicles/day.**

In order to achieve the object of the study, the following factors are investigated or estimated:

- Emissions and consumption of recourses due to raw materials extraction, manufacturing processes and transportation of materials during production processes of bitumen.

- Emissions and consumption of recourses due to raw materials extraction, manufacturing processes and transportation of materials during production processes of cement.

- Emissions and consumption of recourses due to raw materials extraction, manufacturing processes and transportation of materials during production of aggregate materials and other ingredient materials.

- Emissions and consumption of recourses due to raw materials extraction, manufacturing processes and transportation of materials due to paving and maintenance of road pavements over 50 years.

- Dust emissions due to use of roads during 50 years.

- The influence of pavement material on lighting, noise, fuel consumption of traffic and traffic disturbance.

The road construction and the maintenance strategies of the roads are presented in the following:

BASE CONSTRUCTION

- **Broken rock 1.9 - 2.5 m**
- **Gravel bound with bitumen (120 mm)**

CONCRETE PAVEMENT

Concrete 220 mm

ABK 120 mm

Rock 1.9 - 2.5 m

- **220 mm concrete cover (Design depth 180 mm)**
  The breadth of the road 8.5 m (traffic lanes 2 x 3.75 m + inner shoulder 1m)
- **Maximum grain size 20 mm**
- **High-strength concrete**
  Design strength 80 MPa for compression and 7.5 MPa for flexure
  Measured compressive strength 93 MPa and flexural strength K9.3 MPa.
- **Slip forming operation casting**
- **Exposed-aggregate concrete (mortar 2 - 3 mm)**
  (to decrease initial abrasion and improve initial friction)
- **Sawing into 25 m^2 squares (to avoid drying shrinkage)**

ASPHALT PAVEMENT

SMA 50 mm

ABK 70 mm

ABK 120 mm

Rock 1.9 - 2.5 m

- **ABK 170 kg/m^2 and SMA 120 kg/m^2**
- **Maximum grain size of asphalt 20 mm**
- **The breadth of the road 8.5 m (traffic lanes 2 x 3.75 m + inner shoulder 1m)**

MAINTENANCE STRATEGIES

- **Concrete pavement: 2 or 3 grindings during 50 years.**
- **Asphalt pavement:**
  Finnish or Swedish practice (Appendices 4 and 5).

5 INVENTORY BACKGROUND AND DATA QUALITY

The basic data of material and energy flows of the systems studied were collected from the companies involved. The data quality is described in connection of the flow charts. Principally the basic input and output values are annual average values of the studied systems in the Finnish companies involved. The basic data for bitumen is from year 1992. For the cement data from year 1995 was available.

Fuel flows reported by Finncement, Lohja Rudus, Neste, Lemminkäinen, Asfalttiliitto (Finnish Asphalt Association) etc. were converted into emissions and consumption of energy. The emissions from consumption of energy are of two kinds: those generated in the procurement of energy raw materials and those formed during combustion of the raw materials. Procurement of energy raw materials was considered in addition to combustion.

The pre combustion values were national averages. With exception to cement and bitumen also emissions into air from combustion of energy raw materials were national averages (Kronlöf 1994). The emissions due to production process of cement were received from Finncement. The data included information of the corresponding measurement, calculation or assessment methods. The emission values from production processes of bitumen were received from Neste. The fuel flows concerning production of aggregate materials were received from Lemminkäinen and Lohja Rudus. Estimations of the variations of the average values received were included.

Emissions into air from energy raw materials include CO_2, CO, NO_x, SO_2, dust, heavy metals and VOCs. VOCs were divided into four groups: CH_4, PAH, benzene and others.

The total use of energy comprises the HHV (High Heating Value) of the energy raw material and the energy consumed during procurement. The HHV expresses the energy generated when a dry sample burns. It includes the energy of evaporation of the water generated in the burning of the sample's hydrogen.

The inherent energy of organic materials that can be used as fuels are included in the calculations.

In Finland the efficiency of electricity derived from energy raw material to electricity produced is 0.48. This means that 2.08 MJ of energy raw material is needed (calculated according to the higher heating value, HHV) to produce one MJ of electricity. Adding the transportation of raw materials brings the total to 2.16 MJ. Part of the energy consumption and emissions from electricity production has been allocated to the utilised heating energy formed during the production of electricity. The allocation is based on energy contents of electricity and utilised heating energy.

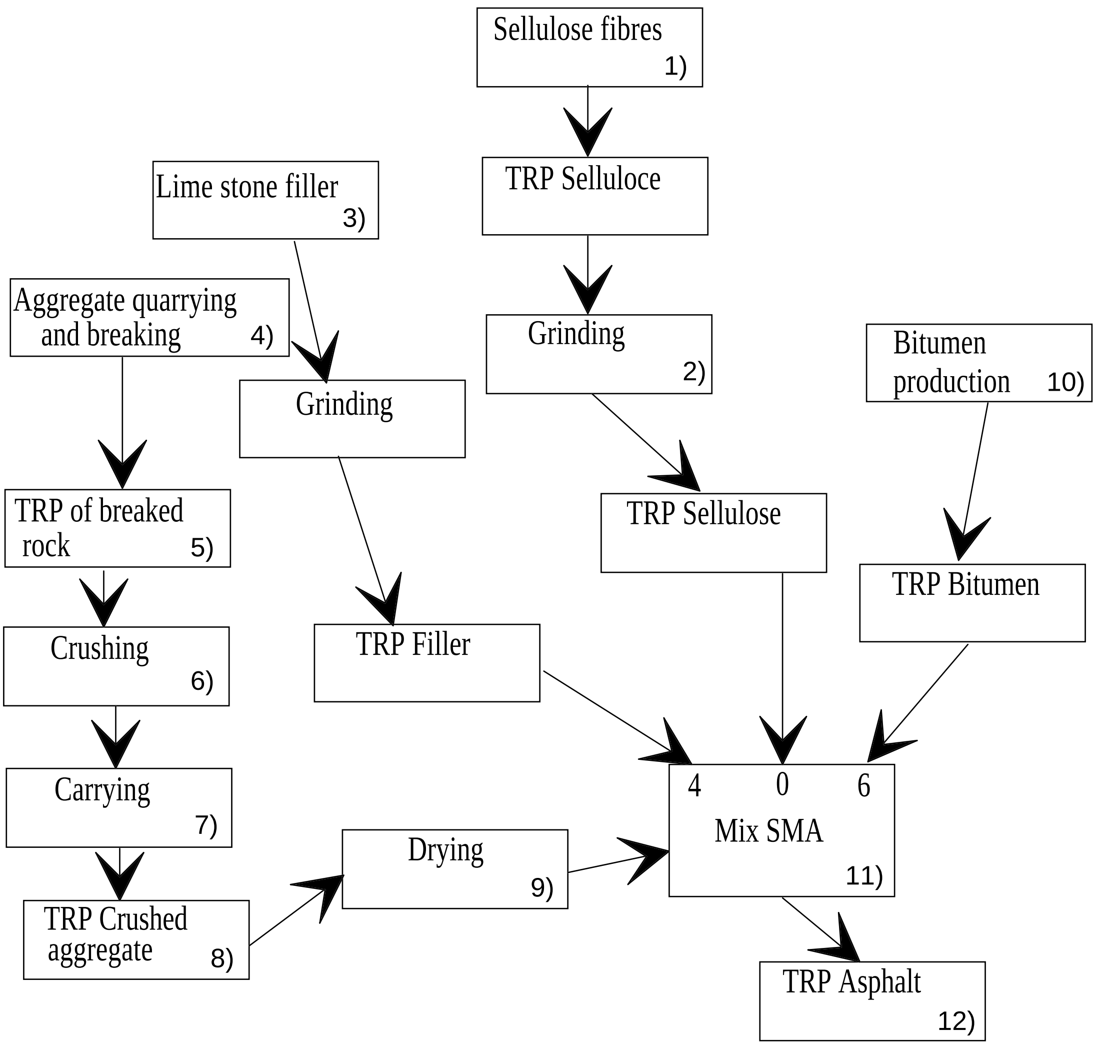
The applied vehicular emissions and emissions generated by the fuel procurement are national averages.

The indirect environmental burdens of pavements were assessed by VTT Communities and Infrastructure. The sub-report is presented in Appendix 3.

The consumption of concrete and asphalt in manufacturing of the pavements is calculated based on the road dimensions.

6 FLOWCHARTS OF THE SYSTEMS STUDIED

The flow charts of the systems studied are presented in Figures 1 - 5.



1) Waste paper is dealt with as waste. No emissions or energy consumption is allocated on waste paper. Energy consumption due to grinding is included (Ylisvilla). It is assumed that waste paper collected and processed in Finland is used. Inherent energy is included (VTT).

.

2) Emissions and energy consumption is assessed based on those caused by production of raw meal (Finncement).

3) Quarrying of limestone in Lappeenranta. Amount of dust is assessed. It is assumed that NO_x emissions are twice as high as those from corresponding amount (4 MJ) of IFO.

4) Fuel consumption due to quarrying and fuel consumption due to preliminary breaking are included. Energy content of explosive materials are assumed as 4 MJ/kg. It is assumed that NO_x emissions are twice as high as those from corresponding amount (4 MJ) of IFO. The fuel consumption data are from Lemminkäinen.

5) Fuel consumption data from Lemminkäinen.

6) Fuel consumption depends on the grain size distribution. Data from Lemminkäinen.

7) Carrying to the side of crushing station. Fuel consumption data from Lemminkäinen.

8) Data of fuel consumption in transportation from Lohja Rudus.

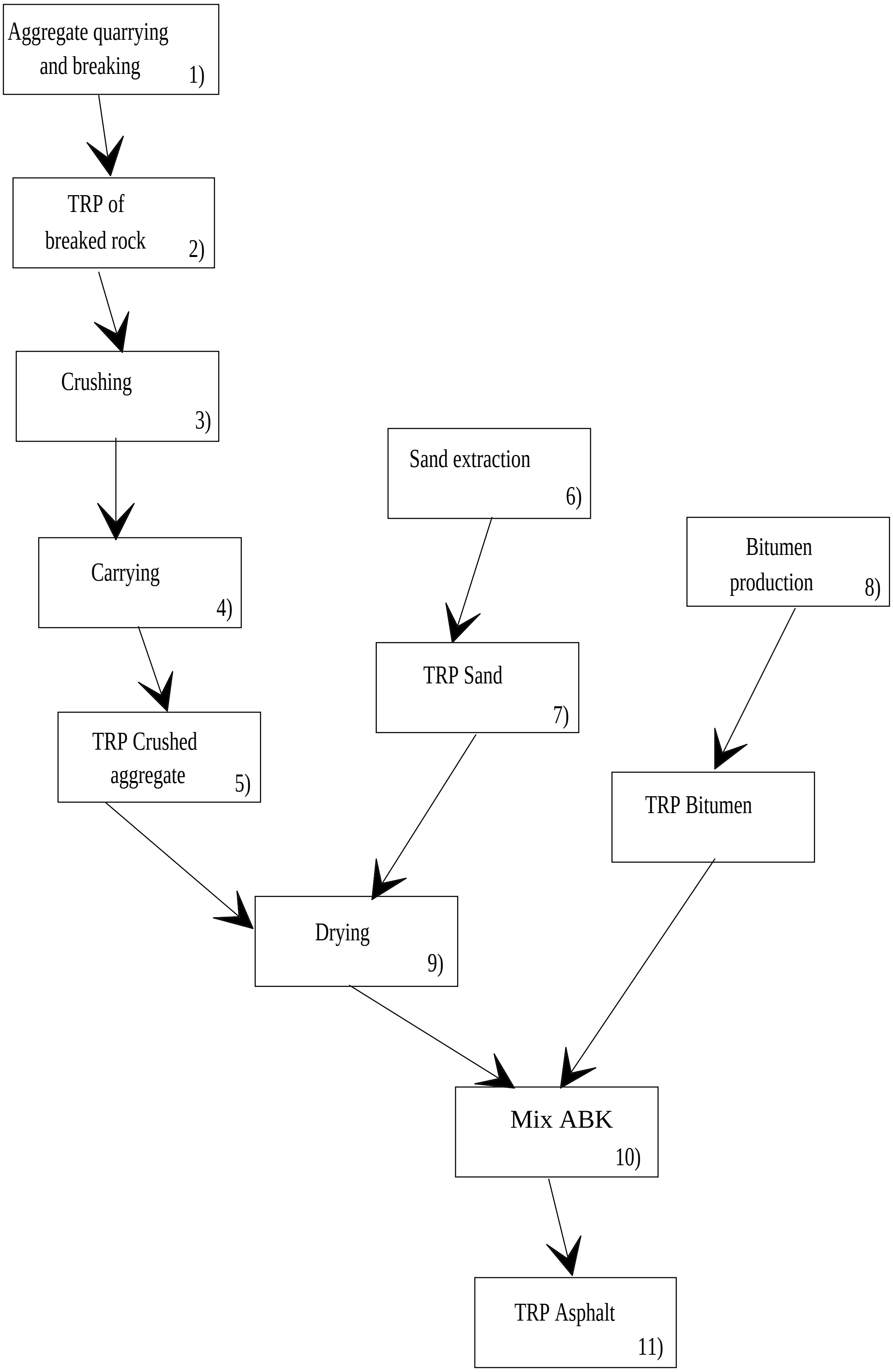
9) Fuel consumption data from the Finnish Asphalt Association.

10) Presumed that inherent energy of bitumen is 42 MJ/kg (HHV) (VTT). Other input and output values from Neste. The production process of bitumen includes the following steps:
- raw oil recovery,
- sea transportation and
- refining.

11) Fuel consumption and electricity data from the Finnish Asphalt Association. Composition is presented in Appendix 4.

12) Transportation data from the Finnish Asphalt Association.

Figure 1. Flowchart of asphalt production (SMA).


Aggregate quarrying and breaking 1)
TRP of breaked rock 2)
Crushing 3)
Carrying 4)
TRP Crushed aggregate 5)
Sand extraction 6)
TRP Sand 7)
Bitumen production 8)
TRP Bitumen
Drying 9)
Mix ABK 10)
TRP Asphalt 11)

1) Fuel consumption due to quarrying and fuel consumption due to preliminary breaking are included. Energy content of explosive materials assumed as 4 MJ/kg. It is assumed that NO_x emissions are twice as high as those corresponding amount (4 MJ) of IFO. Fuel consumption data from Lemminkäinen.

2) Fuel consumption data from Lemminkäinen.

3) Fuel consumption depends on grain size. Data from Lemminkäinen.

4) Carrying to the side of crushing station. Fuel consumption data from Lemminkäinen.

5) Fuel consumption in transportation from Lohja Rudus.

6) Fuel consumption data from Lohja Rudus.

7) Transportation data from Lohja Rudus.

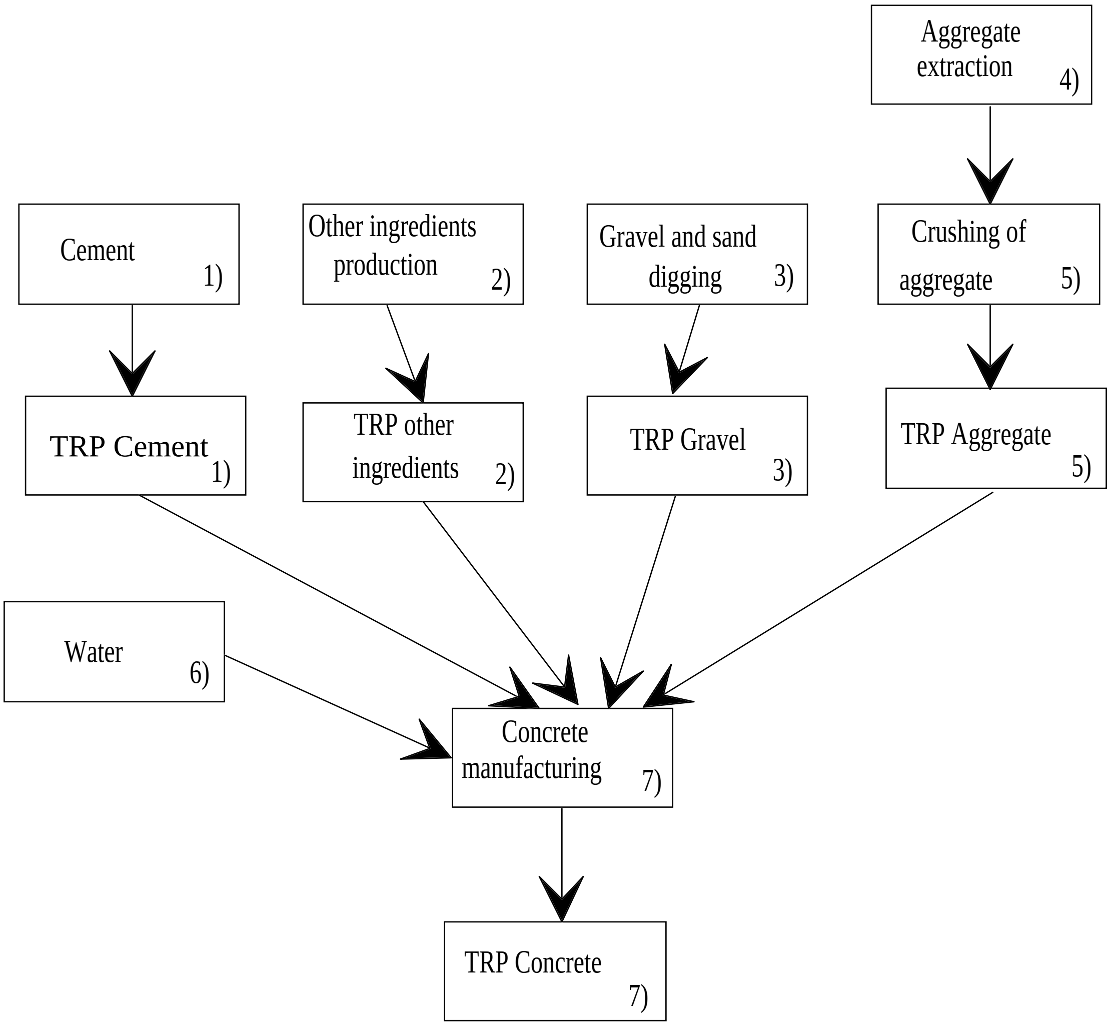
8) Presumed that inherent energy of bitumen is 42 MJ/kg (VTT). Other input and output values from Neste. The production process of bitumen includes the following steps:
   - raw oil recovery,
   - sea transportation and
   - refining.

9) Fuel consumption data from the Asphalt Association.

10) Fuel consumption and electricity data from the Asphalt Association. Composition is presented in appendix 4.

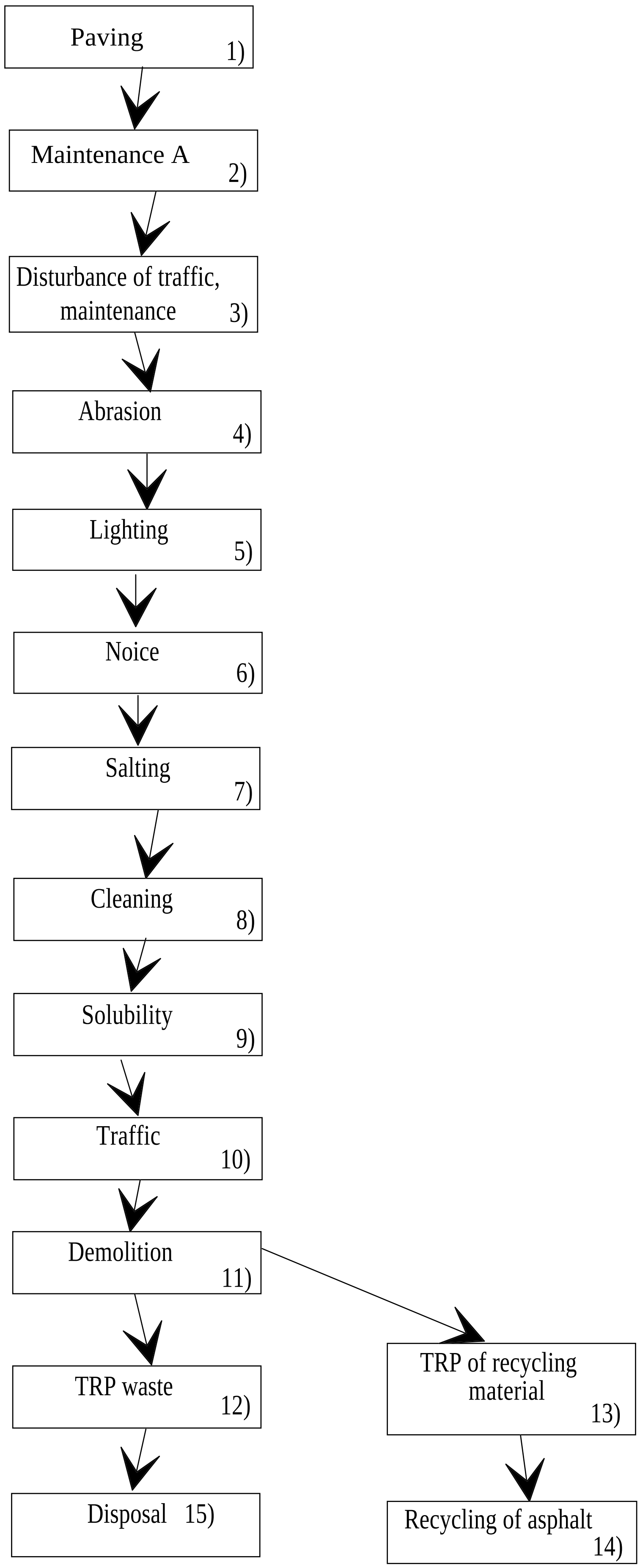
11) Transportation data from the Asphalt Association.

Figure 2. Flowchart of asphalt production (ABK).



1) Environmental burdens from production and transportation of cement (Lappeenranta). Data of energy and material flows are from Finncement.
2) Silica fume is dealt with as by-product. No environmental burdens except those from transportation to the concrete manufacturing place are allocated on it. Concrete additives (total weight < 1% by weight of concrete) are excluded because lack of data.
3) Fuel consumption data from extraction and transportation of gravel and sand from Lohja Rudus.
4) Fuel consumption data from quarrying of crushed aggregate from Lemminkäinen.
5) Fuel consumption data from crushing and transportation of aggregate materials from Lohja Rudus.
6) No environmental burdens are allocated on water.
7) Energy and material flows in concrete manufacturing and transportation from Lohja Rudus.

Figure 3. Flowchart of concrete production.


Paving 1)
Maintenance A 2)
Disturbance of traffic, maintenance 3)
Abrasion 4)
Lighting 5)
Noice 6)
Salting 7)
Cleaning 8)
Solubility 9)
Traffic 10)
Demolition 11)
TRP waste 12)
TRP of recycling material 13)
Recycling of asphalt 14)
Disposal 15)

1) Process emissions from other than use of energy are excluded.

2) Fuel consumption (MJ/km) due to saving of asphalt pavement (0 - 50 years). Milling crush is reused in asphalt stations. No burdens, except those from transportation of milling crash, are allocated on recycling. Data of materials and energy flows are from Lemminkäinen, Asphalt Association, Road Administration and Valtatie. Also an other maintenance strategy was dealt with (Maintenance B). Maintenance strategies are presented in Appendices 4 and 5.

3) Disturbance of traffic due to maintenance is dealt with as increased fuel consumption due to changes of speed (VTT, Appendix 3).

4) Dust formed during 50 years, 20 000 vehicles/day (VTT, Appendix 3).

5) Energy consumption of lighting during 50 years (MJ/km) (VTT, Appendix 3).

6) Noise is dealt with as land use due to noise effect (> 55 dB) (m^2/km). 20 000 vehicles/day. 100 km/h (VTT, Appendix 3).

7) Salting during 50 years (VTT, Appendix 3).

8) Energy consumption due to cleaning measures is excluded.

9) The emissions from pavement due to solubility during service life are excluded because lack of data.

10) Fuel consumption in 50 years, 20 000 v/d (VTT, Appendix 3).

11) Fuel consumption and corresponding emissions due to demolition. Excluded because lack of data.

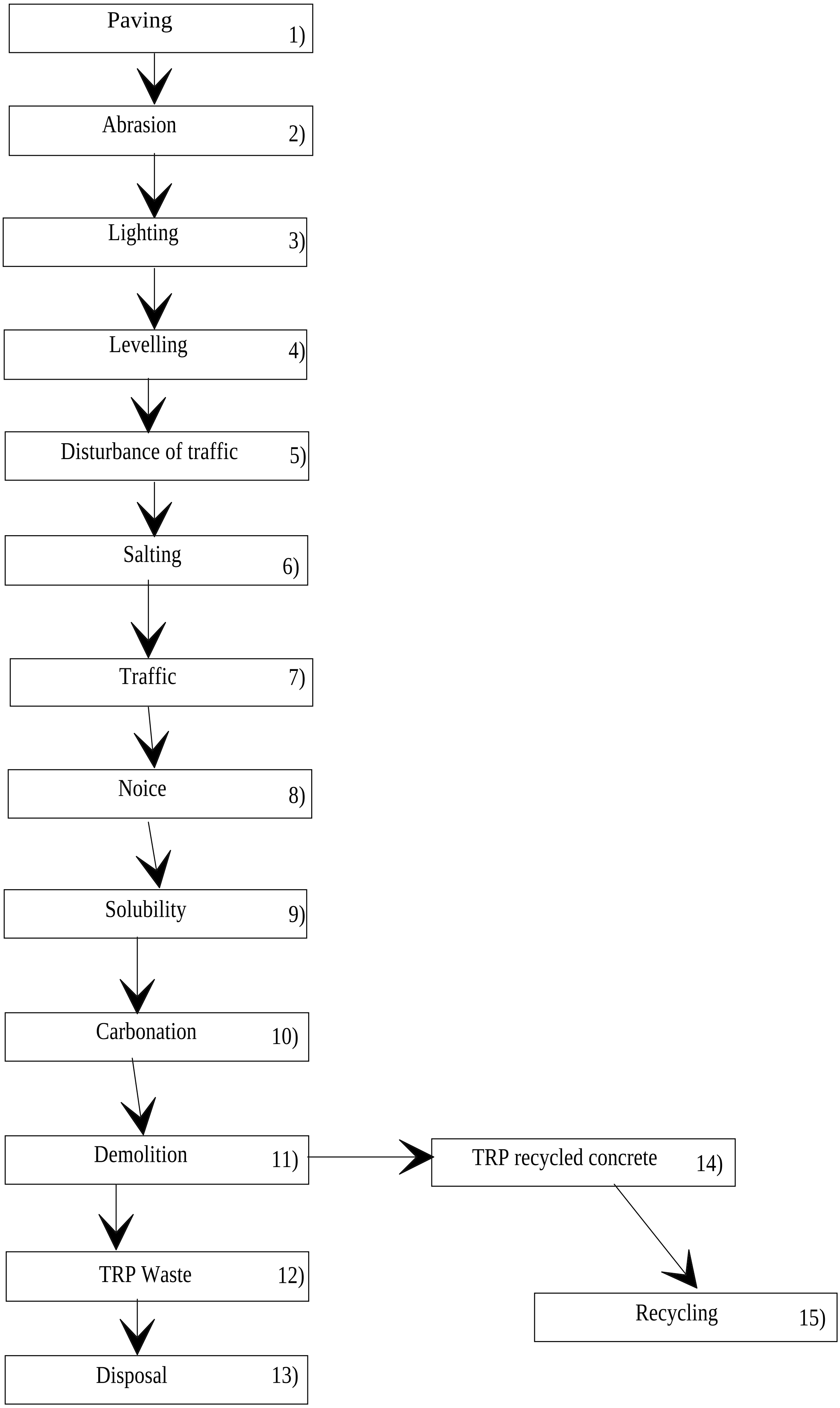
12) Transportation of disposed material after service life. Assumed that all waste can be reused (environmental burdens due to transportation allocated to the recycling system.).

13) Burdens due to transportation of asphalt waste are allocated to reuse of asphalt.

14) All other burdens from asphalt pavements except those from transportation of recycling waste are allocated to the system studied.

15) Excluded because of the assumption that all asphalt waste can be recycled.

Figure 4. Flowchart of use of asphalt pavement.


Paving 1)
Abrasion 2)
Lighting 3)
Levelling 4)
Disturbance of traffic 5)
Salting 6)
Traffic 7)
Noice 8)
Solubility 9)
Carbonation 10)
Demolition 11)
TRP Waste 12)
Disposal 13)
TRP recycled concrete 14)
Recycling 15)

1) Slip forming machine, digger, surface washing machine and tractor are used. Fuel consumption data from Lohja Rudus. Assembling of joint seals and steel bars.
2) Dust formed during 50 years, 20 000 vehicles/day (VTT, Appendix 3).
3) Dealt with as energy consumption of lighting during 50 years (VTT, Appendix 3).
4) Service life 50 years. Diamond dressing 2 x 15 mm = 30 mm (Maintenance A) or 3 x 15 mm (Maintenance B). Fuel consumption and corresponding emissions included. Diamond grinding 0.16 - 0.27 l diesel/m^2 (assessment given by Hallvard Magerøy, Mur- og betongsenteret, Norway).
5) Dealt with as increased fuel consumption due to disturbance of traffic because of maintenance measures (VTT, Appendix 3).
6) Salting during 50 years. Salt and dust emissions (VTT, Appendix 3).
7) Fuel consumption in 50 years with reference to 20 000 v/d (VTT, Appendix 3).
8) Dealt with as land use caused by noise (> 55 dB) (m^2/km). 20 000 vehicles/day. 100 km/h (VTT, Appendix 3).
9) Emissions from concrete pavement compared to natural gravel, excluded because lack of data.
10) Carbonation of concrete surface and dust from abrasion. Assumed that carbonation depth is 3 x 15 mm = 45 mm. Portland Cement content 425 kg/1 m^3 of concrete (2500 kg). Assumed that in carbonated concrete CO_2 bound/CaO = 0.8 (mole ratio) (VTT).
11) Fuel consumption and corresponding emissions due to demolition. Excluded because lack of data.
12) Transportation of concrete waste after service life excluded. All waste can be reused in road and geotechnical constructions. Environmental burdens from transportation allocated to the system using recycling material.
13) Assumed that all waste can be reused in road and geotechnical constructions.
14) Burdens initiated from transportation of concrete waste are allocated to reuse of concrete.
15) All other burdens from concrete pavements except those from transportation of recycling waste are allocated to the system studied.

Figure 5. Flow chart of use of concrete pavement.

7 RESULTS

Environmental burdens induced from the production processes of
- cement (Appendix 6)
- bitumen (Appendix 7)
- synthetic gum used for joint seals (Appendix 8)
- reinforcing steel (Appendix 9)
- gravel (Appendix 10)
- lime stone filler (Appendix 11)
- crushed aggregates (Appendix 12) and

are listed in Appendices. The results of the environmental burdens of the above mentioned systems are assessed "from gravel to gate" (transportation of product is excluded).

The results of calculations are presented in Tables 1 - 19.

Table 1. Environmental burdens of
- the production of SMA-asphalt (per kg) and
- the road pavement (per km) including the original and maintenance SMA-asphalt materials required for the pavement during 50 years.
Maintenance strategy A (Finnish reference) (Appendix 5).

	g/kg or MJ/kg	**kg/km or GJ/km**
Emissions		
CO_2	51	96 000
SO_2	0.19	370
NO_x	0.41	780
CO	0.043	81
HC+VOC	0.17	320
CH_4 *	0.044	83
PAH		
Benzene		
Heavy metals **		
As	$0.79x10^{-6}$	0.0015
Hg	$0.012x10^{-6}$	$23x10^{-6}$
Cd	$0.12x10^{-6}$	0.00022
Cr	$0.35x10^{-6}$	0.00065
Pb	$7.9x10^{-6}$	0.015
Particulates	0.052	98
Problem wastes	0.011	20
N into water	0.00031	0.59
COD	0.0062	12
Energy		
Fossil fuel	0.78	1 500
Electricity	0.061	110
Inherent energy	2.7	5 100

* Assumed that CH_4 content of total VOCs from production of bitumen is 10%. VOCs from production of bitumen are not divided into CH_4, benzene and others because lack of data.

** Assumed that heavy metals from production of bitumen are the same as those from combustion of corresponding amount of natural gas (70%) + LHO (30%) by energy content.

Table 2. Environmental burdens of
- the production of SMA-asphalt (per kg) and
- the road pavement (per km) including the original and maintenance SMA-asphalt materials required for the pavement during 50 years.
Maintenance strategy B (Swedish reference) (Appendix 6).

	g/kg or MJ/kg	**kg/km or GJ/km**
Emissions		
CO_2	51	130 000
SO_2	0.19	500
NO_x	0.41	1 100
CO	0.043	110
HC+VOC	0.17	430
CH_4 *	0.044	110
PAH		
Benzene		
Heavy metals **		
As	0.79×10^{-6}	0.0021
Hg	0.012×10^{-6}	31×10^{-6}
Cd	0.12×10^{-6}	0.00031
Cr	0.35×10^{-6}	0.00090
Pb	7.9×10^{-6}	0.021
Particulates	0.052	140
Problem wastes	0.011	28
N into water	0.00031	0.81
COD	0.0062	16
Energy		
Fossil fuel	0.78	2 000
Electricity	0.061	160
Inherent energy	2.7	6 900

* Assumed that CH_4 content of total HC+VOC from production of bitumen is 10%. VOCs from production of bitumen are not divided into CH_4, benzene and others because lack of data.

** Assumed that heavy metals from production of bitumen are the same as those from combustion of corresponding amount of natural gas (70%) + LHO (30%) by energy content.

Table 3. Environmental burdens of
- the production of ABK-asphalt (per kg) and
- the road pavement (per km) including the original and maintenance ABK-asphalt materials required for the pavement during 50 years.
Maintenance strategy A (Finnish reference) (Appendix 5).

	g/kg or MJ/kg	**kg/km or GJ/km**
Emissions		
CO_2	43	62 000
SO_2	0.18	260
NO_x	0.34	490
CO	0.036	52
VOC	0.13	180
CH_4 *	0.035	51
PAH		
Benzene		
Heavy metals **		
As	0.74×10^{-6}	0.0011
Hg	0.011×10^{-6}	16×10^{-6}
Cd	0.11×10^{-6}	0.00016
Cr	0.32×10^{-6}	0.00046
Pb	7.4×10^{-6}	0.011
Particles	0.044	64
Problem wastes	0.010	15
N into water	0.00022	0.32
COD	0.0044	6.4
Energy		
Fossil fuel	0.68	980
Electricity	0.039	57
Inherent energy	1.9	2 700

* Assumed that CH_4 content of total VOCs from production of bitumen is 10%. VOCs from production of bitumen are not divided into CH_4, benzene and others because lack of data.

** Assumed that heavy metals from production of bitumen are the same as those from combustion of corresponding amount of natural gas (70%) + LHO (30%) by energy content.

Table 4. Environmental burdens of
- the production of ABK-asphalt (per kg) and
- the road pavement (per km) including the original and maintenance ABK-asphalt materials required for the pavement during 50 years.
Maintenance strategy B (Swedish reference) (Appendix 6).

	g/kg or MJ/kg	**kg/km or GJ/km**
Emissions		
CO_2	43	96 000
SO_2	0.18	400
NO_x	0.34	760
CO	0.036	80
HC + VOC	0.13	280
CH_4 *	0.035	79
PAH		
Benzene		
Heavy metals **		
As	$0.74x10^{-6}$	0.017
Hg	$0.011x10^{-6}$	$29x10^{-6}$
Cd	$0.11x10^{-6}$	0.00025
Cr	$0.32x10^{-6}$	0.00071
Pb	$7.4x10^{-6}$	0.017
Particles	0.044	99
Problem wastes	0.010	23
N into water	0.00022	0.49
COD	0.0044	9.8
Energy		
Fossil fuel	0.68	1 500
Electricity	0.039	88
Inherent energy	1.9	4 100

* Assumed that CH_4 content of total VOCs from production of bitumen is 10%. VOCs from production of bitumen are not divided into CH_4, benzene and others because lack of data.

** Assumed that heavy metals from production of bitumen are the same as those from combustion of corresponding amount of natural gas (70%) + LHO (30%) by energy content.

Table 5. Environmental burdens of the production of high-strength concrete. The result is presented both per kg of concrete and per km of pavement including all the concrete materials required per 1 km of pavement.

	g/kg or MJ/kg	**kg/km or GJ/km**
Emissions		
CO_2	160	680 000
SO_2	0.12	570
NO_x	0.78	3 700
CO	0.36	1 700
VOC total	0.044	210
CH_4	0.032	150
PAH	4.0×10^{-6}	0.019
Benzene	0.00035	1.6
As *	4.1×10^{-6}	0.0086
Hg	1.6×10^{-6}	0.0076
Cd *	0.35×10^{-6}	0.0016
Cr	1.4×10^{-6}	0.0066
Tl	4.4×10^{-6}	0.021
Pb	8.9×10^{-6}	0.042
Zn	3.3×10^{-6}	0.015
Particulates	0.077	360
Ashes	0.0078	36
Problem wastes	0.011	52
N total	12×10^{-6}	0.056
COD	75×10^{-6}	0.35
Energy		
Fossil fuel	0.96	4 500
Electricity	0.11	500

* Based on As and Cd measured in Parainen in 1993. As and Cd were not measured in Lappeenranta in 1995.

The concrete pavement under study is a non-reinforced concrete slab. The volume of joint steel bars is 12.7 tons/km. Thus the weight of steel is roughly 0.25% of the weight of concrete. Because of the low volume of steel, the environmental burdens caused by it is excluded. According to Fossdal (1995), the environmental burdens of reinforcement steel produced in Norway are 290 g CO_2, 1.0 g SO_2 and 1.6 g NO_x with respect to 1 kg of reinforcement steel (Appendix 10). That would cause additional emissions of 3700 kg of CO_2, 13 kg of SO_2 and 20 kg of NO_x with respect to 1 km of concrete pavement. The environmental burdens caused by synthetic gum used for joint seals (Appendix 9) are taken into account. According to the maintenance strategy A of concrete pavement it is assumed that the joint seals are renewed once in 50 years. The inherent energy of joint seal material is excluded due to lack of data but its order of magnitude would only be a few percent compared with the fossile fuel consumed in the production processes of concrete.

Table 6. Environmental burdens caused by traffic during 50 years. Assumed passage of 20 000 vehicles per day. All fuel consumed is assumed to be diesel. Assessment of fuel consumption is presented in Appendix 3.

	50 years
Emissions, kg/km	
CO_2	$100\ 000 \times 10^3$
SO_2	110×10^3
NO_x	$2\ 300 \times 10^3$
CO	390×10^3
VOC total	240×10^3
CH_4	94×10^3
PAH	15
Benzene	3.8×10^3
Heavy metals total	1.3
As	0.12
Hg	0.0043
Cd	0.014
Cr	0.0575
Pb	1.2
Particulates	130×10^3
Problem wastes	-
N into water	-
COD	-
Energy, GJ	-
Fossil fuel	1 500 000
Electricity	-
Inherent energy	-

Table 7. Environmental burdens caused by asphalt paving, maintenance and traffic disturbance due to maintenance of asphalt road over 50 years (the maintenance strategies are presented in Appendices.

	Paving *	**Maintenance Strategy A**	**Maintenance Strategy B**	**Traffic disturbance** **
Emissions kg/km				
CO_2	5 000	24 000	27 000	3 200
SO_2	5.2	2.9	5.8	3.4
NO_x	26	100	120	72
CO	6.8	14	18	13
VOC tot. ***	6.8	150	150	7.6
CH_4	5.1	150	150	3.0
PAH	0.0035	0.0042	0.0061	0.00047
Benzene	0.089	0.11	0.16	0.12
Heavy metals total	0.0015	0.00071	0.0015	$43x10^{-6}$
As	0.00013	$61x10^{-6}$	0.00013	$3.7x10^{-6}$
Hg	$1.9x10^{-6}$	$0.92x10^{-6}$	$1.9x10^{-6}$	$0.14x10^{-6}$
Cd	$19x10^{-6}$	$9.2x10^{-6}$	$19x10^{-6}$	$0.46x10^{-6}$
Cr	$63x10^{-6}$	$31x10^{-6}$	$64x10^{-6}$	$1.8x10^{-6}$
Pb	0.0013	0.00061	0.0013	$37x10^{-6}$
Dust	8.1	4.7	9.1	4.0
Energy GJ/km				
Fossil fuel	69	470	510	46
Electricity				

* Calculated from the fuel consumption during paving.

** Calculated from the estimated increase in fuel consumption of traffic because of maintenance operations (Appendix 3).

*** VOC emissions are assessed based on consumption of energy. VOCs from bitumen during asphalt paving are excluded because lack of data.

Table 8. Environmental burdens of the lighting of asphalt road over 50 years. The environmental burdens are assessed based on the estimated electricity consumption during 50 years (Appendix 3). The calculation principals concerning electricity are presented in section 5.

	Lighting
Emissions, kg/km	
CO_2	400 000
SO_2	1 900
NO_x	1 600
CO	450
VOC total *	1 200
CH_4	1 200
PAH	0.088
Benzene	2.2
Heavy metals total	
As	
Hg	
Cd	
Cr	
Pb	
Dust	220
Energy, GJ/km	
Fossil fuel	
Electricity	14 000

Table 9. Environmental burdens caused by paving and maintenance of concrete road. Maintenance A includes 1 grinding and maintenance B includes 2 grindings during 50 years.

	Paving *	**Maintenance A** **	**Maintenance B** **	**Traffic disturbance** ***
Emissions kg/km				
CO_2	2 500	3 500	5 200	1 200
CO_2 bound ****		-62 000	- 62 000	
SO_2	2.6	3.7	5.5	1.3
NO_x	13	78	120	27
CO	3.4	14	20	4.7
VOC total	3.4	8.2	12	2.9
CH_4	2.6	3.2	4.9	1.1
PAH	0.0018	0.00051	0.00076	0.00018
Benzene	0.0451	0.129	0.194	0.0451
Heavy metals total	0.00074	$46x10^{-6}$	$69x10^{-6}$	$16x10^{-6}$
As	$6.3x10^{-6}$	$4.0x10^{-6}$	$6.0x10^{-6}$	$1.4x10^{-6}$
Hg	$0.95x10^{-6}$	$0.15x10^{-6}$	$0.22x10^{-6}$	$0.052x10^{-6}$
Cd	$0.95x10^{-6}$	$0.50x10^{-6}$	$0.74x10^{-6}$	$0.17x10^{-6}$
Cr	$32x10^{-6}$	$2.0x10^{-6}$	$3.0x10^{-6}$	$0.69x10^{-6}$
Pb	0.00063	$40x10^{-6}$	$60x10^{-6}$	$14x10^{-6}$
Dust	4.1	4.4	6.5	1.5
Energy GJ/km				
Fossil fuel	35	50	75	17
Electricity				

* Calculated from the fuel consumption during paving.

** Calculated from the estimated fuel consumption caused by grinding (Figure 5).

** Calculated from the estimated increase in fuel consumption of traffic because of maintenance operations (Appendix 3).

*** Binding of carbon dioxide during carbonation of concrete surface. Assumed that 3x15 mm layers are carbonated.

Table 10. Environmental burdens of the lighting of concrete road over 50 years. The environmental burdens are assessed based on the estimated electricity consumption during 50 years (Appendix 3). The calculation principals concerning electricity are presented in section 5.

	Lighting
Emissions, kg/km	
CO_2	240 000
SO_2	1 200
NO_x	940
CO	270
VOC total	740
CH_4	710
PAH	0.053
Benzene	1.3
Heavy metals total	
As	
Hg	
Cd	
Cr	
Pb	
Dust	130
Energy, GJ/km	
Fossil fuel	
Electricity	8 400

Table 11. Noise effect caused by traffic on asphalt pavement. Noise expressed as use of land (noice area >55 dB around the road). Raw data for the calculation are presented in Appendix 3.

Land use (m^2/km)	520 000

Table 12. Noise effect caused by traffic on concrete pavement. Noise expressed as use of land (noice area >55 dB around the road). Raw data for the calculation are presented in Appendix 3.

Land use (m^2/km)	700 000

*Table 13. Dust formation over 50 years due to abrasion of asphalt pavement caused by traffic. The basis for the estimation is presented in Appendix 3. **

Asphalt dust (kg/km)	1 000 000

* Abrasion dust is also caused by wearing of rubber tyres. Abrasion of rubber tyres is not taken into account because lack of data. The roughness of road surface affects the wearing of tyres. Consequently there possibly is differences in the influence of road pavements on the formation of rubber dust.

*Table 14. Dust formation over 50 years due to abrasion of concrete pavement caused by traffic. The basis for the estimation is presented in Appendix 3. **

Concrete dust (kg/km)	500 000

* Abrasion dust is also caused by wearing of rubber tyres. Abrasion of rubber tyres is not taken into account because lack of data. The roughness of road surface affects the wearing of tyres. Consequently there possibly is differences in the influence of road pavements on the formation of rubber dust.

Table 15. Environmental burdens caused by salting over 50 years. The difference in salting requirements between asphalt and concrete is not taken into account (ranking depends on weather conditions). The basis for the estimation is presented in Appendix 3.

Salt (kg/km)	1 500 000
Dust from salt (kg/km)	150 000

Table 16a. Summary of the environmental burdens of the manufacturing and use of concrete road. Alternative A (grinding 2 times during 50 years). Emissions in kg/km, energy in GJ/km, land use (due to noise >55 dB) in m^2/km.

	Concrete+ Joint seals	Paving	Maintenance A	Lighting	Traffic disturbance	Abrasion	Salting	Traffic	Total, excluding traffic
CO_2	690 000	2 500	3 500	240 000	1 200	-	-	100 000 000	940 000
SO_2	590	2.6	3.7	1 200	1.3	-	-	110 000	1 700
NO_x	3 700	13	78	940	27	-	-	2 300 000	4 700
CO	1 700	3.4	14	270	4.7	-	-	390 000	2 000
VOC tot	270	3.4	8.2	740	2.9	-	-	240 000	1 000
CH_4	160	2.6	3.2	710	1.1	-	-	94 000	880
As	0.019	$6.3x10^{-6}$	$4.0x10^{-6}$	-	$1.4x10^{-6}$	-	-	0.12	0.019
Hg	0.0076	$0.95x10^{-6}$	$0.15x10^{-6}$	-	$0.052x10^{-6}$	-	-	0.0043	0.0076
Cd	0.0016	$0.95x10^{-6}$	$0.50x10^{-6}$	-	$0.17x10^{-6}$	-	-	0.014	0.0016
Cr	0.0066	$32x10^{-6}$	$2.0x10^{-6}$	-	$0.69x10^{-6}$	-	-	0.058	0.0066
Tl	0.021	-	-	-	-	-	-	-	0.021
Pb	0.042	0.00063	$40x10^{-6}$	-	$14x10^{-6}$	-	-	1.2	0.042
Zn	0.015	-	-	-	-	-	-	-	0.015
N_2O	0.17	-	-	-	-	-	-	-	0.17
Dust	370	4.1	4.4	130	1.5	500 000	150 000	130 000	650 000
N tot	0.13	-	-	-	-	-	-	-	0.13
COD	68	-	-	-	-	-	-	-	68
Land use	-	-	-	-	-	-	-	700 000	-
Fossil fuel	4 600	35	50	-	17	-	-	1 500 000	4 700
Electricity	510	-	-	8 400	-	-	-	-	8 900

Table 16b. Summary of the relative environmental burdens of the manufacturing and use of concrete road. Excluding fuel consumption and dust formation due to traffic and salting. Alternative A (grinding two times during 50 years).

	Concrete + joint seals %	Paving %	Maintenance B %	Lighting %	Traffic disturbance %
CO_2	73	<1	<1	26	<1
SO_2	34	<1	<1	66	<1
NO_x	78	<1	2	20	<1
CO	86	<1	<1	13	<1
VOC tot	26	<1	<1	72	<1
CH_4	19	<1	<1	81	<1
As	100	<1	<1	<1	1
Hg	100	<1	<1	<1	<1
Cd	100	<1	<1	<1	1
Cr	100	<1	<1	<1	<1
Tl	100	-	-	-	-
Pb	98	2	<1	<1	<1
Zn	100	-	-	-	-
Dust	73	<1	<1	25	<1
N tot	100	-	-	-	-
COD	100	-	-	-	-
Fossil fuel	98	1	1	-	0.4
Electricity	6	0	0	94	0

Table 17a. Summary of the environmental burdens of the manufacturing and use of concrete road. Alternative B (grinding 3 times during 50 years). Emissions in kg/km, energy in GJ/km, land use (due to noise >55 dB) in m^2/km.

	Concrete + Joint seals	Paving	Maintenance A	Lighting	Traffic disturbance	Abrasion	Salting	Traffic	Total, excluding traffic
CO_2	690 000	2 500	5 200	240 000	1 800	-	-	100 000 000	940 000
SO_2	590	2.6	5.5	1 200	1.9	-	-	110 000	1 800
NO_x	3 70	13	120	940	41	-	-	2 300 000	4 800
CO	1 700	3.4	20	270	7.1	-	-	390 000	2 000
VOC tot	270	3.4	12	740	4.3	-	-	240 000	1 000
CH_4	160	2.6	4.9	710	1.7	-	-	94 000	880
As	0.019	6.3×10^{-6}	6.0×10^{-6}	-	2.1×10^{-6}	-	-	0.12	0.019
Hg	0.0076	0.95×10^{-6}	0.22×10^{-6}	-	0.078×10^{-6}	-	-	0.0043	0.0076
Cd	0.0016	0.95×10^{-6}	0.74×10^{-6}	-	0.26×10^{-6}	-	-	0.014	0.0016
Cr	0.0066	32×10^{-6}	3.0×10^{-6}	-	1.0×10^{-6}	-	-	0.058	0.0066
Tl	0.021	-	-	-	-	-	-	-	0.021
Pb	0.042	0.00063	60×10^{-6}	-	20×10^{-6}	-	-	1.2	0.042
Zn	0.015	-	-	-	-	-	-	-	0.015
Dust	370	4.1	6.5	130	2.3	500 000	150 000	130 000	650 000
N tot	0.13	-	-	-	-	-	-	-	0.13
COD	68	-	-	-	-	-	-	-	68
Land use	-	-	-	-	-	-	-	700 000	-
Fossil fuel	4 600	35	75	-	26	-	-	1 500 000	4 700
Electricity	510	-	-	8 400	-	-	-	-	8 900

Table 17b. Summary of the relative environmental burdens of the manufacturing and use of concrete road. Excluding fuel consumption and dust formation due to traffic and salting. Alternative B (grinding three times during 50 years).

	Concrete + joint seals %	Paving %	Maintenance B %	Lighting %	Traffic disturbance %
CO_2	73	<1	<1	26	<1
SO_2	34	<1	<1	66	<1
NO_x	77	<1	3	20	<1
CO	85	<1	1	14	<1
VOC tot	26	<1	1	72	<1
CH_4	18	<1	<1	80	<1
As	100	<1	<1	-	<1
Hg	100	<1	<1	-	<1
Cd	100	<1	<1	-	<1
Cr	100	<1	<1	-	<1
Tl	100	-	-	-	-
Pb	98	1	<1	-	<1
Zn	100	-	-	-	-
Dust	72	<1	1	25	<1
N tot	100	-	-	-	-
COD	100	-	-	-	-
Fossil fuel	97	1	2	-	<1
Electricity	6	-	-	94	-

Table 18a. Summary of the environmental burdens of the manufacturing and use of asphalt road during 50 years. Alternative A (Appendix 5) (Finnish maintenance strategy). Emissions in kg/km, energy in GJ/km, land use (due to noise >55 dB) in m^2/km.

	Asphalt A *	Paving	Maintenance A	Lighting	Traffic disturbance	Abrasion	Salting	Traffic	Total excluding traffic
CO_2	160 000	5 000	24 000	400 000	3 200	-	-	100 000 000	590 000
SO_2	620	5.2	2.9	1 900	3.4	-	-	110 000	2 500
NO_x	1 300	26	100	1 600	72	-	-	2 300 000	3 000
CO	130	6.8	14	459	13	-	-	390 000	610
HC+VOC	500	6.8	150	1 200	7.6	-	-	240 000	1 900
CH_4	130	5.1	150	1 200	3.0	-	-	94 000	1 500
As	0.0026	0.00013	$61x10^{-6}$	-	$3.7x10^{-6}$	-	-	0.12	0.0028
Hg	$39x10^{-6}$	$1.9x10^{-6}$	$0.92x10^{-6}$	-	$0.14x10^{-6}$	-	-	0.0043	$42x10^{-6}$
Cd	0.00038	$19x10^{-6}$	$9.2x10^{-6}$	-	$0.46x10^{-6}$	-	-	0.014	0.00041
Cr	0.0011	$63x10^{-6}$	$31x10^{-6}$	-	$1.8x10^{-6}$	-	-	0.058	0.0012
Pb	0.026	0.0013	0.00061	-	$37x10^{-6}$	-	-	1.2	0.028
Dust	160	8.1	4.7	220	4.0	1 000 000	150 000	130 000	1 200 000
N into water	0.91	-	-	-	-	-	-	-	0.91
COD	18	-	-	-	-	-	-	-	18
Land use	-	-	-	-	-	-	-	520 000	-
Fossil fuel	2 500	69	470	-	46	-	-	1 500 000	3 100
Electricity	170	-	-	14 000	-	-	-	-	14 000
Inherent energy	7 700	-	-	-	-	-	-	-	7 700

* *Volume of asphalt (during 50 years) accordance to maintenance strategy A.*

Table 18b. Summary of the relative environmental burdens caused by manufacturing and use of asphalt pavement during 50 years, excluding fuel consumption and dust formation due to traffic and salting. Alternative A (Finnish maintenance strategy).

	Asphalt A %	**Asphalt paving %**	**Maintenance A %**	**Lighting %**	**Traffic disturbance %**
CO_2	27	<1	4	68	<1
SO_2	24	<1	<1	75	<1
NO_x	42	<1	3	51	2
CO	22	1	2	73	2
VOC tot	26	<1	8	65	<1
CH_4	9	<1	10	80	<1
As	93	5	2	-	<1
Hg	93	5	2	-	<1
Cd	93	5	2	-	<1
Cr	92	5	3	-	<1
Tl	-	-	-	-	-
Pb	93	5	2	-	<1
Zn	-	-	-	-	-
N_2O	-	-	-	-	-
Dust	41	2	1	56	1
N into water	100	-	-	-	-
COD	100	-	-	-	-
Fossil fuel	81	2	15	-	2
Electricity	<1	-	-	99	-
Inherent energy	100	-	-	-	-

Table 19a. Summary of the environmental burdens of the manufacturing and use of asphalt road during 50 years. Alternative B (Appendix 6). Emissions in kg/km, energy in GJ/km.

	Asphalt B *	Paving	Maintenance B	Lighting	Traffic disturbance	Abrasion	Salting	Traffic	Total, excluding traffic
CO_2	230 000	5000	27 000	400 000	3 200	-	-	100 000 000	670 000
SO_2	900	5.2	5.8	1 900	3.4	-	-	110 000	2 800
NO_x	1 800	26	120	1 600	72	-	-	2 300 000	3 600
CO	190	6.8	18	450	13	-	-	390 000	670
VOC tot	710	6.8	150	1 200	7.6	-	-	240 000	2 100
CH_4	190	5.1	150	1 200	3.0	-	-	94 000	1 500
As	0.0037	0.00013	0.00013	-	$3.7x10^{-6}$	-	-	0.12	0.0040
Hg	$60x10^{-6}$	$1.9x10^{-6}$	$1.9x10^{-6}$	-	$0.14x10^{-6}$	-	-	0.0043	$64x10^{-6}$
Cd	0.00077	$19x10^{-6}$	$19x10^{-6}$	-	$0.46x10^{-6}$	-	-	0.014	0.00081
Cr	0.0016	$63x10^{-6}$	$64x10^{-6}$	-	$1.8x10^{-6}$	-	-	0.058	0.0017
Pb	0.037	0.0013	0.0013	-	$37x10^{-6}$	-	-	1.2	0.040
Dust	230	8.1	9.1	220	4.0	1 000 000	150 000	130 000	1 200 000
N into water	1.3	-	-	-	-	-	-	-	1.3
COD	26	-	-	-	-	-	-	-	26
Land use	-	-	-	-	-	-	-	520 000	-
Fossil fuel	3 500	69	510	-	46	-	-	-	4 200
Electricity	250	-	-	14 000	-	-	-		14 000
Inherent energy	11 000	-	-	-	-	-	-	1 500 000	11 000

* *Volume of asphalt (during 50 years) accordance to maintenance strategy B.*

Table 19b. Summary of the relative environmental burdens caused by manufacturing and use of asphalt pavement during 50 years, excluding fuel consumption and dust formation due to traffic and salting. Alternative B (Swedish maintenance strategy).

	Asphalt B %	**Paving %**	**Maintenance %**	**Lighting %**	**Traffic disturbance %**
CO_2	34	<1	4	61	<1
SO_2	32	<1	<1	68	<1
NO_x	51	<1	3	43	2
CO	28	1	3	66	2
VOC tot	34	<1	7	58	<1
CH_4	13	<1	10	77	<1
As	93	3	3	-	<1
Hg	94	3	3	-	<1
Cd	95	2	2	-	<1
Cr	94	3	3	-	<1
Tl	-	-	-	-	-
Pb	93	3	3	-	<1
N_2O	-	-	-	-	-
Dust	49	2	2	46	1
N into water	100	-	-	-	-
COD	100	-	-	-	-
Fossil fuel	85	2	12	-	1
Electricity	2	-	-	98	-
Inherent energy	100	-	-	-	-

8 VALUATION OF THE RESULTS OF THE INVENTORY ANALYSES

Scenarios valuated according to different valuation methods are presented in Table 20.

Table 20. Scenarios valuated according to different valuation methods. Emissions are given in kg/km, energy in GJ/km, land use in m^2.

	1 Asphalt Maint. A	2 Asphalt Maint. B	3 Concrete Maint. A	4 Concrete Maint. B	5 Concrete Maint. A Including carbonation
CO_2	590 000	670 000	940 000	940 000	880 000
SO_2	2 500	2 800	1 700	1 700	1 700
NO_x	3 000	3 600	4 700	4 700	4 700
CO	610	670	2 000	2 000	2 000
VOC tot	1 900	2 100	1000	1 000	1 000
CH_4	1 500	1 500	880	880	880
As	0.0028	0.0040	0.019	0.019	0.019
Hg	$42x10^{-6}$	$64x10^{-6}$	0.0076	0.0076	0.0076
Cd	0.00041	0.00081	0.0016	0.0016	0.0016
Cr	0.0012	0.0017	0.0066	0.0066	0.0066
Pb	0.028	0.040	0.042	0.042	0.042
Zn	0	0	0.015	0.015	0.015
Dust	1 200 000	1 200 000	650 000	650 000	650 000
N into water	0.91	1.3	0.13	0.13	0.13
COD	18	26	68	68	68
Fossil fuel	15 000 1)	20 000 1)	7 600	7 600	7 600
Nuclear fuel	4 600	4 600	2 930	2 900	2 900
Renewable energy	4 600	4 600	2 900	2 900	2 900

1) Including inherent energy.

1 Asphalt pavement. Maintenance strategy A (Finnish reference). Including
- production processes of asphalt materials
- paving
- maintenance A (Finnish recommendation)
- traffic disturbance due to maintenance
- lighting
- dust burdens from pavement abrasion caused by traffic

- dust from salting

2 Asphalt pavement. Maintenance strategy B. Including
- production processes of asphalt materials
- paving
- maintenance B (Swedish recommendation)
- traffic disturbance due to maintenance
- lighting
- dust burdens from pavement abrasion caused by traffic
- dust from salting

3 Concrete pavement. Maintenance strategy A. Including
- production processes of concrete materials
- paving
- maintenance A (including two grindings of pavement surface in 50 years)
- traffic disturbance due to maintenance
- lighting
- dust burdens from pavement abrasion caused by traffic
- dust from salting

4 Concrete pavement. Maintenance strategy B. Including
- production processes of concrete materials
- paving
- maintenance A (including three grindings of pavement surface in 50 years)
- traffic disturbance due to maintenance
- lighting
- dust burdens from pavement abrasion caused by traffic
- dust from salting

5 Concrete pavement. Maintenance strategy A. Including
- production processes of concrete materials
- paving
- carbonation of concrete surface (3x15 mm)
- maintenance A (including two grindings of pavement surface in 50 years)
- traffic disturbance due to maintenance
- lighting
- dust burdens from pavement abrasion caused by traffic
- dust from salting

The results were evaluated based on the following methods:

- Ecoscarcity method in Switzerland (Reference Ahbe et la. 1990 in Anon 1995a)
- Ecoscarcity method in the Netherlands (Reference SIMA-PRO, 1993 in Anon 1995a)
- Ecoscarcity method in Norway (Reference Baumann, 1992 in Anon 1995a)
- Ecoscarcity method in Sweden (Reference Baumann et al., 1993 in Anon 1995a)
- Effect-category method (CML Sweden) (Reference Baumann et al., 1993 in Anon 1995a) According to the short term goals and long term goals

• EPS system, version 2.0 (References Steen and Ryding, 1992 and Boström and Steen, 1994, in Anon 1995a).

The weighting factors used in valuation are presented elsewhere (Anon 1995a, pp. 167 and 197 - 199). The weighting factors of the Norwegian and Swedish ecoscarcity methods and those of the effect-category method (short term goals) and EPS-system are the same as those used for cements (Vold and Rønning 1995). However, electricity was dealt with based on the energy types used to produce it.

The environmental burdens (harmful emissions and consumption of energy) were valuated according to the weigting factors and added up. The results are presented in Table 21. The weighted proportions of separate environmental burdens in relation to the final result are presented in Appendix 14.

Table 21. Valuation results of the different scenarios. The outflows are expressed in kg (per km and 50 years) and energy resources in GJ (per km and 50 years.

	Eco Scarcity				Effect-category		
	Ahbe 1990	SIMA-PRO 1993	Baumann 1992	Baumann 1993	Short term	Long term	EPS-system
Sce 1	240 000	130 000	110 000	43 000	79 000	110 000	170 000
Sce 2	280 000	140 000	130 000	51 000	87 000	120 000	220 000
Sce 3	290 000	120 000	120 000	63 000	59 000	91 000	120 000
Sce 4	290 000	120 000	120 000	63 000	59 000	90 000	120 000
Sce 5	290 000	120 000	120 000	62 000	59 000	88 000	110 000

As shown in Appendix 14, the dust emissions from the use of roads have a significant effect on the final result. The dust emissions of road pavements consist of stone dust and bitumen or hydrated cement. Below is a short summary of the health effects of dust:

> Quartz, hard metal and asbest dust are considered active dusts. Particles < 5 μ m drift to the walls of the smallest bronchioles and alveoli in the lungs, damaging the cells and causing connective tissue cicatrization. The desease caused by quartz dust is known as silicosis, and may increase the risk of lung cancer (Palomäki 1993). The Finnish standard (HTP) for free fine (< 5 μm) quatz dust in the atmosphere is 0.2 mg/m^3 (Anon 1993b). Amorphous quartz is not regarded as active dust. The HTP value for amorphous silica dust is 5 mg/m^3. For low-affecting inorganic dusts the HTP is 10 mg/m^3. The HTP value for organic dusts (8 hours) is 5 mg/m^3 (Anon 1993b).
>
> Silica exists in many stone materials. The crystalline formats of silica are quartz, cristobalite and tridymite. The quartz content of grey and red granite

is roughly 20 - 50%. However, quartz is enriched in finer aggregate materials. Cement is classified as low-affecting dust because the quatrz content is very low (ACGIH 1984). Cement dust is alkaline in water solutions and may thus have an irrigating effect on the eyes and mucous membranes.

Because the grain size of dust significantly dictates the health effects of dust, and because the grain sizes of dust emitted from road pavements are large compared with combustion processes, the final result was also valuated disregarding the dust from abrasion and salting. The result is given in Table 22.

Table 22. Valuation results of the different scenarios. Dust from abrasion of pavements and salting is excluded.

	Eco Scarcity				Effect-category		
	Ahbe 1990	SIMA-PRO 1993	Baumann 1992	Baumann 1993	Short term	Long term	EPS system
Sce 1	240 000	130 000	110 000	43 000	36 000	62 000	170 000
Sce 2	280 000	140 000	130 000	51 000	44 000	74 000	210 000
Sce 3	290 000	120 000	120 000	63 000	36 000	63 000	120 000
Sce 4	290 000	120 000	120 000	63 000	36 000	63 000	110 000
Sce 5	290 000	120 000	120 000	62 000	35 000	61 000	110 000

9 REVIEW OF THE RESULTS

9.1 ENVIRONMENTAL BURDENS OF CONCRETE PAVEMENT

On the basis of the results with concrete pavements the following was concluded:

• The significance of **joint seals** in the environmental burdens of concrete pavement seems to be roughly 1% (1% from CO_2, 1% from SO_2, 0.3% from NO_x, and 1% from fossil energy), if considered with respect to production processes and use of concrete pavement during 50 years (excluding fuel consumption by traffic, Table 16a). This means that the result is not sensitive to assumptions made with respect to the service life of joint seals. The inherent energy of joint seals was excluded.

• The concrete road construction under study is a non-reinforced concrete slab. Only **joint steel bars** were used. Based on the results given by Fossdal (1995), CO_2, SO_2 and NO_x burdens from joint steel bars are roughly 0.5% of the corresponding total emissions.

• The environmental burdens of high-strength concrete significantly depend on the **cement content** of concrete. In this case the production processes of cement are responsible for roughly 100% of CO_2, 90% of SO_2 and 80% of NO_x emissions caused by production processes of high strength concrete. This means that the cement content of concrete is responsible for roughly 70% of CO_2, 30% of SO_2 and 70% of NO_x emissions caused by production processes and use of concrete pavement during 50 years (excluding fuel consumption by traffic, Table 16a). The environmental profile of concrete pavement is sensitive to the presumptions and choices made with respect to the cement content of concrete. In this case the cement content of concrete was 17.7%. If the content had been 15% lower (that is 15% of concrete by weight) and the difference had been substituted by sand, the total CO_2, SO_2 and NO_x emissions would have been roughly the following (Table 23, Figure 6).

Table 23. Effect of cement content on the CO_2, SO_2 and NO_x emissions of concrete pavement (including production processes, maintenance and lighting, excluding traffic).

	Concrete pavement Cement content 15% (CONC)	Concrete pavement Cement content 17.7% (Table 16a)	Asphalt pavement (Table 19a) (ASPH) (CONC)
CO_2	850 000 kg/km	940 000 kg/km	670 000 kg/km
SO_2	1 600 kg/km	1 700 kg/km	2 800 kg/km
NO_x	4 200 kg/km	4 700 kg/km	3 600 kg/km.

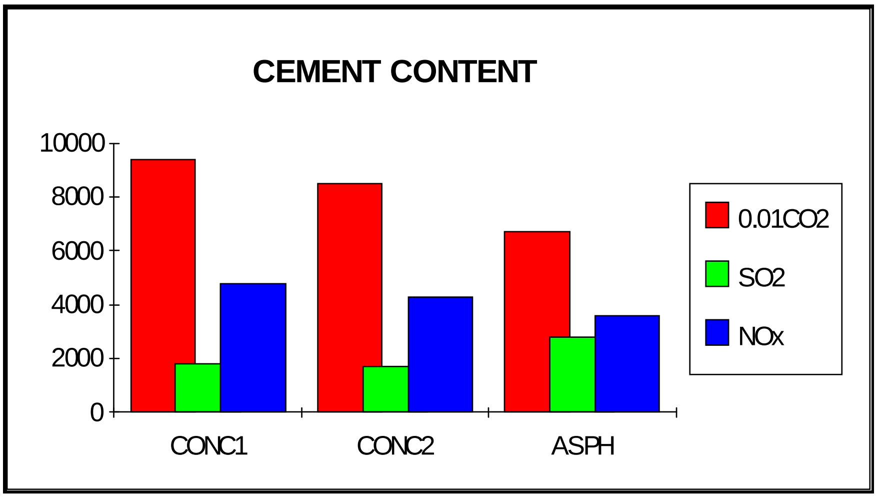


Figure 6. Effect of cement content on the CO_2, SO_2 and NO_x emissions of concrete pavement (including production processes, maintenance and lighting, excluding traffic). Emissions ar given in kg/km.
CONC1: Cement content 17.7% (Table 23)
CONC2: Cement content 15% (Table 23).

Consequently, the environmental profile of concrete pavement also significantly depends on the depth of the concrete layer. Different presumptions are compared in Table 24 and in Figure 7.

Table 24. Effect of presumptions concerning the depth of pavement layers on environmental burdens. Emissions are expressed in kg/km and energy in GJ/km.

	CONC 1 Concrete pavement Strategy A (Table 16a)	ASPH 1 Asphalt pavement Strategy A (Table 18a)	CONC 2 Concrete pavement Depth -10% compared to CONC 1	ASPH 2 Asphalt pavement Depth +30% compared to ASPH 1
CO_2	940 000	590 000	870 000	640 000
SO_2	1 700	2 500	1 700	2 700
NO_x	4 700	3 000	4 300	3 400
Fossil energy	7 600	15 000	7 000	18 000

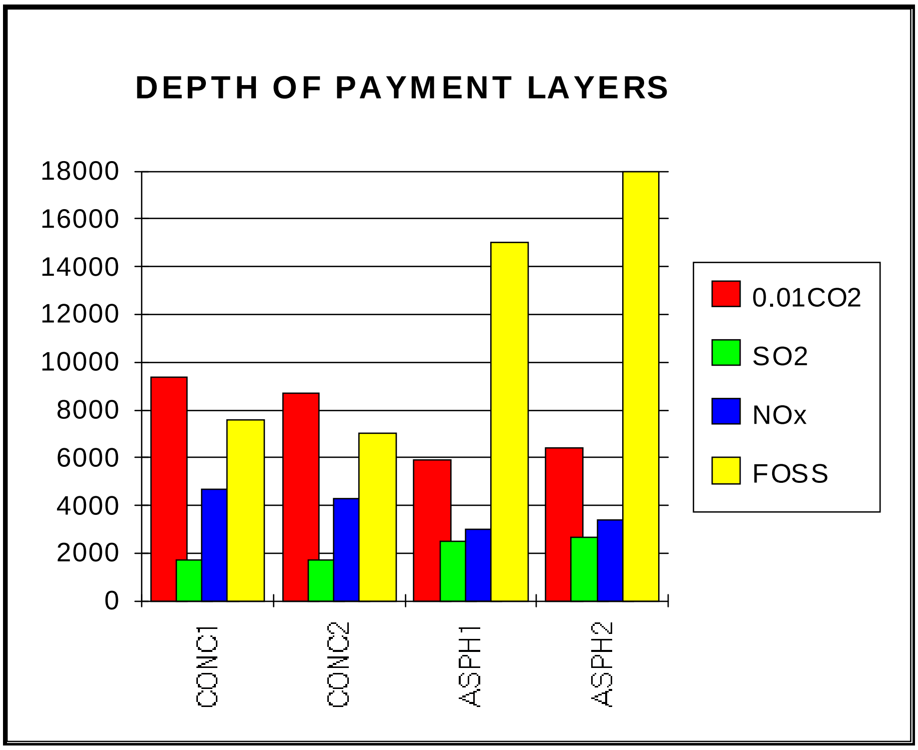


Figure 7. Effect of presumptions concerning the depth of pavement layers on environmental burdens. Emissions are expressed in kg/km and energy in GJ/km.

• Based on the assumptions presented in the previous text, the binding of carbon dioxide during 50 years is roughly 10% of the carbon dioxide emitted in production processes of concrete and ingredient materials. This means that the consideration of **carbonation** affects the final result by roughly 6% (scenarios 3 and 5 in Table 20). In this case it was assumed that a 3x15 mm surface layer carbonates for 50 years (Table 25). The carbonation would significantly affect the final result if complete carbonation (possibly over hundreds or thousands of years) were taken into account.

Table 25. Effect of carbonation on total carbon dioxide emissions.

	CO_2 emmissions
Concrete pavement No carbonation Table 16a	940 000 kg/km
Concrete pavement Carbonation 45 mm Table 20, scenario 5	880 000 kg/km
Concrete pavement Carbonation 90 mm	810 000 kg/km
Asphalt pavement Table 19a	670 000 kg/km

• The environmental burdens from concrete **paving and maintenance** are rather low compared with those caused by production processes of high-strength concrete. The emissions and energy consumption due to pavement construction and maintenance together are roughly 1 - 3% of the total values from CO_2, SO_2, NO_x, CO and VOC emissions and fossil energy (Table 16b). This means that the final result is not sensitive to uncertainty or variations in fuel consumption and process emissions of construction and maintenance processes.

• The significance of **traffic disturbance** with respect to the environmental burdens of a concrete road (Table 16b) is very small (0 - 1%). This also means that the final result is not sensitive to the uncertainty and variations in fuel consumption caused by traffic disturbance due to maintenance operations.

• With respect to the environmental burdens of concrete pavement, the significance of **lighting** (during 50 years) is high. Based on the presumptions presented above, the emissions and energy consumption due to lighting are roughly 30%, 70%, 20% and 30% of CO_2, SO_2, NO_x, emissions and fossil energy of the concrete pavement (Tables 16a and b). The calculations were performed assuming that total energy consumption due to lighting to be 1 800 000 kWh/km and 1 080 000 kWh/km on the asphalt and concrete reference roads respectively during 50 years. If the energy consumption due to lighting on a concrete road was only 50% of that of asphalt road, it would change the result in the following way (Table 26):

Table 26. Effect of changes in presumptions concerning lighting on the results.

	Asphalt pavement (Table 19a)	Concrete pavement Lighting energy consumption 60% compared to asphalt (Table 16a)	Concrete pavement Lighting energy consumption 50% compared to asphalt
CO_2	590 000	940 000	900 000
SO_2	2 500	1 700	1 600
NO_x	3 000	4 700	4 600
Fossil energy	15 000	7 600	7 200

• The **dust emissions** of the concrete pavement studied are mainly (≈ 100%) induced by abrasion and salting of the pavement (and the fuel consumption of traffic, if this is included) (Table 17a). This makes the final result very sensitive to the presumptions concerning the abrasion of concrete and asphalt pavements (Table 27).

Table 27. Effect of presumptions concerning dust emissions on the results.

Dust emissions, kg/km 50 years	Concrete pavement Presumption 0 (Table 17a)	Asphalt pavement Presumption 0 * (Table 18a)	Asphalt pavement Presumption 1**
Materials	370	160	160
Construction	4.1	8.1	8.1
Maintenance	6.5	4.7	4.7
Lighting	130	220	220
Abrasion	500 000	1 000 000	1 500 000
Salting	150 000	150 000	150 000
Traffic	130 000	130 000	130 000
Total	**780 000**	**1 300 000**	**1 800 000**

* Dust formation due to abrasion 100% higher than on concrete pavement.
** Dust formation due to abrasion 200% higher than on concrete pavement.

• The significance of pavement materials, paving, maintenance and lighting is low compared with the environmental burdens caused by **traffic** during 50 years. Emissions and energy consumption induced by other factors (materials, paving, maintenance, lighting) are roughly 0.2 - 2% of those caused by traffic.

However, it would be better to look at the potential indirect effects of pavement materials on fuel consumption than to compare the impacts of whole traffic with those caused by pavement materials. The building sector, including road construction is not alone responsible for traffic, but is responsible for developing pavement materials and improving the influence of these on fuel consumption.

With respect to the effect of material properties of pavement on fuel consumption, the following assumptions have been made in the assessment:

1 The influence on fuel consumption related to the **surface texture** is assumed to be the same for both pavements.

2 It is assumed that the **difference in E-modulus** does not influence the fuel consumption for the heavy vehicles.

3 Measured **differences in rolling resistance** are small compared with insecurities in other factors influencing fuel consumption, i.e. it is at this stage assumed that measured differences in rolling resistance have no influence on fuel consumption

However, any difference in fuel consumption of traffic due to pavement materials would significantly affect the result. For example, a roughly 0.1 - 0.5% decrease in fuel consumption due to lower rolling resistance of concrete pavement would bring the CO_2 emissions of the pavements under study (Tables 16 - 19) to the same level (Table 28).

Table 28. Effect of a 0.5% decrease in fuel consumption of traffic on the results. Emissions are expressed in kg/km, energy in GJ/km.

	Traffic Effect of a 0.5% decrease in fuel consumption (savings in burdens)	Concrete pavement (Table 16a) excluding traffic	Asphalt pavement (Table 18a) excluding traffic
CO_2	- 510 000	940 000	590 000
SO_2	- 530	1 700	2 500
NO_x	- 11 000	4 700	3 000

CO	- 2000	2 000	610
Fossil energy	- 7 300	7 700	15 000

9.2 ENVIRONMENTAL BURDENS OF ASPHALT PAVEMENT

On the basis of results concerning asphalt pavements the following can be summarised:

- The environmental burdens of asphalt significantly depend on the **bitumen content** of the asphalt. In addition, the manufacturing of asphalt including **drying of aggregate** materials significantly accounts for the environmental burdens of asphalt. In this case the bitumen is responsible for 40% of CO_2, 30% of SO_2, 40% of NO_X and 70% of VOC emissions of asphalt (from raw material extraction to transportation of SMA asphalt). Correspondingly, manufacturing accounts for roughly 40% of CO_2, 70% of SO_2, 20% of NO_X and 10% of VOCs.

- According to the two different **maintenance strategies** looked at, the amount of asphalt materials required over 50 years varies significantly. Based on these calculations the environmental burdens of asphalt B (according to the strategy B, Appendix 6) are roughly 40% higher than those of asphalt A (according to the strategy A, Appendix 5) (Tables 18a and 19a). This means that the result significantly depends on the maintenance operations presumed (and on the volume of asphalt or the depth of asphalt layer).

- **Paving and maintenance** together are responsible for <10% of environmental burdens (Tables 18b and 19b). This means that the final result is not especially sensitive to uncertainty or variations in fuel consumption and process emissions due to asphalt paving and maintenance operations.

- The significance of **traffic disturbance** due to maintenance is rather low. According to the results traffic disturbance is responsible for <1% of emissions (Tables 18b and 19b). This means that the final result is not sensitive to the uncertainty and variations in fuel consumption caused by traffic disturbance due to maintenance operations.

- According to the results, **lighting** is responsible for roughly 50 - 70% of the emissions (Tables 18b and 19b).

9.3 COMPARISON OF THE ENVIRONMENTAL BURDENS OF CONCRETE AND ASPHALT PAVEMENTS

The concrete and asphalt pavements are compared in Table 29. Because the difference between concrete pavement alternatives A and B is very small, only the A alternative is given.

Table 29. Environmental burdens caused by concrete and asphalt pavements. Production of materials, paving, maintenance, lighting, traffic disturbance, abrasion and noise effect and carbonation of concrete are included.

	Concrete pavement Maintenance A	Asphalt pavement Maintenance A	Asphalt pavement Maintenance B
CO_2, tons/km	940	590	670
SO_2, kg/km	1 700	2 500	2 800
NO_x, kg/km	4 700	3 000	3 600
CO, kg/km	2 000	610	670
VOC tot, kg/km	1 000	1 900	2 100
Dust, tons/km	650	1 200	1 200
Hg, g/km	7.6	0.042	0.064
Non-renewable energy, GJ/km	11 000	21 000 *	25 000 *
Noise (land use), ha/km	70	52	52

* Including inherent energy.

According to the results, the environmental burdens of concrete pavement are:

- 40 - 60% higher for CO_2 and
- 30 - 60% higher for NO_x
- roughly 3 times higher for CO
- roughly 100 times higher for Hg

compared with the burdens of manufacturing, maintenance and use of asphalt pavement.

Correspondingly, the environmental burdens of asphalt pavement are

- 40 - 60% higher for SO_2
- roughly 2 times higher for VOCs
- roughly 2 times higher for dust and
- roughly 2 times higher for non-renewable energy

compared with the burdens of concrete pavement,
if manufacturing, maintenance and use of roads are taken into account but fuel consumption of traffic is excluded.

9.4 VALUATION OF THE RESULT

The results of the valuation are presented in Table 30. Because the results of the all concrete alternatives 3, 4 and 5 according to Table 20 are quite close to each other, only one of these is included in the following (number 3).

Table 30. Relative results of valuation according to different valuation methods.

	Eco-scarcity Switzerland	Eco-scarcity Holland	Eco-scarcity Norway	Eco-scarcity Sweden	Eco-category Short term	Eco-category Long term	EPS system
1	1	1	1	1	**1.3**	1.2	**1.5**
2	1.2	1.1	1.1	1.1	**1.4**	**1.4**	**1.9**
3	1.2	1	1.2	**1.7**	1	1	1

The differences between different scenarios are rather low according to the Swiss, Dutch and Norwegian ecoscarcity methods. According to the Swedish ecoscarcity method the scenario based on concrete is environmentally more negative than the scenarios based on asphalt. In contrast, according to the eco-category methods and EPS-system the scenarios based on asphalt are more disadvantageous than the scenario based on concrete.

As shown in the figures of Appendix 14, the determining components of the asphalt pavement are carbon dioxide, sulphur dioxide and nitrogen oxide emissions, dust and energy consumption. The same is true with respect to concrete pavement. The negative impact for concrete is partly due to the high valuation factors for mercury and cadmium according to the Swedish political targets.

Because the grain size of dust significantly dictates the health effects of dust, and because the grain sizes of dust emitted from road pavements are large compared with combustion processes, the final result was also valuated disregarding the dust from abrasion and salting. The relative result is given in Table 31.

Table 31. Relative results of valuation according to different valuation methods. Dust from abrasion and salting is excluded.

	Eco-scarcity Switzerland	Eco-scarcity Holland	Eco-scarcity Norway	Eco-scarcity Sweden	Eco-category Short term	Eco-category Long term	EPS system
1	1	1.1	1	1	1	1	**1.5**
2	1.2	1.2	1.2	1.2	1.2	1.2	**1.9**
3	1.2	1	1.1	**1.5**	1	1	1

9.5 INFLUENCE OF RECYCLING OF MATERIALS ON THE RESULTS

In this report the environmental burdens of concrete and asphalt pavings overperiod of 50 years has been studied using LCA methodology. If it is assumed that the road is still needed in the same place after 50 years, there are different possibilities to lengthen the service life of the road:
- A new pavement upon the old ones or if there are
- significant deformations, the road construction must be renewed. In this case the old pavement or parts of it can be used as raw materials in situ or in other places.

In this study it has been assumed that after 50 years
- road construction must be renewed,
- the pavements must be demolished and
- no waste material is formed because all the materials can be used to substitute
  filling or aggregate materials or new asphalt.

All the environmental burdens are allocated to the original systems. This means that the user of recycled materials receives those as "pure" by-products and only additional processing and transportation of the recycled products would cause environmental burdens. This also means that the original product benefits from potential recycling only because of reduced volumes of waste. Thus the actual use of recycled materials and wastes is credited in the LCA instead of crediting possibilities to recycle. When building and road materials with long service life are considered, such an allocating may be justifiable.

After its service life, crushed concrete can be reused as aggregate material in concrete. Fine materials is used as filling material or as aggregate material for soil concrete. In the latter case, possibly cement can be saved in small amounts because crushed concrete shows some hydraulic reactivity. The reuse often is possible on the same working site. However, in both cases concrete mainly substitutes significantly less valuable materials (aggregates instead of cement and aggregates) than its own original value. It seems therefore reasonable that the advantage of recycling concrete lies in the reduced volumes of wastes.

Nowadays quite a high percentage of disposed asphalt is reused. Asphalt can be reused
- to substitute crushed natural materials for example in road sides, if reuse in
  asphalt is not economical e.g. due to long transportation or
- to substitute new materials (bitumen and aggregates) in the production of
  asphalt.

If disposed asphalt is reused, it naturally decreases the amount of wastes with respect to the functional unit under study. In addition, if the value of the material is relatively high compared to the original asphalt, part of the

environmental burdens of the original system could be allocated to the recycling system.
In order to assess the influence of recycling of asphalt on the environmental burdens of asphalt, the following assumptions are made:
- one third of the asphalt pavement material is disposed (one part of which is lost due to dust formation),
- two thirds of the asphalt are used to substitute new asphalt,
- one third of the new asphalt can be substituted with recycled asphalt,
- if asphalt is once manufactured using recycling asphalt it cannot be recycled again due to the ageing of bitumen,
- the advantage of saving bitumen is divided evenly between the original and new asphalt,
- the advantage is only assumed to result from reduced volume of bitumen and
- the advantage is not assumed to result from reduced volume of natural aggregates (because the recycled asphalt must also be crushed and heated).

This means that on average one third of the bitumen, and correspondingly one third of the energy and emissions related to it, is saved. However, because it is also reasonable to assume that
- the recycled asphalt can substitute less valuable (roughly 20% less bituminous) asphalt than the original composition and
- the recycled asphalt cannot substitute the new asphalt identically but a small amount of additional bitumen is needed

it follows that on average roughly one fourth of bitumen and correspondingly one fourth of the energy and emissions related to it can be "saved" within the system. This would mean roughly
- 10% reduction in CO_2, SO_2 and NO_x emissions and
- 20% reduction in VOC emissions and fossil energy.

SUMMARY

The object of the study has been to assess the environmental impact of concrete and asphalt road pavements. The assessment is based on the estimation of service life of road pavements and the environmental burdens caused by their production, use and disposal. Also taken into account is the influence of the pavement on fuel consumption by traffic, noise, lighting requirements and dust formation. The functional unit studied is 1 km of pavement of the Tampere motor way assuming passage of 20 000 vehicles per day. The time scale is 50 years.

On the basis of the results the environmental burdens of concrete pavements significantly depend on the cement content of concrete. Consequently, the environmental profile of concrete pavement also significantly depends on the depth of the concrete layer. The binding of carbon dioxide during 50 years was assessed to be roughly 10% of the carbon dioxide emitted in production processes of concrete and ingredient materials. In this case it was

assumed that a 3x15 mm surface layer carbonates during 50 years. The carbonation would significantly affect the final result if complete carbonation were taken into account.
The environmental burdens from concrete paving and maintenance are rather low compared with those caused by production processes of high-strength concrete. In addition, the significance of traffic disturbance is very small. With respect to the environmental burdens of concrete pavement, the significance of lighting (during 50 years) is high. The dust emissions of the concrete pavement studied are mainly induced by abrasion and salting of the pavement. This makes the final result very sensitive to the presumptions concerning the abrasion of concrete and asphalt pavements.

The significance of pavement materials, paving, maintenance and lighting is low compared with the environmental burdens caused by traffic during 50 years. However, it would be better to look at the potential indirect effects of pavement materials on fuel consumption than to compare the impacts of whole traffic with those caused by pavement materials. The building sector, including road construction is not alone responsible for traffic, but is responsible for developing pavement materials and improving the influence of these on fuel consumption.

With respect to the effect of material properties of pavement on fuel consumption, it was assumed that
- the influence on fuel consumption related to the surface texture is the same for both pavements
- the difference in E-modulus does not influence the fuel consumption for the heavy vehicles
- measured differences in rolling resistance have no influence on fuel consumption.

However, any difference in fuel consumption of traffic due to pavement materials would significantly affect the result. For example, a roughly 0.1 - 0.5% decrease in fuel consumption of traffic due properties of concrete pavement would bring "savings" in emissions of the same order of magnitude than those from all the other parts of the life cycle of concrete roads.

On the basis of the results the environmental burdens of asphalt significantly depend on the bitumen content of asphalt. In addition, the manufacture of asphalt including drying of aggregate materials significantly accounts for the environmental burdens of asphalt pavement. According to the two different maintenance strategies looked at, the amount of asphalt materials required over 50 years varies significantly. Based on these calculations the environmental burdens of asphalt B (according to the Swedish strategy) are roughly 40% higher than those of asphalt A (according to the Finnish strategy). This means that the result significantly depends on the maintenance operations presumed (and on the volume of asphalt or the depth of asphalt layer).

According to the results (based on the assumption presented in the report), the environmental burdens of concrete pavement are
- 40 - 60% higher for CO_2 and
- 30 - 60% higher for NO_x
- roughly 3 times higher for CO
- roughly 100 times higher for Hg

compared with the burdens of manufacture, maintenance and use of asphalt pavement.

Correspondingly, the environmental burdens of asphalt pavement are
- 40 - 60% higher for SO_2
- roughly 2 times higher for VOCs
- roughly 2 times higher for dust and
- roughly 2 times higher for non-renewable energy

compared with the burdens of concrete pavement,
if manufacturing, maintenance and use of roads are taken into account but fuel consumption of traffic is excluded.

The result was also assessed using different valuation methods. The differences between asphalt and concrete scenarios are rather low according to the Swiss, Dutch and Norwegian ecoscarcity methods. According to the Swedish ecoscarcity method the scenario based on concrete is environmentally more negative than scenarios based on asphalt. In contrast, according to the eco-category methods and EPS system, the scenarios based on asphalt are more disadvantageous than those based on concrete.

The determining environmental burdens of asphalt pavement are carbon dioxide, sulphur dioxide and nitrogen oxide emissions, dust and energy consumption. The same is true with respect to concrete pavement. The negative impact for concrete is partly due to the high valuation factors for mercury and cadmium according to the Swedish political targets.

In this study it has been assumed that after 50 years
- road construction must be renewed,
- the pavements must be demolished and
- no waste material is formed as all the materials can be used to substitute filling or aggregate materials or new asphalt.

All the environmental burdens are allocated to the original systems. This means that the user of recycled materials receives those as "pure" by-products and only additional processing and transportation of the recycled products would cause environmental burdens. The influence of recycled of asphalt on the environmental burdens of asphalt pavements was also studied by allocating part of the original burdens to the recycling system.

REFERENCES

ACGIH 1984. Threshold limit values for chemical substances in work environment. Cincinnati: American Conference of Governmental Industrial Hygienists.

Anon 1993a. Guidelines for Life-Cycle Assessment: A Code for Practice, Edition 1. From the workshop held at Sesimbra, Portugal 31.3. - 3.4.1993 Ed. by Consoli, F. et al. SETAC (Society of Environmental Toxicology and Chemistry). 68 p.

Anon 1993b. HTP-arvot (Contents verified to be harmful). Tampere; The Ministry of Labour. Advisory board for occupationnal protection. (In Finnish).

Anon 1995a. Nordic Guidelines on Life-Cycle assessment. Nord 1995:20. Nordic Council of Ministers. 222 p.

Anon 1995b. LCA-NORDIC, Technical Reports No 1 - 9. TemaNord 1995:502. Copenhagen. Nordic Council of Ministers. 120 p.

Anon 1995c. LCA-NORDIC, Technical Reports No 10 and Special Reports No 1 -2. TemaNord 1995:503. Copenhagen. Nordic Council of Ministers. 103 p.

Anon 1995d. Environmental data for building materials in the Nordic countries. TemaNord 1995:577. Copenhagen. Nordic Council of Ministers. 127 p.

Fossdal, S. 1995. Energi- og miljøregnskap for bygg. Fremstilling av beggematerialer. Regnskap for boliger og kontorbygg. Oslo; Norwegian Building Research Institute, Projektrapport 173. 161 p. (In Norwegian).

Häkkinen, T. & Ruohomäki, J. 1992. Rakennusmateriaalien ja tuotanto-prosessien ympäristö- ja terveysvaikutukset. Selvitys 1 - 1992. Helsinki; Ministry of Environment. 74 p (In Finnish).

Häkkinen, T. & Kronlöf, A. 1994. Rakennusmateriaalien ympäristö-vaikutuksien arviointi. Espoo; VTT tiedotteita 1591. 61 p. + app. 21 p. (In Finnish).

Häkkinen, T. 1994a. Environmental impact of building materials. Espoo; VTT Research notes 1590. Espoo. 38 p.

Häkkinen, T. 1994b. Environmental assessment of building materials. In: Sustainable Construction. Proc. of the first Int. Conf, of CIB TG 16, November 1994. Florida, USA; University of Florida. Pp. 213 - 222.

Kronlöf, A. 1994. Environmental loadings from transport and enery use. RTE5-IR-6/1994. VTT, Building technology. Report 6/1994. Espoo. 22 p. (not published)

Palomäki, Eero 1993. Rakennusmateriaalit ja terveys (Building materials and health). Helsinki; Työterveyslaitos, Rakennustieto Oy. 100 p. (In Finnish).

Vold, M. & Rønning, A. 1995. LCA of Cement and Concrete - Main report. Fredrikstad, Norway; Stiftelsen Østfoldforskning. 50 p.

DESCRIPTION OF THE VALUATION MODELS (Vold & Rønning 1995)

In the impact assessment stage, the environmental impacts of the product systems are assessed. This is done by classification, characterisation and valuation of the impacts.

In the classification step the different emissions and energy demand are assigned to different impact categories based on the expected type of impacts on the environment (i.e. resource depletion, human health impacts and ecological impacts). The main purpose of the activity is to describe which potential environmental effects the inputs and outputs may cause.

In the characterisation step the potential contributions from the different inputs and outputs are connected to the different impact categories, and the contributions to the same impact category are added up. Examples of environmental impacts that may be assessed are resource depletion, human health, global warming, acidification, depletion of stratospheric ozone, eutrophication, photo-oxidant formation and ecotoxic impacts.

In the valuation, the relative importance of different environmental impacts are weighed against each other and an index of the relative importance of the environmental impacts is calculated. The valuation is done by applying different valuation models. The goal for all models is to set a one-dimensional value on resource use and emissions in order to calculate the total environmental impact of a product. The relation between environmental loads, total indexes and the total impact of the product is given by:

$$\textit{Total Index (method)} = \Sigma\,(\textit{Load Index}_i\ \textit{(method)} \times \textit{Load}_i) \qquad (1)$$

In the following three methods of valuation are shortly introduced:
- Envirorunental Priority Strategies in product design - EPS
- The Ecological Scarcity Method - BUWAL
- The effect-category method - CML

The EPS Environmental Priority Strategies in product design
(Steen and Ryding 1992).

Two types of load indexes are calculated: a resource index and an emission index.

$$\textit{Resource index} = C \times B / A \qquad (2)$$

where:
A = world-wide per capita of finite natural resource
B = estimated resource irreplaceability factor
C = a scale factor to match the emission index.
It is not clear whether resources are defined as reserves or reserve base.

By this method, 5 safe guard objects are valued according to the willingness to pay to restore them to their normal status.

$$Emission\ index = \Sigma(F_1 \times F_2 \times F_3 \times F_4 \times F_5)_i \times F_6 \quad (3)$$

where:

F_1 factor which gives an image of society's evaluation of the environmental and health costs

F_2 factor which gives an image of intensity and frequency of occurrence of the problem

F_3 factor which describes the geographical distribution

F_4 factor which represents the durability of the problem

F_5 factor which shows how much 1 kg of the substance contributes to the problem

F_6 the average cost of reduction per kg pollutant by means of end-of-pipe as a measure of the possibility of immediate action against the problem.

The total impact is calculated as follows:

$$Total\ Index\ (EPS) = \Sigma\ [(Emission\ index_i \times Emission_i\ ) + \Sigma\ [(Resource\ index_i \times Resource_i\ ) \quad (4)$$

The Ecological Scarcity Method with Norwegian and Swedish data
BUWAL (Baumann, 1992)

The concept of ecological scarcity for product assessment was developed and introduced by BUWAL in Switzerland in 1990 (Ahbe, 1990), but is adapted to Norwegian and Swedish conditions.

In this method the emissions or use of resources by a system are multiplied by an index which expresses the difference between the annual load limits set by national environmental regulations and the actual flow of the system in a geographical area.

BUWAL model based on Swedish political targets has been developed. In the following table the Swedish targets for reduction of $C0_2$, SO_2, $N0_x$, Hg and use of fossil fuels are shown.

Swedish targets and the distance from targets for $C0_2$, SO_2, $N0_x$, *Hg and use of fossil fuels (Chalmers, Industriteknik, Tomas Rydberg)*

	National emissions/ resource use	**Targets for reduction**	**Reference for reduction**
$C0_2$	58,5 Mt./year (1992)	Not increased emissions	90 Mt/year
SO_2	103 000 t/year (1992)	65% reduction before 1995	483 000 t/year (1980)
$N0_x$	383 000 t/year (1992)	30% reduction before 1995	325 000 t/year (1980)
Hg	3.2 t/year (1988)	70% reduction	4.5 t/year (1985)
Fossil fuels	225 tWh (1993) (1993)	Not increased use	247 tWh (1985) 229 tWh (1989)

The environmental index is called ecofactor. Each product-specific emission *(Load$_i$)* is multiplied by its corresponding ecofactor (substance and area specific) as described in equation (1).

The value of the ecofactor, in unit ecopoints, is calculated according to equation (5).

$$Ecofactor = (Load_{i\ total} / Load_{i\ critical}) \times (1 / Load_{i\ critical}) \times K \quad (5)$$

where:

$Load_{i\ total}$ = the current total level of anthropogenic emission or deposition of substance i within a certain area.

$Load_{i\ critical}$ the critical load of a substance i defined for a certain area

K 10^6 to express the ecofactor in ecopoints g^{-1} if the emissions are given in 1000 kg units. .

Critical loads can be defined either as ecologically critical loads (sustainable loads) or as maximum politically acceptable limits (political targets). For the calculation of Swedish and Norwegian ecofactors, the aim has been to use ecologically critical loads. When these were not available, political targets were used. Values for total emissions were taken from official Swedish and Norwegian statistics.

The effect-category method - CML
(Baumann and Rydberg, 1994).

The method is based on a method developed by CML, at the university in Leiden together with the Dutch environmental authorities. In the Swedish adaptation of the method, which is applied in the Nordic project, the impact categories are valuated according to the Swedish environmental goals (1995).

In the method the environmental impact is calculated in three steps.

I. The environmental loads of the product are sorted into selected environmental themes. By using a measure of the relative equivalence of the pollutants, the impacts caused by the product are calculated per theme.
2. The sum of equivalent loads of a theme is divided by the corresponding total pollution relevant to the study, the geographical delimitation relevant to the study (e.g. a country) This calculation produces an Impact Fraction, indicating how much the product contributes per theme to the environmental problems of the geographical delimitation (6).
3. The impact fraction may be summarised in a total impact after applying weighing factors, which take into account the relative severity of the different environmental themes (7).

$$Impact\ Factor_i = (\Sigma\ Load_j \times Equivalency_{ij})/(\Sigma\ Load_{k,total} \times Equivalency_{ik}) \quad (6)$$

$$Total\ Index = \Sigma\ (Weight\ factor_i \times Impact\ Fraction_i) \quad (7)$$

Where

Impact Factor$_i$ =	product specific emissions, sorted into the theme i, divided by the total contribution to the same theme within the studied area
i	environmental theme, e.g. acidification, ozone depletion, etc.
Weight factor$_i$	weight factor of theme i
Load$_j$	emission of substance j from the studied system
Load$_{t\ total}$	total amount within system of pollutant k contributing to the environmental theme
Equivalency$_{ik}$	equivalency of substance k contributing to the theme i.

Environmental index is then calculated from equation (8):

$$Environmental\ index_j = \Sigma\ [\ (Weight\ factor_i \times Equivalency_{ik}) / (\Sigma Load_{k,total} \times Equivalency_{ik})\ ] \quad (8)$$

Reference

Vold, M. & Rønning, A. 1995. LCA of Cement and Concrete - Main report. Fredrikstad, Norway; Stiftelsen Østfoldforskning. 50 p.

VALUATION WEIGHTING FACTORS (Anon. 1995)

Emissions to air (per kg)	Eco-scarcity Swizer-land	Eco-scarcity Nether-lands	Eco-scarcity Norway	Eco-scarcity Sweden	Effect category, Short term	Effect-category, Long term	EPS
CO_2	36.0	6.00	44.6	15.9	11.0	36.0	0.0889
CH_4					233	766	0.978
N_2O			58800		3220	10600	7.02
SO_2	23000	32600	10000	5740	2420	3330	0.0992
NO_x	42300	9900	9190	4740	3950	3660	0.217
H_xC_x					3140	7540	
H-C (without CH4)	14300		9120	10500			
Ethene							0.982
CO					333	824	0.269
NH_3				29600			
HCl	42300		9190		2120	91.0	
HF			3300000				
CFC-11					4920000	3320000	303
HCFC-22					262000	218000	
CFC	4500000	∞	1610000	69800000			
Dichloro-methane					21100	14000	
BHT					102000	204000	
PAH			9800000				1660
Phenol					98400	197000	
Dust					36.0	42.0	0.00752
As							1390
Cd		$1600x10^6$	$47.9x10^6$	$781x10^6$			2500
Cr			$5.54x10^6$	$21.8x10^6$	472000		225
Cu			$6.37x10^6$	$5.92x10^6$	3150000		500
Hg			$802x10^6$	$1700x10^6$			1300
Ni			$200x10^6$	$44.3x10^6$	965000		250
Pb		$1.4x10^6$	$1.75x10^6$	$8.67x10^6$			50.1
Pb (aq)					374000	784000	
Zn		$20.0x10^6$	$0.292x10^6$	$1.39x10^6$			62.5
V				$26.5x10^6$			
Dioxin			$457x10^9$				

Emissions to water (per kg)	Eco-scarcity Swizer-land	Eco-scarcity Nether-lands	Eco-scarcity Norway	Eco-scarcity Sweden	Effect category, Short term	Effect-category, Long term	EPS
Tot-N			121000	29100	7180	3580	0.0800
Tot-P	756000	4200000	930000	621000	7180	2590	0.200
Nitrate (in N)	905	41400	121000				
Ammonium (in N)	10300		121000				
Chloride (Cl-)	26.2		26.2				
Sulphate (SO4)							
BOD				1280	400	320	0.00200
COD	3830		3830	400	400	320	0.00160
TOC					1200	606	
Susp. solids					36.0	42.0	
Oil					2560	102000	
Wastes (per kg)							
Ashes					36.0	42.0	
Waste products					36.0	42.0	
MFA					2020	2020	
Housing wastes	222	150		167			
Special wastes	20300		5000	33400			
Fossile gas							0.400
Oil							0.400
Coal							0.100
Energy resources (per MJ)							
Electric energy					2450	2630	
Fossile, oil					1340	1700	
Coal					161	327	
Gas					804	1340	
Primary energy	1000	400	1000				

Other resources (per kg)	Eco-scarcity Swizer-land	Eco-scarcity Nether-lands	Eco-scarcity Norway	Eco-scarcity Sweden	Effect-category, Short term	Effect-category, Long term	EPS
Ag							2190
Al							0.0893
Au							875000
Co							76.1
Cr							8.75
Cu							30.2
Fe							0.0875
Mn							0.972
Mo							1460
Ni							24.3
Pb							175
Pt							350000
Rh							1750000
Sn							1170
Ti							0.398
V							11.7
Zn							21.3
Land use (per m^2)	Eco-scarcity Swizer-land	Eco-scarcity Nether-land	Eco-scarcity Norway	Eco-scarcity Sweden	Effect-category, Short term	Effect-category, Long term	EPS
Forest area					4060	3780	
Road area					186	173	
Area for waste						3.00	
Arable land (hard making)							0.0871
Arable land (culti-vation)							0.00320
Grassland							0.00820
Forest area							0.00250
Other lands							0.00230

Reference

Anon 1995. Nordic Guidelines on Life-Cycle assessment. Nord 1995:20. Nordic Council of Ministers. 222 p.

INDIRECT ENVIRONMENTAL BURDENS OF PAVEMENTS

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CONTENTS

1 INTRODUCTION

This part of the LCA model project concerning asphalt/concrete pavements gives the background to the choice of figures for describing the indirect environmental effects of pavements. These effects are a vast and complicated subject and are often skipped in modelling. The questions are simple but the answers seldom direct or explicit. Gathering most reliable data has focused on understanding the problem and on generalisation of data derived from source material. For the LCA model, the ideal would be for the factors to be models themselves and for them to be chosen according to base elements like stone material properties, bitumen quality etc. It would then be possible to compare the situation in different countries with different pavement types. This was not possible, however, given the resources allocated to the project. The source and logic behind the figures are therefore described as openly as possible to facilitate comparison between countries.

Measurement figures of pavement characteristics merely show the prevailing situation at a given point and time. Furthermore, intensive development work in recent years has greatly altered the properties of pavements. During this project it became manifestly clear that the concepts "asphalt pavement" and "concrete pavement" are regrettably often understood to be permanent features, whereas nowadays their properties can in most cases be varied on demand.

The question is which properties are considered to be most important. For example, the unfavourable property of asphalt pavements in Finland, strong wear by studded tyres, has largely been solved by the development of both pavements and studs. Uneven movement of concrete pavement blocks is no longer a problem with modern concrete pavements. It is therefore wrong to make sweeping generalisations. We must accept the fact that pavements, methods of pavement construction and environmental effects are constantly changing. Concerning pavement properties, we only have cross-sectional information with respect to time and place. The following therefore gives the grounds for the figures chosen and **does not** constitute a research of these properties.

The reference road is the Tampere Ring Road in Finland, completed in 1994. Both the concrete and asphalt sections of the motorway are modern pavements. Because the road is new, very few measured data are available concerning the properties of the pavements.

2 FUEL CONSUMPTION

Fuel consumption and exhaust emissions from moving vehicles are the greatest individual components in indirect environmental effects of a highway. During the life cycle of a highway (in this case 50 years) with average annual daily traffic (AADT) of 20 000, the fuel consumption of a Finnish vehicle fleet on a highway section of one kilometre is about 27 000 tons. The corresponding carbon monoxide emission is 1 000 tons, hydrocarbons 200 tons, nitrogen oxides 800 tons. Even a small reduction in these figures means tons of harmless compounds less per kilometre. It also indicates the importance of being absolutely sure of the differences, since even a minor error in differences in the consumption data of an individual vehicle will cause an enormous cumulated error in the final life cycle results.

According to the literature much has been done to find the correlation between pavement properties and fuel consumption. Still there are not enough data to give exact figures for fuel consumption differences between asphalt and concrete pavements. The reason is that there are plenty of factors affecting fuel consumption, most of which have to do not with the pavement material itself but with the properties of the surface. Some aspects are listed below which show that a **fuel consumption difference other than zero cannot be used in this LCA model** when comparing **differences** between asphalt and concrete pavements.

1. The literature shows that the most important factor in fuel consumption affected by the road is the property of the road surface (unevenness). The properties of the surface in both asphalt and concrete pavements are very different depending on which desired properties are under consideration. The differences are greater within pavement types (asphalt, concrete) than between them.
2. The properties of the surface of an asphalt pavement vary greatly during the year in countries where studded tyres are in use. In spring the surface is very coarse and in autumn smoother. There are also differences between asphalt pavement types in this respect. Therefore it is impossible to specify a generalised exact figure for the surface type of an asphalt pavement. The roughness of a concrete pavement varies much less during the year.
3. An asphalt pavement is stiff during the frost season, its properties being much like those of a concrete pavement.
4. In field tests the results rarely show differences in fuel consumption between asphalt and concrete pavements. According to measurements done by VTT, fuel consumption on asphalt/concrete pavements varied crosswise depending on the speed used (Figure 1). The same result was obtained from car measurements (Kallio 1992).
5. For the sake of comparison, measurements on a snow-covered surface show that fuel consumption is 4% higher than on a bare surface (Anila 1994).
6. Rolling resistance is one component in factors affecting fuel consumption. The share of rolling resistance in fuel consumption factors varies between 30% and 50% at highway speeds. In many tests the rolling resistance when driving on a concrete pavement is smaller than on an asphalt pavement, which indicates smaller fuel consumption. Pavements have greatly developed during the last few years. The difference in rolling resistance has therefore also changed and we cannot say for sure whether it still prevails. Measures to increase friction on concrete pavements (like exposing aggregate) have led to the rolling resistance approaching that of asphalt pavements. The rolling resistance depends on the type of tyre, springing, damper, the wavelength of the road unevenness, stiffness of the pavement etc. These have different effects at different speeds so that even the figure's sign can change. Rolling resistance measurements at motorway speeds are difficult due to the wide deviation of results.
7. The roughness of the surface depends on the type of aggregate. Aggregate also affects many other features. Choosing it in accordance with friction properties or durability also changes the rolling resistance.

8. There is a much greater difference in rolling resistance between a new concrete pavement and a polished one than between a medium coarse asphalt and a concrete pavement (Ohlsson 1986). Increasing friction on a new concrete surface by exposing the aggregate also means increasing the rolling resistance. In Finland, studded tyres take care of roughening the old concrete surface.
9. The closer the friction properties of concrete are to those of asphalt, the closer are the rolling resistances.
10. Driving speed has a major impact on fuel consumption. If the surface type has even the slightest effect on driving speed, all the results achieved with respect to rolling resistance or fuel consumption are useless as they presuppose the driving speed as constant. No reliable data are available concerning speeds on different pavement types. Do people drive faster on concrete roads because of the lightness of the concrete surface or slower because of possible joints, or ...?
11. A study from 1980 in the USA showed that lorries had 20% greater fuel consumption on asphalt than on concrete pavements (Zaniewski 1983). Such a great difference is unique and supposedly requires circumstances at the test site that are not typical of asphalt pavements in normal circumstances (such as a soft pavement or subgrade material due to heat or some other factor). Exceptional circumstances are also suggested by results with light vehicles in the same study in which no such differences were observed. If differences in fuel consumption are found to be so great between asphalt and concrete pavements, the circumstances at the test site should be studied very carefully.
12. Even if differences in fuel consumption could be shown at one test site, the generalised model of fuel consumption dependence on pavement type (asphalt / concrete) would still be difficult for the reasons mentioned above.

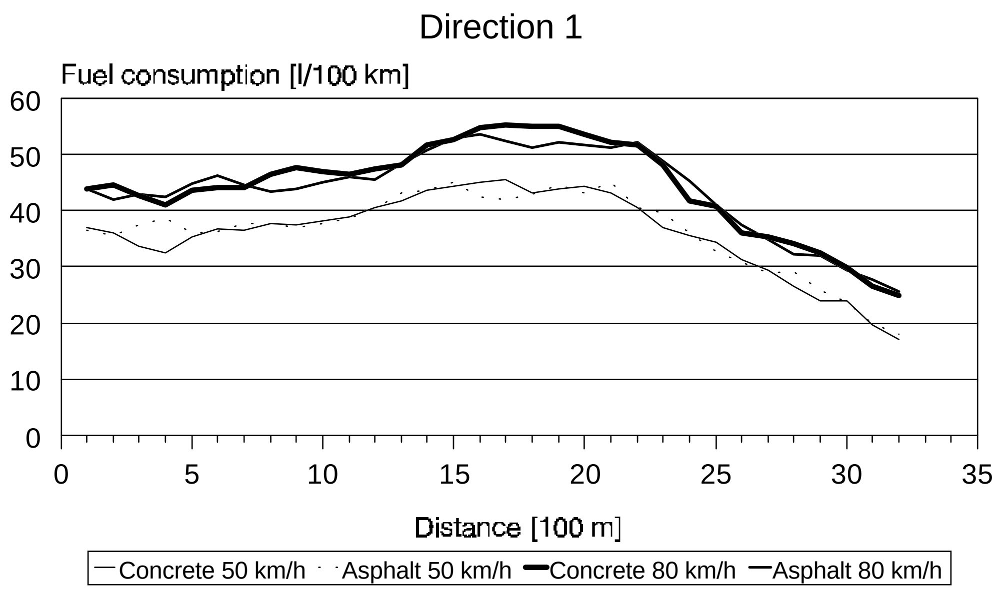


Figure 1. Example of the results of fuel consumption measurements with a lorry. Consumptions are average values over 100 m sections. The hump form of the curves is due to the road gradient (Kallio 1992).

To determine concretely what the fuel consumption difference might mean in the model, Table 1 shows a hypothetical calculation with a 1% difference. This shows that even a small difference in the fuel consumption of an individual vehicle means large amounts of fuel during the life cycle. **The calculation shown in Table 1 is not used as basic assumption, but the assumption is that the difference is zero**.

Table 2. Calculation example of the effects of a hypothetical 1% difference in fuel consumption between asphalt and concrete pavements on the Tampere reference road.

	AADT veh./d	Fuel consump. l/100 km/veh.	Difference %	Difference l/km	Time years	Total litres/km	Total tons/km
Light vehicles	18 000	8	1	0.0008	50	262 800	197
Heavy vehicles	2 000	25	1	0.0025	50	91 250	77
TOTAL	20 000					**354 050**	**274**

3 ABRASION

Asphalt pavements have generally been thought to wear faster than concrete pavements. This trend is indicated by almost all the researches done so far. An additional problem with asphalt is plastic deformation, which deepens ruts. Concrete pavements do not undergo plastic deformation. More recently, however, views have changed due to intensive research. Split mastic asphalt (SMA), in particular, has proved highly tolerant against wear by studded tyres. The type of aggregate is a dominant feature in the strength of an asphalt pavement. Traditionally aggregate for a concrete pavement has been chosen more carefully than for an asphalt pavement. Careful selection of aggregate and a new mix design have remarkably increased the strength of asphalt pavements. Still, concrete pavements are more tolerant to stud wear.

Pavements in Finland are worn mainly by the abrasive impact of studs in winter. The amount of abraded material was estimated to 338 000 tons in 1992 and is estimated to have decreased to about 171 000 tons during 1995 thanks to intensive development work on both pavements and studs (Karhula 1994). In Norway the corresponding abraded material is 250 000 tons per year (Myran 1994). In Finland an even greater dust problem arises from sanding and salting. Roughly 1.3 million tons are spread yearly on Finnish roads (Karhula 1994).

Table 2 shows wear figures measured over a 4-year period in Nurmijärvi, Finland. The figures are the results of profilometer measurements showing the shape of the pavement surface. They are expressed in area units (cm^2), the difference between measurements showing the material lost. Winter losses are due to studded tyres. The difference of 30 cm^2 in the asphalt pavement between spring and autumn 1992 (i.e. during summer) is most likely caused by deformation. The stone material exposed during the winter has again sunk into the mixture. The wear proportion shows how many times greater the asphalt wear is compared with that of concrete. The total wear of asphalt is 2.6 times that of concrete.

Table 2. Wear measurements in Nurmijärvi, Finland. Cumulative cross-sectional areas measured by profilometer on the right lane of the motorway. Differences show the material lost between measurements. (VTT)

Cumulative cross-sectional area [cm^2]							
Pavement type	Time of measurement						
	1991 autumn	1992 spring	1992 autumn	1993 spring	1994 spring	1995 spring	
Asph. (SMA)	50	107	137	173	207	251	
Concrete	40	58	68	91	96	116	
Asph. (SMA)	difference	57	30	36	34	44	
Concrete	difference	18	10	23	5	20	
Wear proportion asphalt / concrete		3.2	3.0	1.6	6.8	2.2	

According to Table 2 the average wear for asphalt on the right lane of the motorway is 42.8 cm^2 and for concrete 16.5 cm^2. Calculations for the total wear (Table 3) are based on the assumption that the left lane wears only 10% by comparison with the right lane. Finnish motorways are two-lane dual carriageways. The volume density used here for asphalt is 2.35 t/m^3 and for concrete 2.5 t/m^3. The asphalt pavement in Nurmijärvi had worn so much during the 4 years that it was necessary to repave it in summer 1995 because of rut depth.

Table 3. Average wear in Nurmijärvi. Two-lane dual carriageway, wear on the second lane 10% that of the first lane.

	Average wear cm^2/a	Wear $m^3/a/km$ motorway	Wear t/a/km m.way	Wear t/km/50 years
Asphalt (SMA)	42.8	9.46	22.2	1112
Concrete	16.5	3.63	9.1	454
Difference	26.3	5.83	13.1	658

The reference road in Tampere, Finland, has existed for only one year, which is why only measurements for one winter are available. Traffic situation is very much the same as in Nurmijärvi with AADT ca. 15 000 veh./d. In recent years tyre studs have became lighter, reducing wear to almost half that experienced with old stud models. Currently some 40% of cars are equipped with light studs. This change affects both asphalt and concrete pavements.

The stone material in Nurmijärvi is the same in both asphalt and concrete. It is tonalite, a diorite containing a lot of quartz. In Tampere it is fine-grained volcanic material in both pavement types. These stone materials are both very hard and their properties very similar (Table 4).

Table 4. Some measurement values (average) describing the properties of stone material used in aggregates in Nurmijärvi and Tampere.

Measurement	Nurmijärvi	Tampere
Los Angeles value [%]	17	8
Abrasion value [cm^3]	1.6	1.7
Point load index [MPa]	13	11
Shape index. elongation/flakiness	2.2/1.4	2.2/1.5
Dmax [mm]	18	18

Results of the measurements in Tampere are shown in Table 5. Unfortunately only 1 years worth of measurements are available. According to the table, asphalt has worn 1.4 times more than concrete. There are many reasons why the first year's results are unreliable. For example, first year wear depends on the surface conditions after paving. In this case the concrete was exposed-aggregate concrete, which may also affect first year wear. Weather conditions and winter maintenance may have different effects on different pavements.

Table 5. Profilometer measurement results during the first winter in Tampere. Two carriageways, wear on the second lane 10% that of the first lane.

	Wear cm^2/a	Wear m^3/a/km motorway	Wear t/a/km motorway	Wear t/km/50 years
Asphalt	31.5	6.9	16.3	814
Concrete	21.8	4.8	12.0	600
Difference	9.7	2.1	4.3	214

Taking into account the above mentioned results, we decided to use the average abrasion value of 20 tons/km/a for asphalt pavements and 10 tons/km/a for concrete pavements. For the entire life cycle this translates as 1 000 tons for asphalt and 500 tons for concrete.

4 NOISE

Concrete pavements normally produce more traffic noise than asphalt pavements, mainly due to the compact and even surface of the concrete. Measures producing a rougher surface also reduce noise.

It is possible to reduce traffic noise from concrete surfaces by choosing the right aggregate stone size and mix design. Here again the question is which properties are considered to be the most important. Noise is a special problem, for example in Austria, and much research is being done to produce more silent concrete surfaces. In the Nordic countries traffic noise has not been an issue in choosing the type of pavement. The problem is more complicated than elsewhere due to harsh winter conditions and the use of studded tyres.

The first traffic noise measurements from new surfaces on the Tampere reference road show clearly that in such circumstances the coast-by noise level (Lmax) difference between asphalt and concrete is about 2 dB(A) Table 6). Lmax noise levels correlate well with traffic noise levels. This 2 dB(A) difference is a typical value found in many studies of other roads with traditional pavements and with large aggregate (Hultqvist 1989). In Sweden equal decibel values for both asphalt and concrete has been measured (Hultqvist 1995). Concrete was exposed aggregate concrete which diminish noise. When comparing, much depends on which kind of asphalt is in comparison. After the first winter much of the advantage of exposing the aggregate is lost because of stud wear. 2 dB(A) difference is chosen as a basis for values used in the LCA model (Figure 2).

Table 6. Noise measurements with a test car on the Tampere reference road. Coast-by distance 7.5 m, measuring height 1.2 m. (VTT).

Noise level (peak) [dB(A) Lmax]

Pavement type	Coast-by speed [km/h]		
	60	80	100
Asphalt (SMA), direction 1	88.1	92.1	94.5
Concrete, direction 1	90.3	95.0	96.3
Concrete, direction 2	89.5	94.0	96.5

The noise measurement unit dB(A) is a complicated unit to use in LCA models. What does a difference value of 2 dB(A) between asphalt and concrete actually represent? The figure is expressed in logarithmic scale and cannot be used directly in the LCA model. A 2 dB(A) increase in noise level corresponds to e.g. a speed increase from 67 km/h to 80 km/h or a traffic flow increase from 20 000 AADT to 32 000 AADT.

The method used in this connection is based on land use effects. The higher the traffic noise the greater is the area around the road within the 55 dB(A) border value. Figure 2 shows the calculation method for determining the area difference between asphalt and concrete pavement noise levels. The 55 dB(A) distance has been calculated using the Nordic traffic noise calculation model (Sisäasiainministeriö 1981).

Base values for the calculation were: AADT 20 000 with 11% share of heavy traffic, calculation point height 2 m, embankment 1 m. As shown in Figure 2, the area under the 55 dB(A) noise level is 193 m on both sides of the road when driving at a speed of 80 km/h on an asphalt pavement and 252 m on a concrete pavement. The area inside 55 dB(A) is 38.6 hectares with an asphalt pavement and 50.4 hectares with a concrete pavement at a speed of 80 km/h. The difference is **12 hectares** per kilometre of road. The corresponding areas at a speed of 100 km/h are 51.8 and 69.6 hectares. The difference is **18 hectares**.

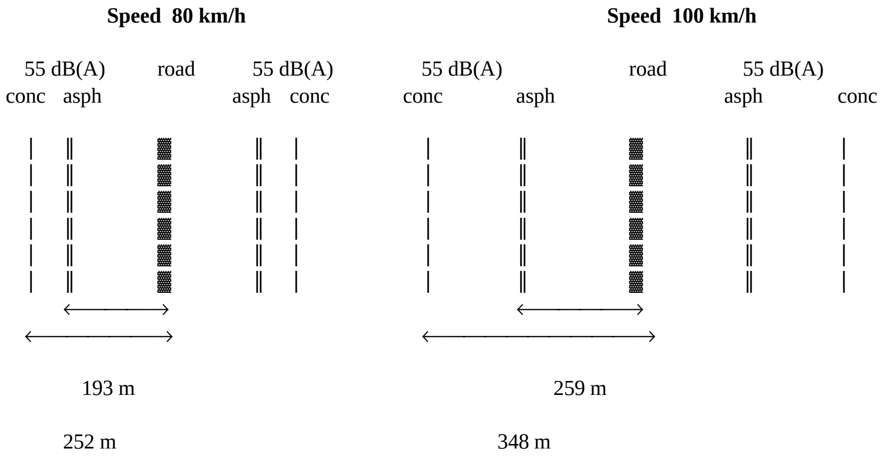


Figure 2. Method in noise area calculations.

Following the first winter and the use of studded tyres, the texture of the road surface on tracks had changed. No traffic noise measurements were made from these.

5 LIGHTING

Visibility on roads depends on the amount of natural light, road lighting, lights in vehicles, lightness of the pavement colour, contrast, road markings, weather, surface roughness etc. Which features are the most important depends on what kind of visibility we mean. Road markings, i.e. contrast, are important when trying to keep the vehicle on the road in bad weather. A light pavement is important for detecting pedestrians or animals on the road.

A light pavement colour is commonly considered a desirable feature. However, finding a figure for the LCA model that describes the difference in degree of lightness between asphalt and concrete pavements is not a simple task. With respect to night driving with headlamps, retroreflectivity is a main factor. Table 7 shows the results from a highway section in Finland very similar to that of the Tampere reference road.

Table 7. Results of retroreflection measurements on a highway section in Finland.

Type of pavement	Reflection mcd/lx/m^2
New asphalt	24
Old asphalt	32

New concrete	38
Old concrete	31

The table shows that new asphalt is very dark, i.e. reflects light poorly. This improves following winter and studded-tyre period. In contrast, concrete reflects headlamp light well when the pavement is new, and increasingly less so with time. Retroreflectivity values are the same for both types of pavements when they are old. Actually, if the concrete is very tight and the asphalt is porous, visibility is better on asphalt than on concrete in rainy weather at night. Rain at night makes for the worst possible driving conditions, and good visibility is essential for traffic safety. Retroreflectivity is, however, but one factor in the complexity of pavement lightness and luminance.

The situation is different in daylight or if the road is lighted. Then the lightness of the pavement, when measured as luminance, is a clear advantage. The problem is that there are no specific data on how light asphalt pavements in Finland actually are in practice.

According to Swedish results the luminance (Qd) of a concrete pavement depends 35% on the mortar and 65% on the aggregate. The luminance of a mortar is about 140 (mcd/m^2)/lux and that of aggregate around 90, resulting in a total luminance of about 105 (mcd/m^2)/lux. The luminance of an asphalt pavement (SMA) depends 20% on bitumen and 80% on aggregate. The luminance of old bitumen is about 50 (mcd/m^2)/lux and that of old aggregate ca. 90, resulting in a total luminance of about 80 (mcd/m^2)/lux. The luminance of an asphalt pavement depends far more on the lightness of the aggregate than that of a concrete pavement. If special attention is paid to the lightness of the aggregate, asphalt pavements can be made to be as light as normal concrete pavements. To date, however, this has not been considered of sufficient importance.

According to the CIE classification, Finnish asphalt pavements are of the R2 type (new asphalt is R4) and concrete pavements R1. No lightness statistics for Finnish SMA pavements are available.

When planning road lighting in Finland, the R classification is used. This was also the case with the Tampere reference road. **According to norms, the same luminance effect on the Tampere road is achieved with 150 W lamps on concrete sections as with 250 W lamps on asphalt sections. It should be noted that this plan was based on norms, not on measurements on site**. We therefore do not know the exact degree of lightness on the Tampere road.

Although the luminance situation is somewhat unclear, we used in the LCA model the following values derived from the calculations shown in Table 8:

Table 8. Calculation of the use of energy in lighting the Tampere reference road.

	Lighting time h/a	Lamp W	Lamps posts/km	Energy kWh/km/a	Time year	Total energy kWh/km
Asphalt	4 000	250	36	36 000	50	1 800 000
Concrete	4 000	150	36	21 600	50	1 080 000

Difference	**14 400**	**720 000**

6 DISTURBANCE OF TRAFFIC DURING ROAD-WORKS

Asphalt and concrete pavements differ in their need for maintenance and repaving. For an asphalt pavement (SMA) the Finnish maintenance strategy foresees six maintenance operations over a 50 year life cycle (the seventh when the pavement is 50 years old, but the time span is so long that it is not clear whether the road would then need a total renovation). A concrete pavement would be abraded twice during that time. These maintenance operations involve roadworks.

Roadworks disturb traffic, often increasing energy consumption. The amount of disturbance depends on the type of work, management of the work process, road conditions, traffic volume etc. Each workplace is organised differently.

Roadworks on Finnish motorways are arranged so as to cause minimum disturbances to traffic. The whole carriageway is seldom closed, traffic being diverted to an adjacent traffic lane. Traffic seldom needs to stop, flowing at a steady speed of 80 km/h. In advantageous circumstances fuel consumption is even lower than at speeds of 120 km/h.

Finland has no suitable data concerning traffic disturbances during roadworks. To demonstrate the order of magnitude of the amount of fuel consumed in such a situation, a hypothetical calculation is presented in Table 9. The calculation assumes that one fourth of the traffic is forced to stop and accelerate again. The results show that the fuel consumption difference between asphalt and concrete pavements is minimal compared with other energy consumption for maintenance during a life cycle of 50 years.

Table 9. Calculation of the fuel consumed by traffic during roadworks.

		Vehicles AADT veh./d	Vehicles disturbed veh./d	Consump. difference l/km	Road-works time d/km	Road-works number pcs/LC	LC time Years	Consump. total kg fuel
Asph	Light veh.	18 000	4 500	0.01	1	6	50	203
	Heavy veh.	2 000	500	0.2	1	6	50	507
	Total	20 000	5 000					**710**
Conc	Light veh.	18 000	4 500	0.01	1	2	50	68
	Heavy veh.	2 000	500	0.2	1	2	50	169
	Total	20 000	5 000					**237**

It has been suggested that traffic signs on the sides of asphalt pavements become dirty more quickly than those beside concrete pavements. This is due to bitumen particles abraded from the asphalt pavement. According to the road authorities in Tampere there is no clear difference between concrete and asphalt sections in this respect after one winter's experience.

Road salt (NaCl) used on the Tampere reference road in winter 1994/95 amounted to 264 tons, which means 30 tons per kilometre of road. This includes two carriageways and ramps. The road length is 9 km and total ramp length 15 km. Salt use was the same on both asphalt and concrete sections. Fine particles rising into the air and floating for some time are estimated to amount to 10% of the salt used.

REFERENCES

Anila M., Kallberg V.-P. 1994, Talvikelin vaikutus henkilöauton polttonesteen kulutukseen (The effect of icy and snowy road surface conditions on fuel consumption). Helsinki 1994. Finnish National Road Administration, FinnRA Internal Report 27/1994. 57 p.

Hultqvist et al., 1989. 70-talets betongvägar, Tillstånd och underhållskostnader. Nordiska Vägtekniska Förbundet, Svenska utskottet nr 34, Vägars konstruktion. 25 p.

Hultqvist B-Å, Carlsson, B. 1995. Betongväg på E6 vid Falkenberg. Byggnadsrapport för delen Heberg-Långås 1993. Linköping 1995. Väg- och transportforskningsinstitutet, VTI Meddelande 758. 47 p.

Kallio M. 1992, Polttonesteenkulutus betoni- ja asfalttipäällysteellä. (Fuel consumption on cement concrete and asphalt concrete road) Espoo 1992. Technical Research Centre of Finland, Road, Traffic and Geotechnical Laboratory, Contractor Report 72. 18 p.

Karhula M. 1994, Tieliikenteen, kunnossapidon ja nastojen vaikutus pölyyn ilmassa. Helsinki 1994. Finnish National Road Administration, FinnRA Internal Report 60/1994. 28 p.

Myran T., Hedalen T. 1994, Traffic air pollution. Trondheim 1994. SINTEF, Report STF36 A 94014. 2p.

Sisäasiainministeriö 1981. Tieliikennemelun laskentamalli (Model for calculation of road traffic noise). Helsinki 1981. Sisäasiainministeriö, Ympäristönsuojeluosaston julkaisu A 10/1981.

Ohlsson E. 1986, Inverkan på ett fordons rullmotstånd av vägens textur, ojämnhet och tvärfall. Linköping 1986. Statens väg- och trafikinstitut, VTI Meddelande 494. 27 p.

Zaniewski, J.P. 1983, Fuel consumption related to roadway characteristics. Washington 1983. Transportation Research Board, Transportation Research Record 901. Pp. 18 - 29.

VTT. Measurements made by VTT communities and Infrastructure, Finland.

MAINTENANCE STRATEGY A OF ASPHALT ROAD

Finnish recommendation

Measure	**Right lane**	**Left lane**	**Width**	**Volume of asphalt (t/km)**	**Energy * Gas (kg/km)**	**Energy * Heating oil (kg/km)**
0 ABK 170 kg/m^2 + SMA 120 kg/m^2	0 years	0 years	8.5	1445 + 1020	-	
1 M-I SMA 80 kg/m^2	7 years	7 years	8.5	680	1700	85
2 M-II SMA 15kg/m^2	16 years		4.0	60	2800	40
3 M-III	25 years		5.0	(-100)		150
4 M-IV SMA 15kg/m^2		27 years	4.0	60	2800	40
5 M-V SMA 100 kg/m^2	34 years		3.6	360 (-288)		144
6 M-VI	42 years	42 years	8.5	(-170)		255
7 M-VII SMA 80 kg/m^2	50 years	50 years	8.5	680	1700	85

* Excluding energy due to production of asphalt.

M-I = Facing by hot milling, new asphalt SMA 80 kg/m^2
M-II = Remixing (heating, milling, reuse, new asphalt 15 kg/m^2)
M-III = Fine milling (cold), transportation of milling crush, no new asphalt
M-IV = Remixing (heating, milling, reuse, new asphalt 15 kg/m^2)
M-V = Box milling (cold), transportation of milling crush, new asphalt 100 kg/m^2

- Measures at 50 years excluded.
- Asphalt waste is reused, not dealt with as waste.
- Environmental burdens due to transportation of asphalt waste are allocated to reuse of the material.
- All environmental burdens due to manufacturing of asphalt are allocated to the specific construction, not to reuse of material.

MAINTENANCE STRATEGY B OF ASPHALT ROAD

Strengthening according to Swedish recommendation (VÄG 94)

With reference to the Finnish recommendation (Appendix 1) the measure number 5 is substituted by

- SMA layer is milled away and
- substituted by:
  40 mm middle layer (ABK / AG) + 40 mm surface layer (SMA).

ENVIRONMENTAL BURDENS FROM CEMENT

Production of cement in Lappeenranta in 1995.

The data is received from Finncement (Stefan Lindfors).
The system includes:

- Extraction and transportation of energy raw materials
- Extraction of cement raw materials
- Transportation of cement raw materials to the cement factory
- Production of raw meal
- Burning of clinker
- Grinding of cement

Emissions	
CO_2	780 g/kg
NO_x	3.7 g/kg
SO_2	0.63 g/kg
CO	1.9 g/kg
HC	0.13 g/kg
VOC tot	0.91 g/kg
CH_4	0.75 g/kg
PAH	3.6×10^{-6} g/kg
Benzene	6.9×10^{-6} g/kg
Phenol	2.1×10^{-6} g/kg
Particulates	0.39 g/kg g/kg
N_2O	2.1×10^{-6} g/kg
Cr	7.8×10^{-6} g/kg
Pb	0.49×10^{-6} g/kg
Zn	0.18×10^{-6} g/kg
Hg	9.2×10^{-6} g/kg
Tl	0.25×10^{-6} g/kg
As	23×10^{-6} g/kg *
Cd	2.0×10^{-6} g/kg *
COD	0.00042 g/kg
N tot.	0.69×10^{-6} g/kg
Oil (aq)	0.00014 g/kg
Energy	
Fossile fuel	4.9 MJ/kg
Electricity	0.45 MJ/kg
Limestone use	1 200 g/kg

* Not measured in Lappeenranta. The value is based on measurement result in Parainen in 1993.

ENVIRONMENTAL BURDENS FROM BITUMEN

The data is received from Neste (Jouko Nikkonen).
Production process includes:
Production of raw oil
Transportation of raw oil
Refining
References:
Production of raw oil: Plastic Waste Management Institute Data
Transportation of raw oil: Neste Varustamo
Refining: Neste Refinery in Porvoo

The data concerning refining is from the year 1992.
The energy consumption consists of LH-values of energy raw materials.
The energy content of bitumen is 40 MJ/kg (LHV).
VOCs are not divided into CH_4 and other compounds.

Energy, MJ/kg	
Consumption of energy	6.0
Water, g/kg	
Consumption or raw water	370
Emissions into air, g/kg	
CO_2	330
SO_2	0.80
NO_x	2.9
CO	0.10
Particles	0.30
C_xH_y + VOC	2.0
Emissions into water, g/kg	
Oil	0.030
Nitrogen	0.0050
COD	0.10
Solid matter	0.060
Wastes, g/kg	
Wastes	1.9

ENVIRONMENTAL BURDENS FROM SYNTHETIC GUM USED FOR JOINT SEALS

Reference: Håkan Stripple, 1995. Livcykelanalys av avloppsrör får SIS miljömärkning - Förstudie. IVL Report L95/199.

Synthetic gum - EPDM	
Heating oil, diesel	21 MJ/kg
Coal	5.6 MJ/kg
Electricity	5 MJ/kg
SO_2	5.7 g/kg
NO_x	4 g/kg
CO_2	2300 g/kg
NMVOC	19 g/kg
PAH	0.00003 g/kg
Particulates	2.1 g/kg
N_2O	0.050 g/kg
CH_4	3.5 g/kg
CO	0.80 g/kg
COD (aq)	20 g/kg
N total	0.040 g/kg

Environmental burdens caused by joint seals with respect to 1 km of concrete pavement

	Joint Seals, g/kg or MJ/kg	**Pavement, kg/km or GJ/km**
Emissions		
CO_2	2 400	8 000
SO_2	5.9	20
NO_x	4.3	15
CO	0.84	2.8
VOC total	19	64
CH_4	3.5	12
PAH *		
Benzene *		
Heavy metals total *		
As		
Hg		
Cd		
Cr		
Pb		
N total	0.040	0.13
N_2O	0.050	0.17
COD	20	67
Particles	2.1	7.2
Problem wastes *		
Other wastes *		
By-product stones		
Energy		
Fossil fuel	27	91
Electricity	5.0	17
Inherent energy	*	

* Not included because lack of data.

ENVIRONMENTAL BURDENS FROM REINFORCING STEEL

Reference: Fossdal 1995

Production of reinforcement steel for the Norwegian market at Fundia Norsk Jernverk in Mo. Data from 1992, based on assumption of 100% Norwegian scrap iron.

PRODUCTION PROCESSES	**ENERGY CONSUMPTION**		**EMISSIONS**		
			CO_2	**SO_2**	**No_x**
	Electr.	Fossile fuel			
	MJ/kg	MJ/kg	g/kg	g/kg	g/kg
Transportation of scrap iron to Mo	0.040	0.58	45	0.22	0.64
Oil included in scrap	0.21	0.14	14	0.12	0.11
Steel oven	1.7		22		
Oxygenisation	0.11		2.0		
Consumption of electrodes		0.090	9.0		
Additives	0.23	0.67	72	0.12	0.070
Reffinery oven	0.11				
Casting	0.18				
Billet oven		1.00	80	0.29	0.10
Rolling mill	0.27				
Various	0.25				
Transportation to consumer	0.030	0.57	44	0.23	0.63
Total	3.1	3.1	290	0.98	1.6

ENVIRONMENTAL BURDENS FROM GRAVEL

Including
- Extraction and
- transportation.

	g/kg or MJ/kg
Emissions	
CO_2	1.7
SO_2	0.0018
NO_x	0.014
CO	0.0031
VOC total	0.0026
CH_4	0.0017
As	$0.037\text{x}10^{-6}$
Hg	$0.00056\text{x}10^{-6}$
Cd	$0.0055\text{x}10^{-6}$
Cr	$0.018\text{x}10^{-6}$
Pb	$0.37\text{x}10^{-6}$
Particles	0.0027
Problem wastes	0.0030
Energy	
Fossil fuel	0.024
Electricity	-
Inherent energy	-

ENVIRONMENTAL BURDENS FROM LIME STONE FILLER

Including
- Extraction,
- grinding and
- transportation.

	g/kg or MJ/kg
Emissions	
CO_2	7.9
SO_2	0.040
NO_x	0.031
CO	0.0075
VOC total	0.021
CH_4	0.020
As	0.042×10^{-6}
Hg	0.00063×10^{-6}
Cd	0.0063×10^{-6}
Cr	0.017×10^{-6}
Pb	0.42×10^{-6}
Particles	0.021
By-product and waste stones	1 000
Energy	
Fossil fuel	0.023
Electricity	0.22
Inherent energy	-

ENVIRONMENTAL BURDENS FROM CRUSHED AGGREGATES FOR ASPHALT

Including
- Quarrying and breaking,
- transportation of breaked rock,
- crushing and
- transportation of crushed materials.

	g/kg or MJ/kg
Emissions	
CO_2	2.0
SO_2	0.0065
NO_x	0.012
CO	0.0025
VOC total	0.0047
CH_4	0.0043
As	0.018×10^{-6}
Hg	0.00027×10^{-6}
Cd	0.0027×10^{-6}
Cr	0.0090×10^{-6}
Pb	0.18×10^{-6}
Particles	0.0019
Energy	
Fossil fuel	0.011
Electricity	0.041
Inherent energy	-

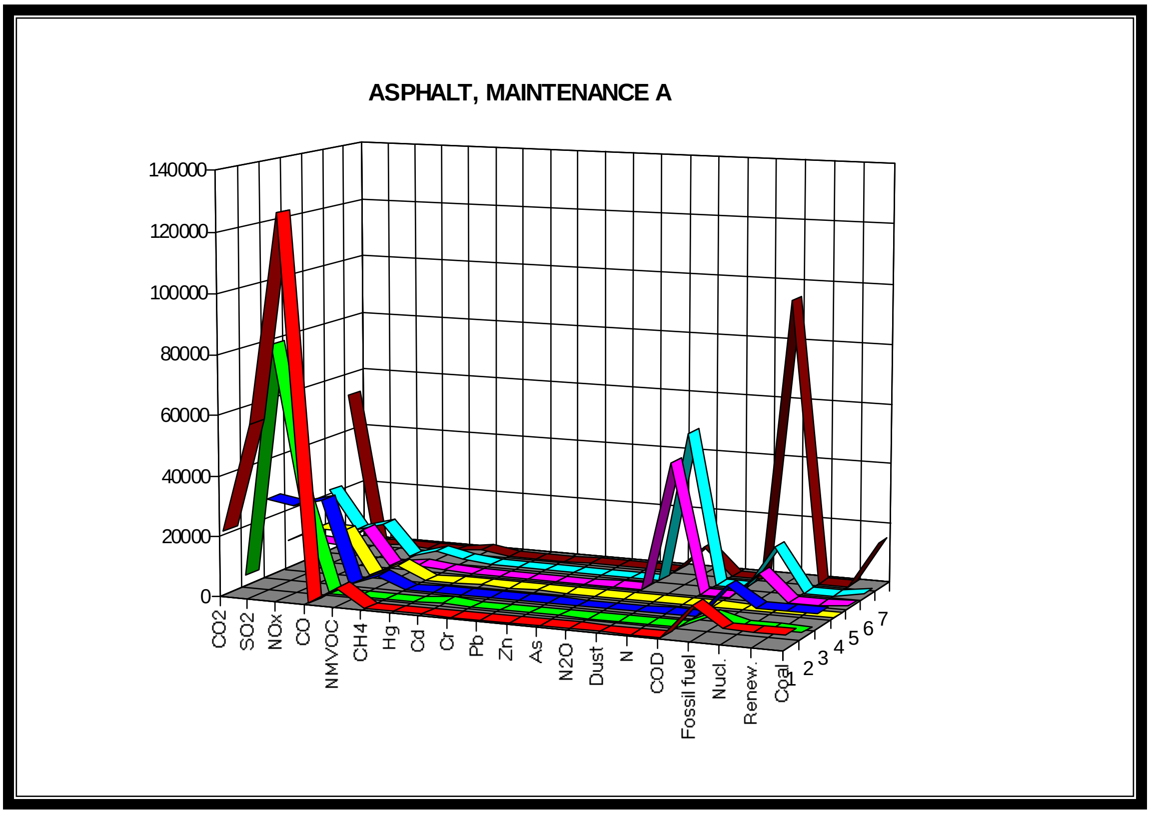
COMPOSITION OF SMA AND ABK ASPHALT

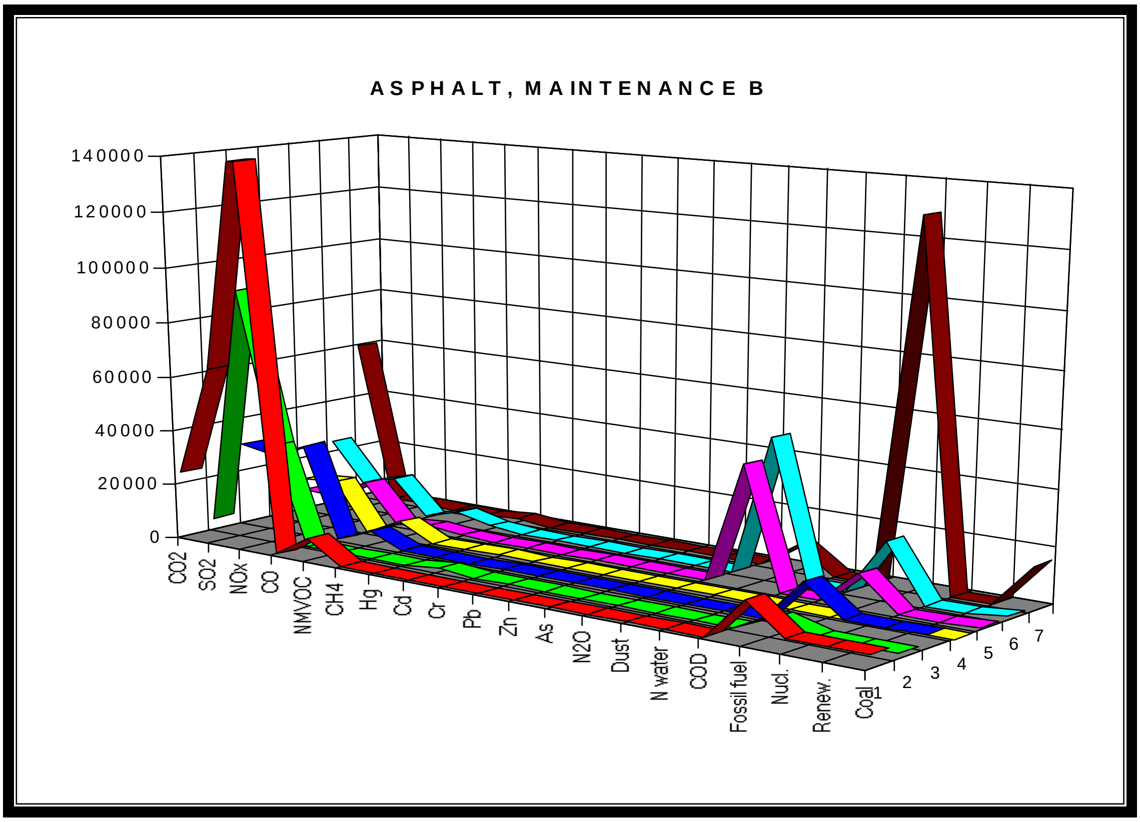
ABK	
Bitumen content	4.4%
Aggragate materials	95.6%
of which	
- Crushed materials	95%
- Sand	5%

SMA	
Bitumen content	6.2%
Cellulose fibres	0.3%
Aggragate materials	93,5%
of which	
- Crushed materials	95%
- Lime stone filler	5%

WEIGHTED PROPORTIONS OF SEPARATE COMPONENTS ACCORDING TO DIFFERENT VALUATION METHODS

Series 1 = Ecoscarcity method, Switzerland (BUWAL)
Series 2 = Ecoscarcity method, Netherland (BUWAL)
Series 3 = Ecoscarcity method, Norway (BUWAL)
Series 4 = Ecoscarcity method, Sweden (BUWAL)
Series 5 = Effect category method, Sweden, short term goals (CML)
Series 6 = Effect category method, Sweden, long terms goals
Series 7 = EPS system

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Zn
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Coal
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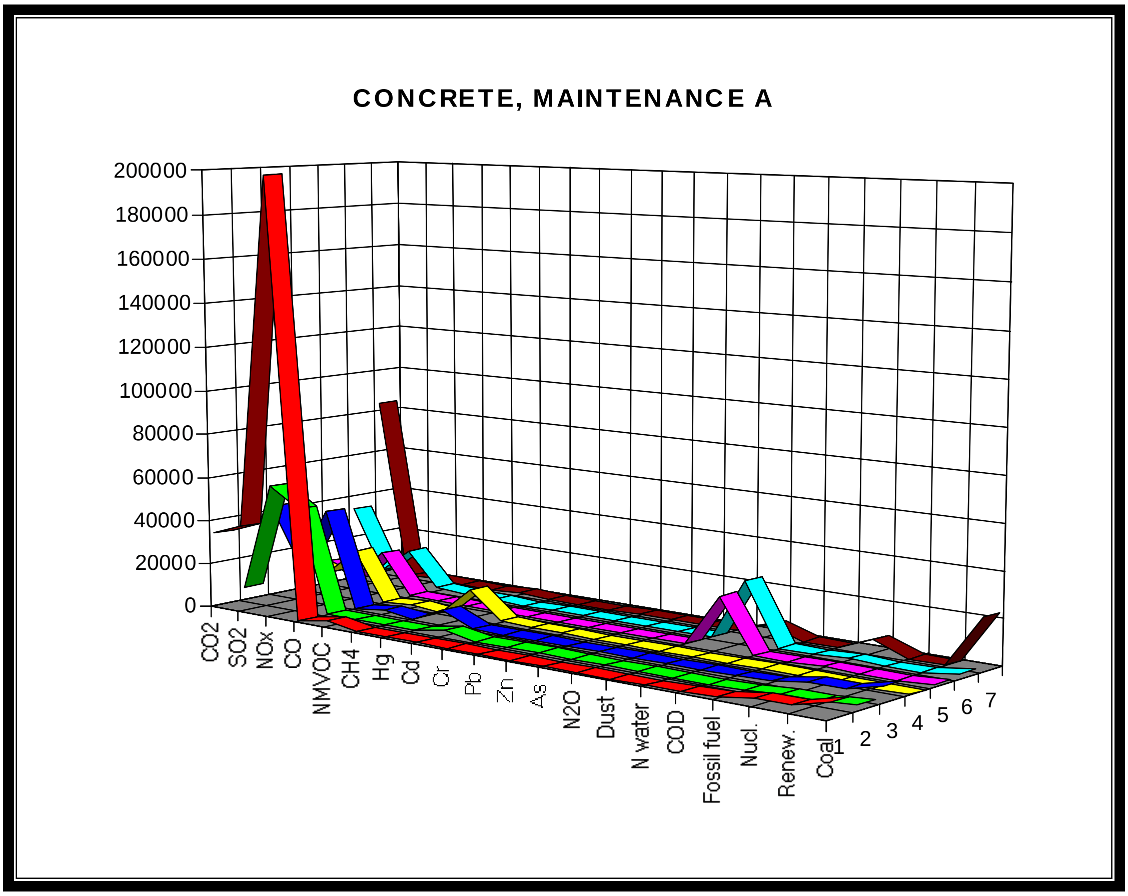
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CO
NMVOC
CH4
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Cd
Cr
Pb
Zn
As
N2O
Dust
N water
COD
Fossil fuel
Nucl.
Renew.
Coal
1
2
3
4
5
6
7