RESEARCH REPORT

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Pervious pavement testing methods. State-of-the-Art and laboratory and field guideline for performance assessment

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In the Finnish CLASS-project (Climate Adaptive Surfaces, 2012–14) new pervious surfacing materials and pervious pavement structures are developed to mitigate climate change associated with increased rain intensities and amounts. These pervious structures can decrease flooding for instance in cities with large areas of impervious surfaces. They can be a part of the overall stormwater system decreasing the need of conventional drainage systems.

This CLASS-project State-of-the-Art Report reviews the main testing methods and standards related to pervious pavements and the materials and products used in these pavements. Especially the methods for the hydraulic properties as hydraulic conductivity or water infiltration capacity are included. Methods used in the simulation and monitoring of the pervious structures are also included. Methods for pavement or material durability, especially freeze-thaw resistance, with and without salt, are also reviewed. Besides methods for the mechanical properties as material strength and pavement load carrying capacity, methods for material density, effective void content, workability, entrained air content and microstructure are included. Some information is included on the testing methods for geosynthetics, pipes and water storage and detention systems. Requirements, type testing, or quality control for subgrade, pavement test area, pavers, pervious concrete, porous asphalt, and plastic pipes are additionally reviewed at the end, to give some more knowledge on the quality assurance methods in use.

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Preface

This is a WP2 State-of-the-Art report in the Finnish CLASS-project (Climate Adaptive Surfaces, 2012–14). This project develops surfacing materials and pavement structures to mitigate impacts of climate change in urban environments. The new materials are surfacing layers of porous concrete, porous asphalt and interlocking modular paving stones together with subbase structures of aggregate, pipes, geotextiles and water storage tanks and other systems. The CLASS-project is funded by TEKES (Finnish Funding Agency for Technology and Innovation) together with VTT, Finnish cities, companies and organizations.

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All of the CLASS-project State-of-the-Art Reports were made to serve as the basis for the Finnish guidelines on the construction and maintenance of pervious pavements in Finnish environment.

Yhteenveto

Suomalaisessa CLASS projektissa (Climate Adaptive Surfaces, 2012–14) kehitetään uusia vettä läpäiseviä ympäristörakenteiden pinnoitteita sekä niihin oleellisesti liittyviä alusrakenteita, jotka ovat myös vettä läpäiseviä, ja toimivat ennen kaikkea myös vettä varastoivina kerroksina. Oleellista koko rakenteen toiminnan kannalta on se, että rakenteen kantavuus ja muut ominaisuudet ovat käyttökohteen asettamien vaatimusten mukaisia. Projektissa kiinnitetään erityisesti huomiota siihen, että tällaiset rakenteet soveltuisivat Suomen ilmasto- ja muihin olosuhteisiin. Kylmässä ilmastossa on otettava huomioon sekä routa että jäätymis-sulamissyklien vaikutukset. Sekä tämä että muut CLASS-projektin State-of-the-Art raportit palvelevat projektin Suomeen ja sen olosuhteisiin soveltuvan läpäisevien rakenteiden ohjeistuksen laadinnassa.

Tämä State-of-the-Art -raportti (nykytilakatsaus), joka on tehty CLASS-projektin WP2:ssa (Material and Product Development), sisältää tietoa testausmenetelmistä ja standardeista, joita käytetään tai voidaan käyttää läpäisevien rakenteiden sekä niissä käytettävien materiaalien tutkimuksessa ja testauksessa. Raportissa käsitellään myös läpäisevien rakenteiden simulointikokeissa ja pilot-tutkimuksissa käytettyjä menetelmiä. Säilyvyyden, kuten erityisesti pakkasenkestävyyden ja pakkas-suolakestävyyden menetelmiä tarkastellaan läpäisevien rakenteiden kannalta. Lisäksi raporttiin sisältyvät mekaanisten ominaisuuksien, kuten materiaalien lujuuden sekä rakenteen kantavuuden testausmenetelmät, kuten myös materiaalien tiheyden, efektiivisen (avoimen) huokoisuuden, työstettävyyden, ilmamäärän (suojahuokoset) ja mikrorakenteen tutkimusmenetelmät. Jossain määrin käsitellään myös geosynteettisten tuotteiden sekä putkien ja veden varastoinnissa ja viivytyksessä käytettävien tuotteiden testausmenetelmiä. Lopuksi esitetään täydentävää tietoa tyyppitestauksesta sekä laadunvalvonnasta ja -varmistuksesta eräiden materiaalien tai tuotteiden osalta (maaperä, läpäisevän rakenteen koealue, betoniset päällystekivet, läpäisevä betoni, avoin asfaltti ja muoviputket).

Contents

Abbreviations

AASHTO	American Association of State and Highway Transportation Officials
ACI	The American Concrete Institute
AOS	Apparent Opening Size
ASTM	American Society for Testing and Materials
AVA	Air Void Analyzer testing
CBR	California Bearing Ratio
CE	Conformité Européene
DRIT	Double-ring infiltration testing
ERT)	Electrical resistivity
FWD	Falling Weight Deflectometer (test)
FWGR	Flexible wall gradient ratio
GBR-B	Bituminous biosynthetic barrier
GBR-C	Clay biosynthetic barrier
GBR-P	Polymeric biosynthetic barrier
GSI	The Geosynthetic Institute
HC	Hydraulic conductivity
HCR	Hydraulic Conductivity Ratio
HMA	Hot mix asphalt
ICBP	Interlocking concrete block pavement
IGS	The International Geosynthetics Society
PA	Porous asphalt
PANK	The Finnish Pavement Technology Advisory Council (Päällystealan neuvottelu-kunta ry)
PAP	Porous asphalt pavement
PC	Pervious concrete
PCP	Pervious concrete pavement
PIBP	Permeable interlocking block pavement
PICP	Permeable interlocking concrete pavement
PNSP	Permeable natural stone pavement
PP	Pervious pavement
RDM	Relative dynamic modulus of elasticity
RTL	Repeated Load Triaxial (test)
SFS	Finnish Standards association SFS (Suomen Standardisoimisliitto SFS ry)
TEPPFA	The European Plastic Pipes and Fittings Association
TPPT	Finnish Road Structures Research Programme (Tien pohja- ja päällysrakenteet -tutkimusohjelma)
TSR	Tensile strength ratio
UPTT	Ultrasonic pulse transit time
VFB/A	Voids filled with binder/asphalt
VMA	Voids in mineral aggregate
VTM	Voids in total mix
VTT	Technical Research Centre of Finland

1. Introduction

Pervious pavements (PP) have normally a somewhat similar structure, consisting of a surface pavement layer, an underlying reservoir layer composed normally of stone aggregates, and usually also a filter layer or fabric installed on the bottom. Besides there are several modifications which can include for instance different kinds of pervious subbase materials, and also water collection pipes, tanks or other systems in connection with more or less impervious layers. PP materials and structures need to be selected and dimensioned for each case taking into consideration all local demands and circumstances.

PP can be defined as porous or permeable pavement based on the surface type, and it can be either monolithic or modular. Porous pavements are constructed with pervious material, such as pervious concrete and porous asphalt, where water can infiltrate through the entire surface area. However, for permeable pavements, the paver material is made out of impervious blocks while the spaces between the paver blocks are typically filled with coarse grained materials, normally stone aggregate, which allow water to pass through. [Ferguson 2005, Zhang 2006, Kuosa et al. 2013a]

There are also other paver options, such as concrete grid pavers and reinforced turf pavers. These solutions are not widely covered by this review. Open void fill media may be aggregate, topsoil and grass. These structures function in the same general manner as permeable pavement. [Kuosa et al. 2013a]

This report is based on literature information on the testing methods used in the previous pavement material development and testing, in the simulation of the hydrological behaviour of different pavement structures, and in the monitoring of pilot structures or structures in service. The emphasis is on the hydrological functioning of the materials and structures, but also several typical material specific testing methods are included, as methods for pervious concrete and porous asphalt material properties. European standardised or other standardised methods are included, and are preferred when available. For many pervious material and pavement studies there are no standardised methods available.

Besides this report there are separate CLASS-project State-of-the-Art Reports (VTT Research Reports; see References) on pervious pavement systems and materials, winter performance of pervious pavements, impact of pervious pavement on water quality as well as pervious pavement dimensioning and hydrological permeable pavement models and their parameter needs.

2. Hydraulic properties – materials and pavement

2.1 Void content, porosity, effective porosity, density

2.1.1 Aggregates

EN 1097-3:1998 (*Tests for mechanical and physical properties of aggregates Determination of loose bulk density and voids*) specifies the test procedure for the determination of the loose bulk density of dry aggregate and the calculation of the voids. This test is applicable to natural and artificial aggregates up to a maximum size of 63 mm. The dry mass of aggregates filling a specified container is determined by weighing and the corresponding loose bulk density is calculated. The percentage of voids is calculated from the loose bulk density and the particle density.

For particle density and water absorption there is European method EN 1097-6:2013 (*Tests for mechanical and physical properties of aggregates Determination of particle density and water absorption*). For Finnish aggregates water absorption (WA_{24}) is normally < 1%.

ASTM C29/C29M - 09 (*Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate*) covers the determination of bulk density ("unit weight") of aggregate in a compacted or loose condition, and calculated voids between particles in fine, coarse, or mixed aggregates based on the same determination. This test method is applicable to aggregates not exceeding 125 mm in nominal maximum size. [Ferguson 2005]

2.1.2 Pervious concrete

Density and void content of pervious concrete (PC) needs to be measured during the product development, and also in the production and quality control of PC. ASTM standard methods are available for these measurements. There are standards both for fresh and hardened pervious concrete void content and density.

ASTM C1688/C1688M: 2012 (*Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete*) provides a procedure for determining the density and void content of freshly mixed pervious concrete. The measured fresh density may be used as verification of mixture proportions. This method uses a standard consolidation procedure to measure fresh density and void content of a pervious concrete mixture as delivered. Test results are not intended to represent the density and void content of the in-place pervious concrete. This method is described by figures in Appendix A.

ASTM C1754/C1754M: 2012 (*Standard Test Method for Density and Void Content of Hardened Pervious Concrete*) provides a procedure for determining the density and void content of hardened PC specimens. It applies to either core specimens or moulded cylinders. There are two different drying methods to choose (A and B). Drying Method B is faster because it uses a much higher temperature than method A but specimens tested using drying method B shall not be used to determine other properties of the pervious concrete (e.g. strength or water infiltration). Drying method B may produce lower densities, and also shrinkage cracks, and correspondingly higher void contents than drying method A. Results from the two methods should be treated separately and not combined.

Lian & Zhuge (2010) measured the open porosity (at 28 day of age) as the percentage of pore volume or void space within PC. The sample was first oven dried at 110 °C and was left to cool for measurement. The dimensions of the sample were measured in dry condition and the total volume of sample (V_T) including the solid and void component was determined. Then the sample was sunk into a bucket filled with sufficient water to cover the whole sample and the water level was marked. After 24 h, the sample was moved out from the bucket and the water was refilled up to the marked level. The weight of water added was read by the scale and the magnitude of this reading was equal to the changed volume (V_C), using the concept of 1 g = 1 cm^3 for water. The open porosity of the concrete sample was calculated by Equation 1:

$$P(\%) = \left(\frac{V_T - V_C}{V_T} \right) 100\% \qquad (1)$$

Where P is the open porosity (%), V_T is the total volume of specimen (mm^3), "V_T - V_C" is the volume of void space (mm^3). [Lian & Zhuge 2010]

Sumanasooriya et al. (2009) determined the porosities of PC by using a volumetric method described in [Neithalath et al. 2006]. 200 mm long cylindrical specimens were trimmed to 150 mm length by cutting 25 mm thick sections from the top and bottom. The specimens were immersed in water for 24 h to saturate the pores in the paste phase. The saturated specimens were removed from water, allowed to drain, and enclosed in a latex membrane. The bottom of the specimen was firmly sealed onto a stainless steel plate and the mass of the system was accurately measured. Water was then added to the top of the specimen until all the larger pores were filled with water and the mass of the system was measured again.

The mass of the added amount of water was converted into a volume, which when represented as a ratio to the specimen volume, provided the porosity of the specimens. [Sumanasooriya et al. 2009]

Optical and image analysis methods can also be used to get information on the material porosity, and also to predict permeability (see Chapter 5 (*Optical microscopy)).*

Density and void content determined by different test methods may produce different numerical results, which may not be fully comparable.

Porous asphalt

The percent of air voids in a bituminous mixture is used as one of the criteria in the design methods, and for evaluation of the compaction imparted in bituminous paving projects.

According to European standard EN 13108-20:2005 (*Bituminous mixtures. Material specifications. Type testing*), the void content for porous asphalt (PA) is determined by testing, according to the below standards:

- EN 12697-8:2003 (*Determination of void characteristics of bituminous specimens*). This standard describes a procedure for calculating the percentage of air voids in a compacted bituminous specimen. The air voids content can be used as a mix-design criterion or as a parameter for evaluating the mixture after placing and compaction in the road.
- EN 12697-6:2003 (*Determination of bulk density of bituminous specimens*). This standard describes test methods for determining the bulk density of a compacted bituminous specimen. The test methods are intended for use with laboratory compacted specimens or specimens from the pavement after placement and compacting, either by coring or sawing. It describes four procedures. The choice of the procedure is dependent on the estimated content and accessibility of voids in the specimen. General (informative) guidance is given on the selection of the appropriate procedure.
- EN 12697-5:2009 (*Determination of the maximum density*). This standard specifies test methods for determining the maximum density of a bituminous mixture (voidless mass). It specifies a volumetric procedure, a hydrostatic procedure and a mathematical procedure. General guidance on selection of a test procedure to determine the maximum density of a bituminous mixture is also given.

ASTM D7063/D7063M: 2011 (*Standard Test Method for Effective Porosity and Effective Air Voids of Compacted Bituminous Paving Mixture Samples*) method covers the determination of effective porosity or effective air voids of compacted mixtures by the use of a vacuum sealing method. It can be used for compacted field and laboratory bituminous paving samples, as well as other compacted samples with well-defined geometrical shapes, such as concrete cylinders. The results of this test method can be used to determine the degree of interconnectivity of air voids within a sample and can be correlated to permeability of compacted bituminous paving mixture samples. In this method a compacted sample is vacuum sealed inside a plastic bag. The density of the sample, Sample 1, is calculated using a water displacement method, with the sample sealed. With the sample still in water, the bag is cut open. Since the sample is under vacuum and the air voids are evacuated, water will rush in to fill all the water accessible air voids in the compacted sample. With a known saturated weight of sample, an apparent maximum density, Sample 2, can be calculated. The difference between Sample 2 and Sample 1 is the measure of the amount of water that has penetrated the compacted sample. This difference can be used to determine the fraction of total number of voids that are accessible to water, i.e. the results obtained from this method can be used to determine the percentage of total air voids in a compacted sample that can be filled with water through the surface or interconnected paths within the sample. This method can be used for 100 mm and 150 mm diameter cylindrical samples and cubical samples.

2.2 Permeability, hydraulic conductivity, water infiltration capacity, water penetration coefficient

Permeability (m^2) is a measure of how well a porous media transmits a fluid. It has nothing to do with the fluid itself. The hydraulic conductivity (m/s) is a measure of how easily water moves through the porous media. It depends on the permeability of the matrix, but is also a function of the fluid. Sometimes ´hydraulic conductivity´ is called ´permeability´, in spite of the different meaning of these concepts.

Hydraulic conductivity, water infiltration capacity and water penetration coefficient can be measured by constant-head or falling-head type methods. Hydraulic conductivity is also dependent on the water content which must be considered in the testing. There are some standardised (e.g. EN/ASTM) laboratory and field testing methods for the testing. Besides several tailored methods have been used both in laboratory and field measurements of pervious materials and structures. For comparable results it is essential to do the measurements by the same methods whenever possible.

Figure 1 presents hydraulic conductivity determination methods (for soil/subground). Correlation methods, i.e. empirical approach, is based on the knowledge on the correlation between hydraulic conductivity and some essential material properties such as pore size distribution or grain size distribution. [Wikipedia 2104, Orazulukwe 2013]

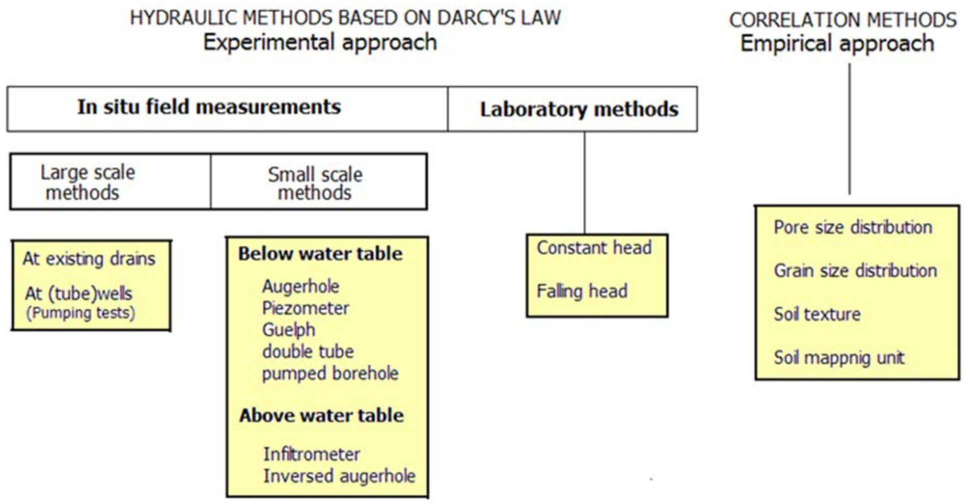


Figure 1. Hydraulic conductivity determination methods. [Wikipedia 2104]

Standardised (EN/ASTM) laboratory and field testing methods for pervious materials or pavements are:

- EN 12697-19: 2012. Bituminous mixtures – Test methods for hot mix asphalt. Permeability of specimen. (Figure 2)
- EN 12697-40: 2012: 2005. Bituminous Mixtures – Test methods for hot mix asphalt – Part 40: in situ drainability. (Figure 3)
- ASTM C1701/C1701M-09. Standard test method for infiltration rate of in place pervious concrete. (see Appendix A). (Figure 4a)
- ASTM C1781/C1781M-13. Standard test method for surface infiltration rate of permeable unit pavement systems. (Figure 4b)
- ASTM D 3385: 2009. Test method for infiltration rate of soils in field using double-ring infiltrometers. (Figure 5)

Below is some information on the above testing methods for pervious materials and structures, and additionally on some other methods.

EN 12697-19 (*Bituminous mixtures – Test methods for hot mix asphalt. Permeability of specimen*) is a laboratory testing method, which requires a cored sample or a laboratory sample of a certain size. This standard is suitable for pervious specimens having interconnecting voids. Permeability can be measured either horizontally or vertically, and the immeasurable side is sealed with a rubber cuff or paraffin wax. The water pressure above the measured specimen is constant. (Figure 2)

There is also PANK-method PANK-4212 (*Vedenläpäisevyys. Permeability to water (in Finnish)*) but it is meant for denser asphalts; permeability k range is <10^{-5} m/s. This test is carried out in a triaxial cell, which has adjusted rear and cell pressures for getting a sufficient, even pressure gradient to get the water flow vertically through the dense specimen.

Both EN 12697-19 method and PANK-4212 are based on measuring the amount of water flowing through the specimen in a known time period. Permeability (m/s) is calculated according to Darcy´s law. Usually permeability of porous asphalts measured according to EN 12697-19 is 0.5 - 3.5 × 10^{-3} m/s.

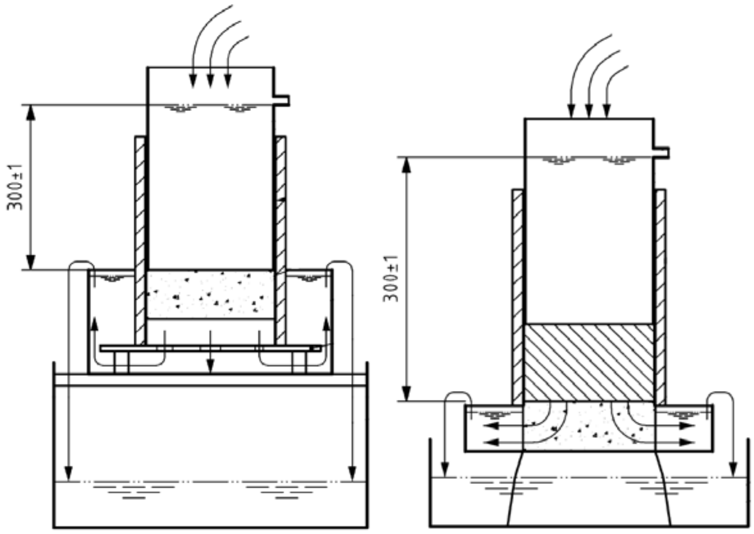
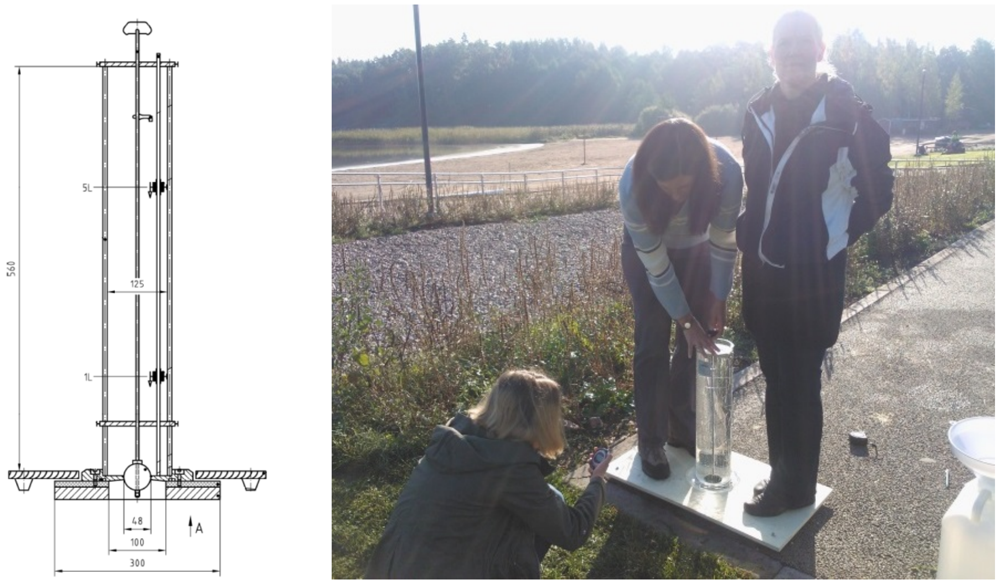


Figure 2. Permeability testing of specimen according to EN 12697-19. a) vertical permeability; b) horizontal permeability.

Methods EN 12697-40, ASTM C1701/C1701M-09, ASTM C1781/C1781M-13 and ASTM D3385-09 D are for measuring water infiltration on site without breaking the surface.

When permeability is measured according to the EN 12697-40 in situ method, it is a combination of vertical and also some horizontal permeability (Figure 3). A known amount of water in the vertical cylinder flows through the hole in the bottom of the measuring device, and outflow time is measured. The water pressure in the cylinder is changing, i.e. it is a falling-head method. The results by this method are not fully or directly comparable with the constant head method results (e.g. EN 12697-19). It is a method to determine the in situ relative hydraulic conductivity of a road surfacing that is designed to be permeable. Relative hydraulic conductivity (HC) is calculated based on the measured outflow time. An estimate of the average value for the surfacing is obtained from the mean value of a number of determinations on each section of road. This method is suitable as a compliance check to ensure that a permeable surface course has the required properties when it is laid. The test can also be used subsequently to establish the change of drainage ability with time. For the test to be valid, the surface of the test area should be clean and free from debris. Measurements can be made when a road is either wet or dry, but normally not if it is in a frozen state.



a) b)

Figure 3. a) Permeability testing device EN 12697-40; b) Measuring at the field.

ASTM C1701 method (see Appendix A and Figure 4a) is for the determination of the field water infiltration rate of in place pervious concrete. This method was modified to be ASTM C1781 (Figure 4b). It covers the determination of the field surface infiltration rate of in place permeable unit pavement systems surfaced with solid interlocking concrete paving units, concrete grid paving units, or clay paving brick. This standard includes instructions for the placing of the ring over the surface of the pavement so that the drainage voids framed within the infiltration ring are representative of the entire paving pattern. In the most accurate method the procedure includes the normalization of the drainage area within the infiltration ring to the average drainage area of the pavement as a whole.

a) b)

Figure 4. a) Determination of water infiltration rate: a) of pervious concrete (at VTT laboratory); b) of in place permeable unit pavement systems surfaced with solid interlocking concrete paving units [Smith 2014].

ASTM D3385 (2009) Double-ring infiltrometer is a field measuring device for in situ soils (Figure 5). It is also suitable for some porous and pervious materials, especially with some modifications (see Figure 6). The sealing method and the materials used for the sealing are essential. The results by the ASTM D3385 method are most reliable in range between about 10^{-5} and 10^{-9} m/s. In some cases pervious materials, as for instance pervious concrete, are too pervious to be measured by this method. The device has two bottom opened cylinders inside others (e.g. with diameters 300 and 600 mm). The purpose of the outer ring is to promote one dimensional, vertical flow beneath the inner ring. The cylinders are filled with water at a constant level. Water infiltrates to the soil/bottom and additional water is continuously supplied to maintain the level height. The volume of the added water is measured in a regular time interval (cm^3/h). There are alternative water supply and measure devices: manual adding and measuring, graduated cylinder with flow-control valve, or Mariotte tube (Figure 5). When water is added manually, the hook or point gages help to monitor the water level. A graduated cylinder or Mariotte tube adjusts the water flow through valves. A plot of the incremental infiltration rate (m/s) versus total elapsed time is created.

The corresponding DIN-standard for the infiltration rate by double-ring infiltrometer is DIN 19682-7 (2007) (*Soil quality. Field tests. Determination of infiltration rate by double ring infiltrometer*).

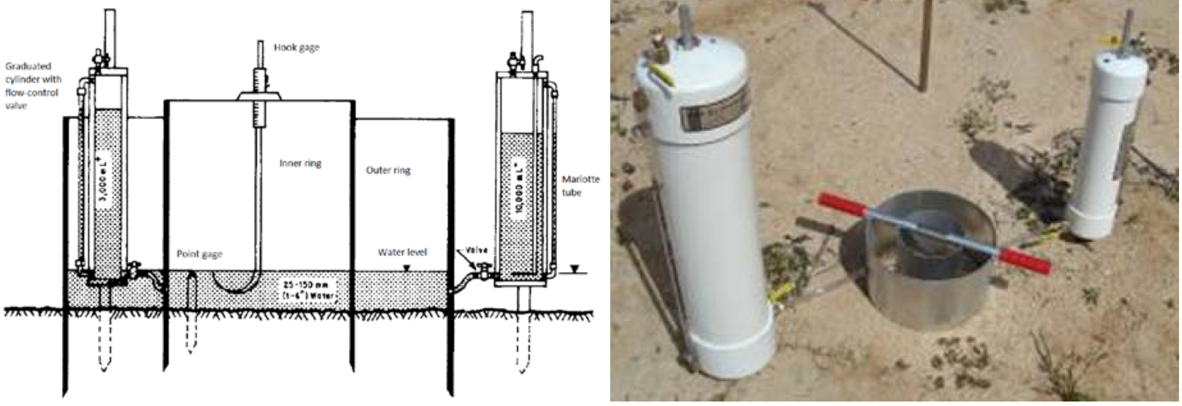


Figure 5. A Double-ring infiltrometer. [ASTM D3385-09, Turf Tech International 2013]

Figure 6 shows a double-ring infiltrometer set up which was used by Beeldens et al. (2009). The dimensions of the rings are different from the ASTM D3385 method for in situ soil. This system includes also sealing of the rings on the pavement surface. Sealing is a critical phase in the measurement as no leakage is allowed. The measurements by Beeldens et al. (2009) were made after the PICP structure was built, and were repeated over time, to reveal changes in permeability. [Beeldens et al. 2009]

Figure 6. A Double-ring infiltrometer for the measurement of PICP. [Beeldens et al. 2009]

DIN 19682-8: 2012 (*Soil quality – Field tests – Part 8: Determination of the hydraulic conductivity by auger hole method*) method is an in situ method for the measurement of the soil hydraulic conductivity (horizontal). When the water table is shallow, the augerhole method can be used for determining the hydraulic conductivity below the water table. The method uses the following steps:

- an augerhole is perforated into the soil to below the water table,
- water is bailed out from the augerhole,
- the rate of rise of the water level in the hole is recorded, and

- the K-value is calculated from the data; K-value is the horizontal saturated hydraulic conductivity (m/day or mm/s).

ASTM D5084: 2010 (*Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*) methods apply to one-dimensional, laminar flow of water within porous materials such as soil and rock. The hydraulic conductivity of porous materials generally decreases with an increasing amount of air in the pores of the material. These test methods apply to water-saturated porous materials containing virtually no air.

ASTM D2434: 2006 (*Standard Test Method for Permeability of Granular Soils (Constant Head))* covers the determination of the coefficient of permeability by a constant-head method for the laminar flow of water through granular soils.

Yang & Jiang (2003) used a simple falling head method to measure ´water penetration coefficient´ (m/s) (Figure 7). The device size is 100×100×300 mm^3. The surface of the sample was air-proofed with wax before measuring. The device was put on the sample. The warm wax was used to air-proof the space between the device and sample. After the wax became cold and hard, water was injected into the device. When the water line reached 200 mm, the injection of water was stopped. When the water line decreased to 160 mm, the timer was started. When the water line reached 140 mm, the timer was stopped. The water penetration coefficient (V) was calculated by Equation 2.

$$V = \frac{H}{t} \tag{2}$$

where:
V is the water penetration coefficient (m/s),
H is the height of the water line from 160 to 140 mm (20 mm), and
t is the time (s) when the water line fell from 160 to 140 mm.

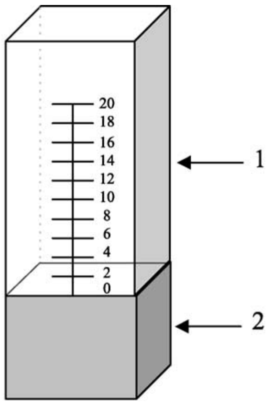
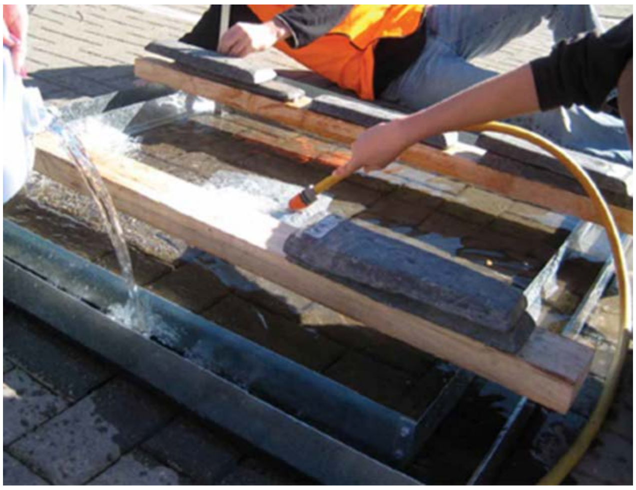


Figure 7. Water penetration coefficient measuring sketch (1 = device, 2 = specimen). [Yang & Jiang 2003]

Haider et al. (2008] measured the permeability of the pavements by a simple tube method (´Becker’s tube´). In this method a transparent tube with a diameter of 140 mm is placed on the road, and the joint is sealed with putty. (Figure 8) A measurement is done by filling the tube with water and registering how long it takes 100 mm of water to drain down into the pavement. When the run out time was over 75 seconds the measurement was stopped and the pavement was considered clogged. The measurements are repeated three times at points close to each other. The result is the average of the three measurements. The permeability has been measured some days before each cleaning procedure and again some days after the cleaning procedure.

Figure 8. Becker's tube which is used for measuring the permeability of porous pavements. [Haider et al. 2008]

Lucke & Beecham (2011) used in their field studies for the effect of clogging a specially constructed double-ring infiltration testing (DRIT) apparatus (Figure 9). This method of infiltration testing was also used successfully in previous research studies [Beecham et al. 2009, Pezzaniti et al. 2009]. In some cases the infiltration rate was too high and it was not possible to use the DRIT to record the infiltration rate. In these three locations, a different *inundation method* was utilized to record the infiltration rate. In this method, a section of 300 mm diameter pipe was sealed against the pavement, and the infiltration time of a known volume of water completely through the pavers was determined.

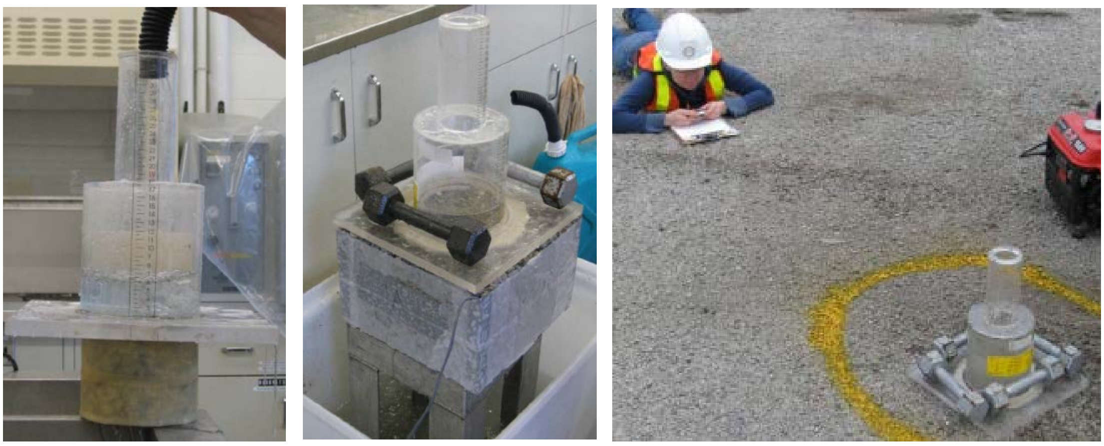


Test location	Infiltration rate (mm/h)	Infiltration rate (l/s/ha)	Joint sediment accumulation condition
1	97	269	MB
2	10	28	FB
3[b]	11 100	30 830	UB
4[a]	293	814	MB
5	182	506	MB
6	19	53	FB
7[b]	8 820	24 500	UB
8[a]	10	28	FB
9	88	244	MB
10	6	17	FB
11[b]	13 230	36 750	UB
12[a]	972	2700	UB

Notes: [a] = Location selected for excavation and investigation.
[b] = Inundation method used to test the infiltration rate.
FB = fully blocked; MB = medium blocked; UB = unblocked.

Figure 9. a) Double-ring infiltration testing apparatus in a study by Lucke & Beecham (2011), and the test results.

´A Gilson Permeameter´ is a tool from the Gilson Company Inc. The permeameter is sealed to the pervious concrete surface. This is done by applying a thick (approximately 25 mm) ring of plumber's putty to the bottom of the permeameter. The permeameter is then placed on the surface and pushed into the surface to move the putty into the pervious concrete voids around the edge. By sealing the permeameter to the surface the water is then forced to enter the pervious concrete during testing and not drain along the surface. After sealing the permeameter to the surface, four weights are placed along the base to ensure that leaks do not develop due to the pressure of the water if the permeability rate is low. (Figure 10) [Henderson 2012]



a) b) c)

Figure 10. A Gilson Permeameter tool in use for the water permeability testing: a) a cylinder (core) in the laboratory; b) a slab in the laboratory; c) field testing. [Henderson 2012]

ASTM D5084-10 (*Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*) is a laboratory method for measuring the hydraulic conductivity of water saturated materials such as soil and rock. There are six alternate methods or hydraulic systems that may be used. The correlation between results obtained using these test methods and the hydraulic conductivities of in-place field materials has not been fully investigated. Experience has sometimes shown that hydraulic conductivities measured on small test specimens are not necessarily the same as larger-scale values. Therefore, the results should be applied to field situations with caution and by qualified personnel. [Ferguson 2005]

ASTM D2434-68 (2006) (*Standard Test Method for Permeability of Granular Soils (Constant Head)*) covers the determination of the coefficient of permeability by a constant-head method for the laminar flow of water through granular soils. The procedure is to establish representative values of the coefficient of permeability of granular soils that may occur in natural deposits as placed in embankments, or when used as base courses under pavements. In order to limit consolidation influences during testing, this procedure is limited to disturbed granular soils containing not more than 10% soil passing the 75 µm sieve.

ASTM D5101-12 (*Standard Test Method for Measuring the Filtration Compatibility of Soil-Geotextile Systems*) is recommended for the evaluation of the performance of water-saturated soil-geotextile systems under unidirectional flow conditions. See also Chapter 8.1 (*Geosynthetics*).

It is also possible to get an estimation on hydraulic conductivity by using methods which are based on the known aggregate properties. Chapuis (2004) predicted saturated hydraulic conductivity of clean sand and gravel by using effective diameter (d_{10}, mm) and void ratio (e). Using the values of d_{10} and e, his equation predicted a k value usually between 0.5 and 2.0 times the measured k value for the considered data. There are also other (older, more traditional) equations for the hydraulic conductivity prediction. [Chapuis 2004]

2.3 Simulation and monitoring

Simulation of pervious pavement hydraulic properties can be done by using mock-ups or rigs, including all the structural layers. Also test areas can be built including special short and long term monitoring and long term follow-up and measurements of the hydraulic behaviour of the pavement. Monitoring can also be included in real construction projects, especially in pilot projects. Examples of the methods used in the simulation and monitoring of pervious pavements are presented here. Kuosa et al. (2013) includes also several examples of long term monitoring of pervious pavement hydraulic properties, especially as examples of the effect of surface clogging and maintenance actions. Studies related to winter performance simulation and monitoring are included in [Kuosa et al. 2013b]

James & von Langsdorff (2003) present information from Wilson (2002) who studied a pavement in the special apparatus depicted in Figure 11. Parking lot particulates (1.4–3.9 kg/m^2) were applied to a permeable concrete block paving stone pavement, and subject to intense rain. It was found that the quantities of sediment that can be applied without causing a decline in performance of the pavers is determined by the porosity of the drainage cell fill material. [James & von Langsdorff 2003]

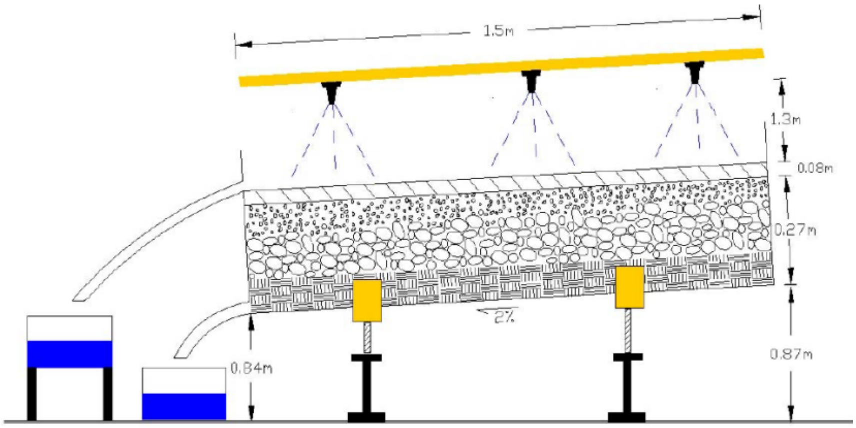


Figure 11. Experimental apparatus used for particulate rate clogging studies. [James & von Langsdorff 2003]

Sañudo-Fontaneda et al. (2013) studied the infiltration behaviour of PICP during their operational life in a car park using an improved version of the Cantabrian Fixed (CF) Infiltrometer. The CF Infiltrometer is a laboratory device that allows testing of any kind of permeable pavement surface using 0.25 m^2 test specimens under rainfall intensities in the range of 0.01–0.15 m/h (10–150 mm/h) for any storm duration and slopes between 0 and 10%. The laboratory device (Figure 12) simulated direct rainfall and runoff from adjacent impervious areas over an PICP surface of 0.25 m^2 for different slopes (0, 3, 5, 7 and 10%) and three scenarios of clogging (surface newly built, surface clogged and surface clogged with maintenance). In this research the aim was to develop three regression models (each one corresponding to the three different clogging levels chosen for the study) based on the topographic variables such as runoff surface length and surface slope. [Sañudo-Fontaneda et al. 2013]

For clogging Sañudo-Fontaneda et al. (2013) used limestone silt with 14% of organic matter with the size distribution shown in Figure 13. Sawdust was employed to simulate the organic matter and replaced limestone silt in the particle size diameter ranges of 250–500 μm and <80 μm. The average amount of sediments used to clog the treated surface was 3900 g/m^2, lower than the 4000 g/m^2 used by Castro et al. (2007) with the same surface type and particle size distribution of the sediments. This fact was explained by the higher percentage of organic matter used, which has less density than the limestone silt sediments.

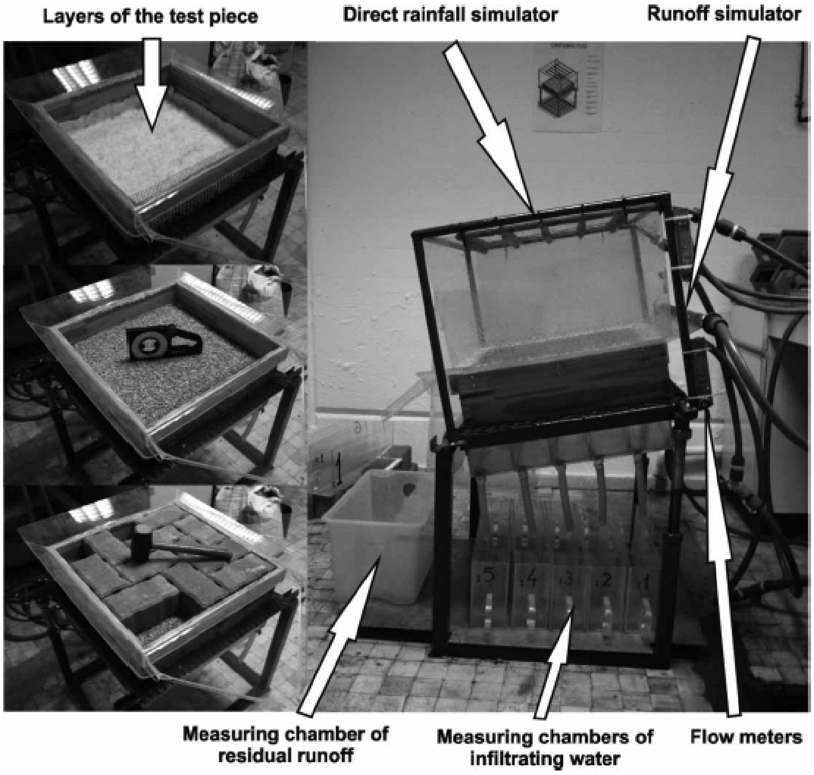


Figure 12. Scheme of the improved CF Infiltrometer of the University of Cantabria with the layers of the test piece. [Sañudo-Fontaneda et al. 2013]

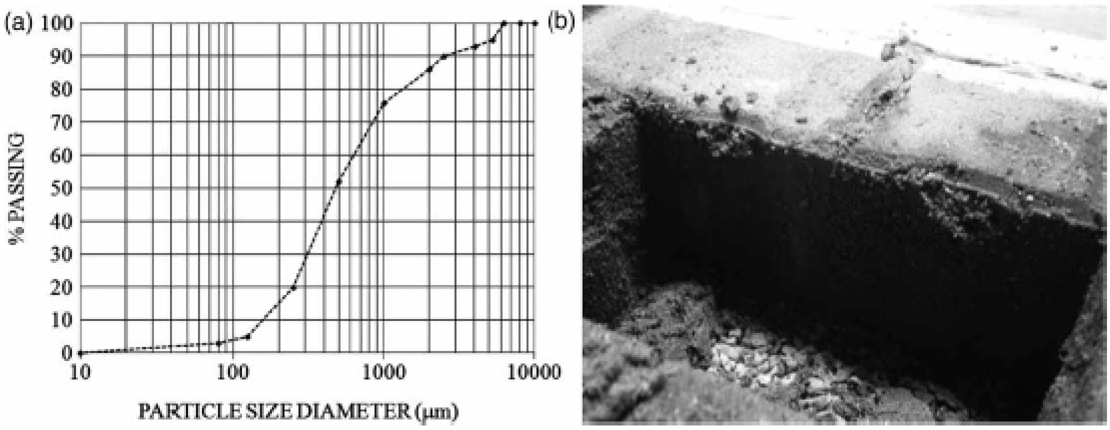


Figure 13. a) Particle size diameter distribution of the sediments used to clog the pavement surface; b) Sediments clogging the slots between blocks in the clogged surface scenario. [Sañudo-Fontaneda et al. 2013]

A major database of runoff and infiltration performance was generated by James & von Langsdorff (2003) within an extensive lab scale test series. Rig-testing was used for this purpose (Figure 14). The variables in these testing were:

- type of pervious pavement,
- pavement constructions, including pavers, bedding and base layers,
- precipitation impacts (sprinkling system),
- surface slope (0–10%),
- stage of surface clogging and
- base and subgrade layer characteristics.

120 tests were completed and analyzed for surface runoff, infiltration and percolation rates, as well as for changes of volumetric water content at several depths of the base layer. TDR

probes were used for water content measurements. The sprinkling unit provided variable rain intensities between 30 l/(s·ha) and 1000 l/(s·ha) (= 0.0108–0.36 m/h).

According to James & von Langsdorff (2003) the major advantage of the lab scale test series is the opportunity to evaluate systematically the impact of each single key influence under boundary conditions whereas all other parameters are left unmodified. The impact of the surface slope of a particular pavement, for instance, was analyzed by experiments with a gradually varied slope of 2.5%, 5.0% and 7.5%, each for several rain intensities. Figure 15 presents results from another test series where infiltration rate and runoff rate were dermined as a function of clogging degree and rain intensity.

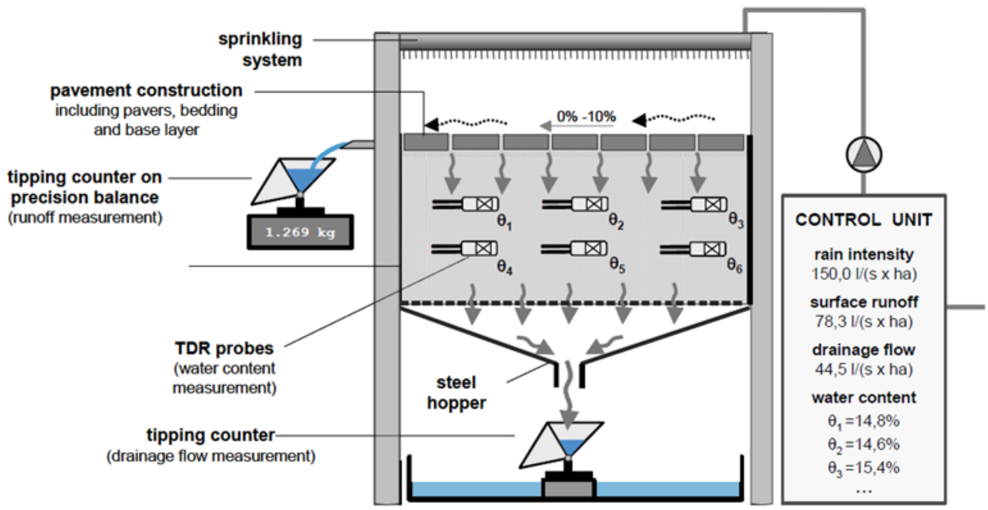


Figure 14. A Rig-testing facility composed of a major steel framework with an integrated hopper and a removable sprinkling unit on top. [James & von Langsdorff 2003]

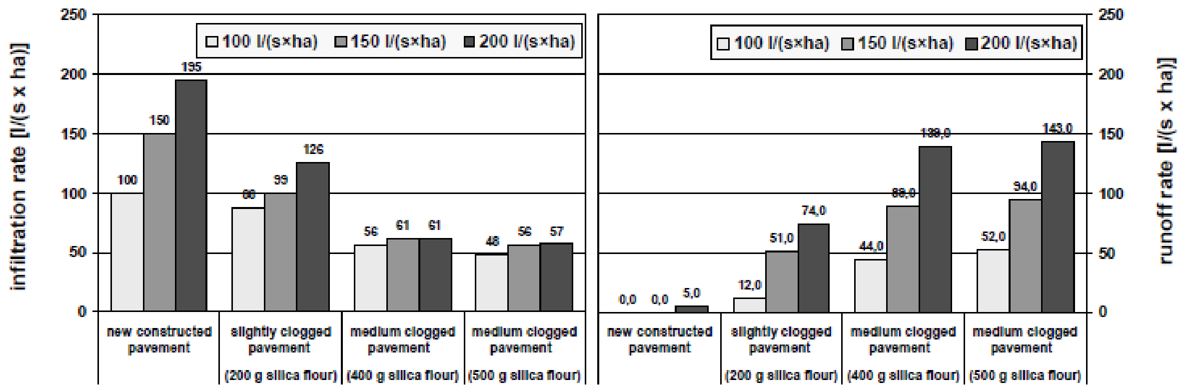


Figure 15. Mean infiltration and runoff rates depending on rain intensity and grade of clogging (a pavement with joints of 4 mm and slope of 2.5% over 20 min. of irrigation). [James & von Langsdorff 2003]

Hou et al. (2008) made an experimental study on rainfall-runoff relation for porous pavements. They simulated different kinds of porous pavements having different sub-base materials in different cells (Figure 16). The discharge volumes were monitored from each cell, and the relationship between rainfall intensity, outflow and outflow duration was analyzed. Porous pavements increased infiltration and decreased runoff. The cells included also a subgrade layer which was first compacted. The infiltration coefficient of the subgrade soil was 2.28 $\times 10^{-7}$ m/s. Soil layer moisture was also monitored. Four pairs of TDR probes (type 6050X1Trase, Aozuo Ecology Instrumentation Ltd) were arranged in each cells' subgrade.

Figure 16. A Porous pavement test cells. [Hou et al. 2008]

Dierkes et al. (2005) measured infiltration capacity by a drip infiltrometer (Figure 17). In this method a metal ring of 30 mm in height (d = 540 mm) is set on a test area and is sealed by mortar against the surface. The ring marks the inner test area and prevents water flowing out of this area. The test area and the area outside the ring was rained during the test period by a sprinkler device. By irrigating the outer section of the ring, the water inside the test area is forced to infiltrate vertically but not laterally at the ring boundary. To simulate realistic rain conditions, the sprinkler system is designed in such a way that a water film with a thickness of just a few millimetres is created, so no unrealistically high water pressure is realized as is the case with some infiltration tests. The idea of the test is to irrigate the test area at an intensity at which no surface runoff is created. The maximum infiltration capacity of the surface is determined as a function of time.

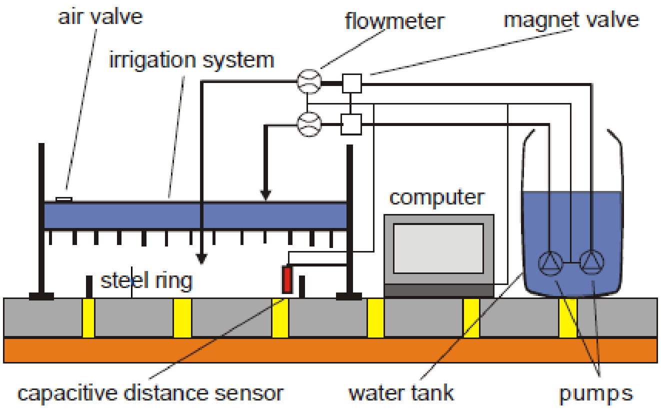


Figure 17. Schematic illustration of the infiltrometer. [Dierkes et al. 2005]

Lucke & Beecham (2013) studied infiltration rates on a prototype scale sloping permeable pavement bed (18 m^2). Porous pavers and impermeable concrete pavers with narrow infiltration joints were tested at slopes of 5% and 10% (Figure 18). They found out that for all flow rates, the applied water travelled much further down the surface of the porous pavers while for the impermeable concrete pavers, most of the water infiltrated into the gaps between the first few pavers. The next stage for their research was to include a rainfall simulator over the entire pavement bed and then to introduce sediment to the inflow in order to examine the effect of clogging on sloping pervious pavements. [Lucke & Beecham 2013]

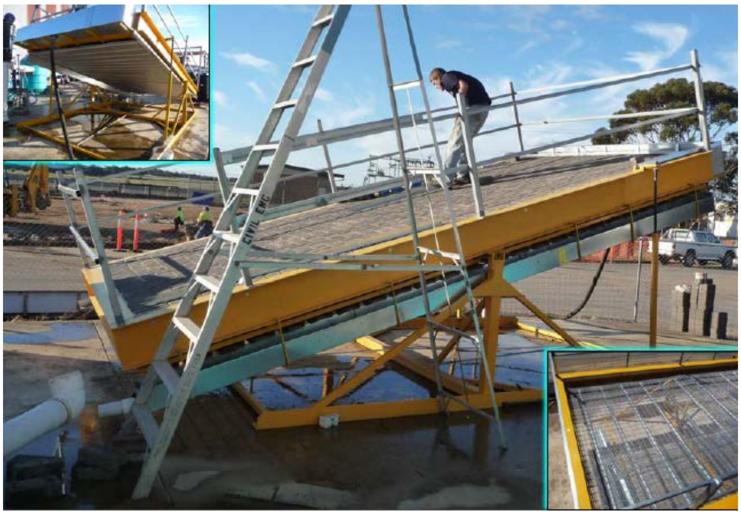


Figure 18. Full-Scale variable-slope experimental test rig. [Lucke & Beecham 2013]

The infiltration capacity of existing pavements and the temporal distribution of the infiltration rate are evaluated by infiltrations tests. This kind of data collection indicate the infiltration capacities of the pavement structures after several years of use, and enable the evaluation of the spatial and temporal variability of the infiltration rate depending on clogging effects, mechanical impacts by car traffic and the particular weather condition and maintenance practices. In addition, this kind of data has been also used as reference values for the imitation of clogging effects within the lab scale test series. [James & von Langsdorff 2003, Wanielista & Chopra 2007, Al-Rubaei et al. 2013, Beeldens et al. 2009, Kuosa et al. 2013a]

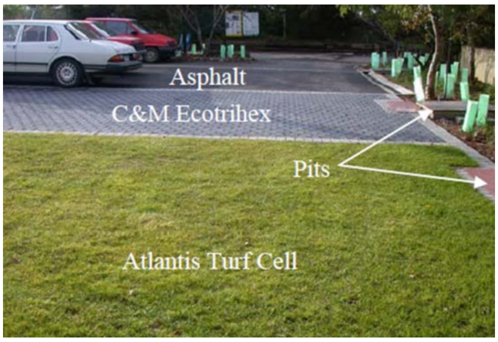
In pilot projects and field studies of pervious pavements several methods have been used to get information on the hydraulic functionality of the pervious structures. [Roseen et al. 2012, Brattebo & Booth 2003, Lucke & Beecham 2011, Jayasuriya & Kadurupokune 2008] These have included:

- Surface infiltration capacity:
    - by different methods (see Chapter 3 *Hydraulic properties*),
    - also during the frost penetration to assess winter performance [Roseen et al. 2012].
- Rainfall measurement, e.g. at 5-min intervals (e.g. ISCO 674 rain gauge, heated during winter months)
    - for the water balance analysis (measurements in contrast to effluent flow volume from the subdrains, e.g. a monthly ratio of precipitation to effluent volume.
- Flows in the downstream end of subsurface collection pipes (volumetric weirs, e.g. Thel-Mar weir).
- Surface runoff measurements (e.g. by tipping-bucket gauges)
- Water-quality treatment performance (petroleum hydrocarbons, zinc, and total suspended solids, phosphorous, nitrate). (see also CLASS project report [Loimula & Kuosa 2013])
    - Comparison of porous pavement effluent with the influent water quality (from adjacent impervious watershed).
    - Real-time water quality parameters, e.g. by using YSI 6000-XL sensor for temperature, pH, specific conductivity, and dissolved oxygen (logging every 5 min.)
    - Water samples, e.g. by using ISCO 6712FR automatic samplers (e.g. max. 24 samples per a storm event).
    - Determination of e.g. [Roseen et al. 2012]:
        - nitrate as nitrogen,
        - total phosphorus as phosphorus,
        - total petroleum hydrocarbons as diesel (TPH-D),

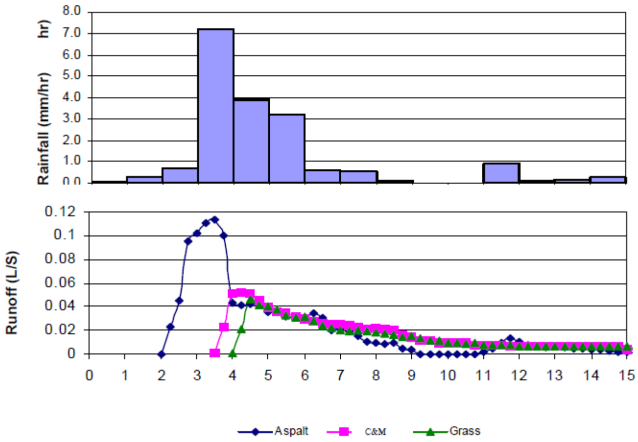
  - total suspended solids, and
  - zinc.
- Frost depth (by frost gauge measurements)
  - comparison with traditional structures.

In all there are numerous field studies on pervious pavements [Kuosa et al. 2013a, Kuosa et al. 2103b, Kuosa & Loimula 2013]. As an example, in the field study by Jayasuriya & Kadurupokune (2008), the methods and testing included (Figure 19):

- Different pavement types were made to form effectively isolated ´catchments´ separated from each other and from the surrounding landscape to avoid runoff contamination of the individual test site. Each test surface type consisted of 2 car park/entry spaces of 50 m^2 (5 m×10 m).
- A subsurface geo-membrane structure was used to mitigate lateral water flow between experimental sites.
- Stormwater drained through the pervious surface and subsurface media and was drained to the outlet via a geo-sock protected perforated header pipe.
- Agricultural pipes were placed around the catchment to prevent stormwater from the surrounding areas entering the experimental site and the surfaces subject to experimentation.
- Three on-line flow meters were installed to measure the surface flow from the control surface and infiltrated water from the two pervious surfaces.
- The flow meters were calibrated to activate when the depth of water in the channel was above 10 mm.
- Three water quality auto samplers were also installed in special pits in the field to collect event based water quality samples from the different types of pavements.
- Rainfall data were collected from a Tipping Bucket rain gauge installed at the site.
- Field rainfall values were compared with the nearby continuous rain gauges to determine the rainfall pattern and the intensity of the rain event at the experimental site.
- A lack of significant rainfall events necessitated the installation of sprinklers to simulate rainfall to compliment the few natural events observed. The sprinklers were selected and placed so that the water was uniformly sprayed over each surface. The flow rate from the sprinklers was adjusted to simulate different rainfall intensities between 14 mm/hr to 21 mm/hr. The storm durations varied from 25 min to 55 min, to cover typical rainfall events (Melbourne, Australia).



a)



b)

Figure 19. a) an experimental pervious car park; b) an example of the measured rainfall (mm/hr) and the resulting runoff (liters/s) for three different surfaces: Asphalt (not pervious), C&M Ecotrihex paver (PICP, www.cmbrick.com.au) and Grass (Atlantis turf cell; www.atlantiscorp.com.au). [Jayasuriya & Kadurupokune 2008]

VTT (Technical Research Centre of Finland) has applied over the years many monitoring techniques and approaches to monitor the geotechnical, geochemical and hydrological behaviour and integrity of the built environment. Many of these methods are also applicable to monitor the behaviour of permeable pavement structures and the surrounding soil and groundwater environment as well as the overall stormwater effects on scales from the real-estate to catchment levels.

In the developed and piloted concept of the early warning system for urban floods the precipitation now-casting is based on real-time, continuous weather radar and rain gauge measurements. These measurements together with the flow and water level information from the combined sewer network are sent wirelessly through the internet server, analysed and connected almost in real-time into fully coupled surface, subsurface and stormwater/sewer network flow simulations. The overall system can combine the location based up-to-date information of flood, alarms based on simulated water levels in different places in the coming minutes and hours and report it to end users. The system utilises oBIX, Google Maps, GPS, 3G, Web server (SmartAlarm server), IP based data communication and IOS based tablet (iPad) and smart phone (iPhone) technologies [Korkealaakso & Piira 2013; Korkealaakso et al. 2012]

A good understanding of the potential and results of the different road monitoring techniques is given in the studies carried out as a part of the Finnish Road Structures Research Programme (TPPT) financed by Finnish Road Administration (1994-2001). The objective of the program was to reduce the annual costs and to decrease the unpredictable damages of the roads. The major environmental aspect was the use of local second class materials with the aim of saving natural gravel deposits. The road structure design system was developed based on the functional properties of the roads and materials. In the program 19 test roads were constructed. In each test road there were 2 -10 test sections. The road structures were designed for local circumstances and to solve different problems taking into account the main stress factors (traffic, frost, subgrade settlement). The test structures were instrumented with different gages to measure frost penetration, frost heave, soil temperature at various depths, groundwater table, snow depth beside the road, variation of moisture content, thermal conductivity, FWD-measurements, stress and strains in pavement due to moving wheel load, longitudinal unevenness (roughness) and visual condition survey. Conclusions of the behaviour of the test structures as well as recommendations to monitor the test roads in future are presented in the summary report by Kivikoski et al. (2002).

Geophysical (non-destructive) imaging techniques like electrical resistivity (ERT) and induced polarization tomography as well as seismic and radar soundings have been applied in studying non-destructively structural behaviour of underlying soil and rock structures under the roads, streets and embankment dams as well as in following in situ soil stabilization processes [Korkealaakso 1998, Saarenpää & Korkealaakso 1999, Maula et al. 2005, Korkiala-Tanttu et al. 2007, Korkealaakso 2013]. ERT has also been applied in many environmental studies for groundwater protection as well as to monitor dynamically in-situ remediation and water infiltration processes in soil and rock [Käpyaho et al. 2012, Aalto et al. 2011, Kling et al. 2004]. The monitoring field of the Ämmässuo bioreactor landfill site (~50 ha) is an example of a permanent implementation of ERT and IPT in time-lapse (4D) mode. The changes in 3D moisture distribution is monitored through repeated measurements and analysed using coupled ERT and thermo-hydro-geochemical modelling to control leachate recirculation in the unsaturated zone [Kling & Korkealaakso 2006, Korkealaakso & Kaila 2013]

As a good example of demanding long-term monitoring implementation is the recent in situ designing, commissioning and monitoring of the bentonite buffer tests commissioned to simulate geological disposal of nuclear waste according to the current reference design concept adopted in Finland. These tests were implemented in the testing place located 140 m underground in the crystalline rock characterization facility. Thermocouples (at 30 points), relative humidity transducers (at 8 points), total (at 10 points) and pore pressure (at one point) sensors were installed into the bentonite buffer blocks to monitor the system behaviour. The testing lasted two years and measurements were recorded in one-minute intervals. The data acquisition system was controlled remotely using custom made programs [Kivikoski et al. 2014 Juvankoski et al. 2012].

3. Workability (PC)

Fresh pervious concrete is typically stiff, with low workability compared to conventional concrete. The normal concrete slump testing method is rarely a useful or appropriate method to determine mixture consistency. Instead, fresh density according to [ASTM C1688] is recommended in [ACI 522.1-13] as the preferred measurement for quality control or quality assurance purposes. Acceptance should be based on ±80 kg/m^3 of the specified fresh density.

One kind of estimation on PC workability can be made by The Inverted Slump Cone Test – See Appendix A. [CPG 2013]

Tennis et al. [2004] recommended that workability for pervious concrete should be assessed by forming a ball with the hand to established mouldability of pervious concrete. Mouldability of pervious concrete is quite sensitive to water content, hence the amount of water should be strictly controlled. Fresh PC properties such as workability are controlled by all the PC mix design parameters, such as water and cement amounts and admixtures.

4. Air content (entrained air pores in PC)

Kevern et al. (2009) studied if different traditional methods for the measurement of air pore content and quality (spacing factor, specific surface of entrained air pores, amount of small air pores) both in fresh and hardened concrete can be adapted to PC.

Traditional pressure or volumetric air measurements appeared not appropriate for pervious concrete. They overestimated the air content due to the inability to remove all of the atmospheric air attached inside the water-permeable voids.

Air Void Analyzer testing (AVA) involved testing mortar obtained from fresh pervious concrete through a vibrating screed. When properly tested on traditional concrete, it is possible to analyse the amount and size distribution of entrained pores, and to calculate e.g. the amount of pores <300 µm and spacing factor of entrained air pores by this method. In the adaptation of this method to PC, excessive vibration and time were required to obtain sufficient mortar samples for an AVA test. This was expected to have some effect on the air pores. It was concluded that more studies are needed to further evaluate if this test method is suitable to PC.

In all, the findings in [Kevern et al. 2009] suggested that current criteria and test methods for air content and air void systems in fresh concrete did not apply with any reliability to pervious concrete. Some of the conventional test methods may be used with modification; however more research is needed to determine appropriate acceptance criteria for pervious concrete.

AASHTO T 199-00: 2014 (*Standard Method of Test for Air Content of Freshly Mixed Concrete by the Chace Indicator*) method covers the determination of the air content of freshly mixed concrete by displacing the air with alcohol and observing the change in level of the liquid in a tube. The apparatus is light and small. Only the mortar phase of concrete is used for the testing. This method has been found satisfactory only for determining the approximate air content of freshly mixed concrete. According to the standard, in no case should the value obtained through the use of this method be accepted as determining the compliance of the air content of concrete with the requirements of specifications. The method is most useful for determining whether the concrete has a low, medium, or high air content, and whether the air content is reasonably constant from batch to batch of concrete. As only the mortar phase can be tested, this method is not especially suitable for PC. It is not easy to get enough mortar phase out of the PC mix for the measurement.

5. Optical microscopy

Plane surfaces and thin sections are typically prepared and used in optical microscopy studies of concrete and other cement based materials. Also asphalt plane and thin sections can be prepared. Especially for concrete these preparation methods and optical studies are common. For preliminary studies also fracture surfaces can be used.

A plane surface sample preparation includes after sawing several grinding steps. Contrast enhancement steps can also be included especially in the case of automatic image analysis method, to ensure white air voids in black concrete.

A prepared thin section may have an area of 35 x 50 mm^2, but can also be larger. The thickness of a thin section is normally only 25–30 µm. Thin sections are typically strengthened with for instance fluorescent epoxy. All the pore spaces, including interconnected voids, small spherical air pores, as well as very small pores (as capillary and gel pores in concrete) are filled with it.

ASTM C856-11 (*Standard Practice for Petrographic Examination of Hardened Concrete*) covers the preparation of thin sections, as well as the petrographic examination of concrete.

By inspecting thin sections under a microscope it is possible to study the structure, and also microstructure, of a material, and to determine for instance the condition and possible causes for failure for both cementitious and bituminous materials.

For instance The Danish Road Institute has routinely used plane and thin sections to investigate failures in bituminous materials. In many cases these techniques have provided answers to pavement problems for which normal tests had not revealed any reason for failure.

In optical studies, especially in thin sections studies, it is also possible to study the quality of the interfaces between the binding material and aggregates. For the material strength and durability properties, good bonding and transition zone properties are essential.

Examining plane sections by image analysis provides information on the voids content of the surfacing, the size of the voids, their form and distribution. It is often also possible to see the presence of relatively large amounts of “dirt” when viewed under a microscope. [Bendtsen et al. 2002]

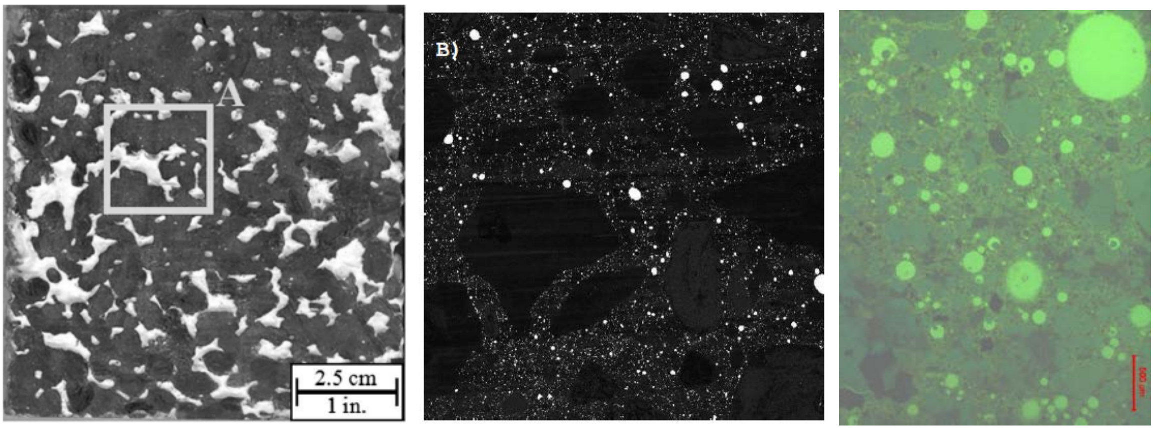
In optical concrete air pore analysis normally the main determined parameter is Powers´ spacing factor (L). It is an attempt to calculate the fraction of paste within some distance of an air void (paste-void proximity). Also other parameters can be determined, and are also used for the calculation of Powers´ spacing factor, or for the evaluation of concretes air pore structure, e.g. specific surface area of the air pores, amount (vol.-%) of air pores in different size classes i.e. air pore size distribution or volume of air pores below some size, e.g. < 0.300 mm pores or < 0.800 mm pores. [Vesikari 1985]

There are somewhat different methods and standards for concrete air pore analysis and determination of Powers´ spacing factor. The most known methods are:

- ASTM C 457 (especially in U.S.A and Canada),
- EN 480-11 (in Europe),
- NT BUILD 381 (in Nordic countries) and

- VTT-TEST-R-00-11 (in Finland).

Kevern et al. (2009) found that all test methods evaluated for characterizing air system of pervious concrete, the spacing factor determined by the RapidAir test correlated best with the freeze-thaw mass loss behaviour. The RapidAir method is a commercial image analysis method based on the use of plane sections with enhanced contrast between air pores and solid phase (aggregates and cement paste). (Figure 20)



a) b) c)

Figure 20. a) Sample prepared for the RapidAir testing; b) A plain section (100 x 100 mm^2) for air pore analysis prepared by using a surface contrast enhancement technique; c) Thin section micrograph (red scale bar 500 µm - the area of this micrograph is ca. 0.2% of the total area for the analysis according to [VTT-TEST-R-00-11]). [Kevern et al. 2009, Kang 2010, Kuosa & Vesikari 2000]

Optical image analysis is possible after preparation of planar images. Before this cutting, grinding, and dying/painting is necessary to enhance the contrast between the solid and pore phases. By optical methods it is possible to get versatile qualitative and quantitative information on the pore structure. Optical images can be used for analysis of the pore structure features such as the area fraction of pores, pore size distribution, and mean free spacing of the pores. 3D-reconstruction is also possible, in order to for instance predict the material permeability (Figure 21). [Sumanasooriya et al. 2009]

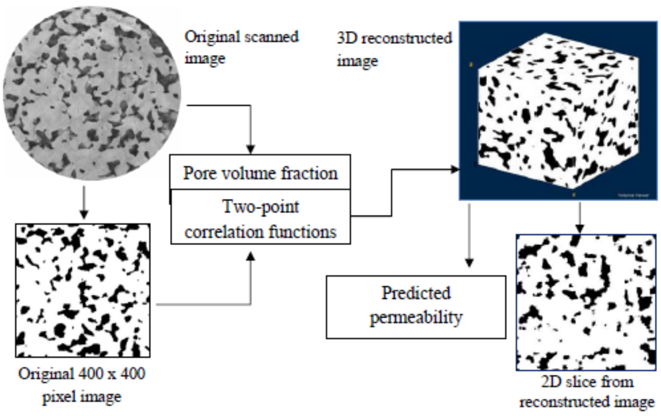


Figure 21. Steps involved in 3D reconstruction and permeability prediction (PC). [Sumanasooriya et al. 2009]

A study by Chindaprasirt et al. (2008) the bottom surface of concrete cylinders were dyed with a colour stamp pad. The dyed bottom surfaces were then dried, photographed and compared. It was possible to get information on the bottom pore structures and paste drainage.

6. Mechanical properties

6.1 Aggregates and soil

In the U.S. the California Bearing Ratio (CBR) test method is used to evaluate the potential strength of subgrade, subbase, and base course material, including recycled materials. The test is performed by measuring the pressure required to penetrate a soil sample with a plunger of standard area (this can be in the laboratory or on site). The force (load) required to cause the penetration is plotted against measured penetration, the readings noted at regular time intervals. This information is plotted on a standard graph, and the plot of the test data will establish the CBR result of the soil tested. The CBR value obtained in this test forms an integral part of several flexible pavement design methods in the U.S. The CBR test is described in:

- ASTM D1883-07e2 (Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils)
- ASTM D4429-09a (Standard Test Method for CBR (California Bearing Ratio) of Soils in Place).

There are also other geotechnical methods to evaluate the bearing strength of subgrade and subbase. [EN 1997-2: 2007, CEN ISO/TS 17892-7: 2004, PANK-9001: 2002]

The Loadman Portable Falling Weight Deflectometer (FWD) is a useful tool for the pavement engineering practitioner. The Loadman consists of a closed, 1170 mm long aluminium tube of 132 mm diameter. The tube contains a free moving 10 kg steel weight suspended by an electro-magnet; controls, electronics and electro-magnet are positioned at the top of the tube, as shown in Figure 22. By this equipment and method it is possible to determine the bearing capacity of a structural layer expressed as E-modulus, as well as the degree of compactness [PANK-9001: 2002]. Bartley Consultants Ltd (1998) compared the results of laboratory Loadman tests with data obtained using Repeated Load Triaxial (RLT) tests. In a RLT test a repeated axial cyclic stress is applied to a cylindrical test specimen, and it is also subjected to a static confining stress provided by a triaxial pressure chamber. The total resilient (recoverable) axial deformation response of the specimen is measured and used to calculate the resilient modulus.

The analysis shows that the two test procedures correlate reasonably well although the level of stress imposed by the Loadman may be greater than that occuring in-service, especially for subgrade soils. [Bartley Consultants Ltd. 1998, PANK-9001: 2002]

Pidwerbesky (1997) describes comparative trials of five non-destructive pavement tests (Loadman, FWD, Benkelman Beam, Nuclear Density Meter and Clegg Hammer). Overall, considering the cost per test (including personnel and skills required), rate of testing and the quality of data produced, his study found that the Loadman was the most cost-effective testing device for quality control during compaction monitoring and pavement condition evaluation. [Pidwerbesky 1997]

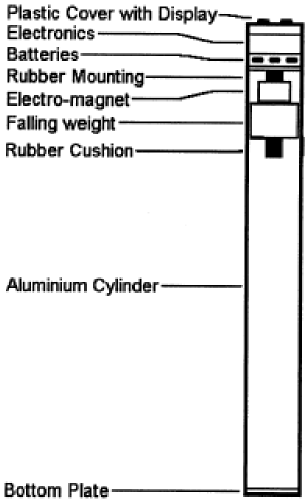


Figure 22. Loadman Portable Falling Weight Deflectometer (FWD). [Pidwerbesky 1997]

In Europe, EN 1097-2: 2010 (*Tests for mechanical and physical properties of aggregates. Methods for determination of resistance to fragmentation*) describes the reference method, the density test, used for type testing. In case of dispute (and an alternative method, the impact test) it is also used for determining the resistance to fragmentation of coarse aggregates and aggregates for railway ballast. For other purposes, in particular factory production control, other methods may be used provided that an appropriate working relationship with the reference method has been established. EN 1097-2 applies to natural, manufactured or recycled aggregates used in building and civil engineering.

In the USA, ASTM C131-06 (*Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*) and ASTM C535-12 (*Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*) are widely used as an indicator of the relative quality or competence of various sources of aggregate having similar mineral compositions. The results do not automatically permit valid comparisons to be made between sources having distinctly different in origin, composition, or structure. Specification limits should be assigned with extreme care in consideration of available aggregate types and their performance history in specific end uses. ASTM C131-06 standard is for <37.5 mm aggregates, and ASTM C535-12 is for >19 mm aggregates.

6.2 Pervious concrete and porous asphalt

ASTM and ACI are working to develop standardised tests for compressive and flexural strengths, abrasion resistance, etc. for pervious concrete. Standards for conventional concrete strengths do not apply as such for pervious concrete [CPG 2013]. Anyway, tests for normal structural concrete have been used also to test PC. Both field sawed beams and cores as well as laboratory cast specimen as cylinders and beams have been used for this. [Crouch et al. 2008, Huang et al. 2010b]

For instance Crouch et al. (2008) measured PC compressive strength, splitting tensile strength, flexural strength and static modulus of elasticity in accordance with methods ASTM C39 (*cylinders*), ASTM C496 (*cylinders),* ASTM C78 (*beams, three point testing*), and ASTM C469 (*cylinders/drilled concrete cores*) respectively. There are corresponding European (and/or Finnish (SFS)) standards for all these mechanical properties of concrete: EN 12390-3 (*Compressive strength of test specimens*)/EN 12504-1 (*Testing Concrete in Structures – Cored Specimens Taking and Testing in Compression*), EN 12390-6 (*Tensile splitting strength of test specimens*), EN 12390-5 (*Flexural strength of test specimens*) and SFS 5450 (*Concrete – Modulus of elasticity).*

Abrasion resistance of pervious concrete can be seen by observing how much and how quickly the surface aggregate particles ravel. This is of particular concern in locations with turning traffic or locations that use snow ploughs, and also if studded tystnadardizeres are used during the winter season. ASTM C1747 (*Standard Test Method for Determining Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion*) method provides a procedure for evaluating the potential resistance to degradation by impact and abrasion of pervious concrete mixtures. This test allows the comparison of the relative potential resistance to ravelling of pervious concrete mixtures of varying proportions and raw materials. The test method covers determining the potential resistance to degradation of pervious concrete by measuring the mass loss of specimens subjected to combined action of impact and abrasion in a rotating steel drum. [Dong et al. 2010]

ASTM C944 (*Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method)* has also been used to study PC abrasion. In this method a constant load of 98 N is applied through rotary cutter dressing wheels in contact with the sample surface for two minutes. The diameter of the circular abraded area is 80 mm (Figure 23a). Figure 23b presents a PC surface before and after abrasion. [Kevern et al. 2008]

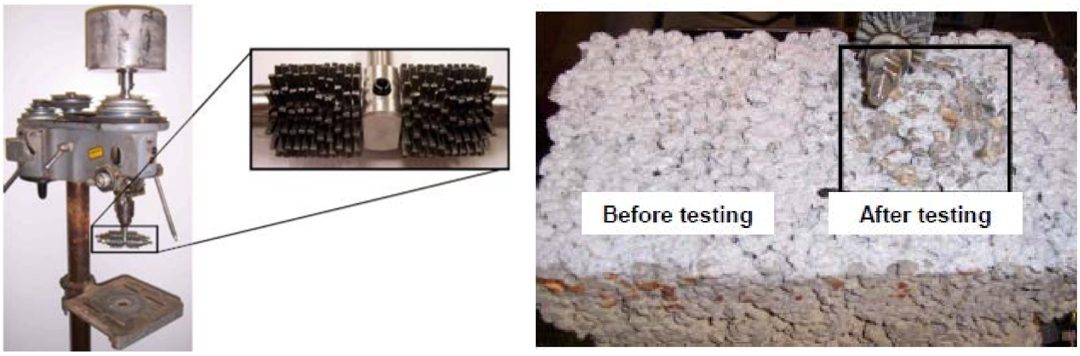


Figure 23. a) Abrasion apparatus ASTM C944 and the cutting head; b) Pervious concrete surface before and after abrasion. [Kevern et al. 2008]

For asphalt, resistance to wearing by studded tyres may also be an importat property, and testing may be demanded (see Chapter 9 (Requirements, type testing and quality control)).

7. Durability

Durability of a material, as concrete or asphalt, determines how it maintains all the material properties in the environment it is used. Environmental exposure can be very different in different places of use. This is why it is common to have different demands for the material properties in different countries. Testing methods may also be different.

7.1 Concrete

In the Nordic countries freeze-thaw testing (concrete) is normally included in the durability studies. Internal deterioration caused by freeze-thaw without salt (internal cracking), and freeze-thaw scaling with salt solution are separated because these degradation mechanics are different. This means that also different testing methods must be used. [By 50 2012]

Freeze-thaw deterioration, and especially salt scaling with freeze-thaw, is complex. For instance, in the case of concrete the suitability of the available testing methods is often discussed. For pervious materials, such as for pervious concrete (PC), the selection of the right method is even more difficult. There are no standardised methods for these studies yet. This means that the methods for normal concrete must be adapted to pervious concrete. In the CLASS-project report [Kuosa et al. 2013a] the testing methods for freeze-thaw, and some methods used for the pervious concrete freeze-thaw durability testing, was reviewed. The main part of this review is repeated here in Appendix B, for easy access.

Clearly there is a need for more studies on the ways to test the freeze-thaw durability of pervious concrete. It should be possible to ensure a long enough service life in the actual exposure, and on the other hand without any unnecessary heavy demands. In this durability parameter especially the water saturation degree is decisive. Because of the pervious structure of PC/PA, all the normal testing methods are not adaptable. [Kuosa et al. 2013a]

For instance Kevern et al. (2009) concluded that although the ASTM Standard C666 (Method A, i.e. freezing and thawing in the saturated condition) test results indicated that the freeze-thaw durability factors of pervious concrete studied were very low, no freeze-thaw related durability distresses have been observed after 3 years of service. According to Kevern et al. (2009) the ASTM Standard C666 freeze-thaw test method is an overly severe test, and a more realistic test may be required to related pervious concrete freeze-thaw durability in the laboratory with that experienced in the field. [Kevern et al. 2009, ASTM C666]

7.2 Asphalt

The loss of bond between asphalt binder and aggregate is called stripping. Sensitivity of asphalt mixtures to this kind of moisture-induced damage can be evaluated by AASHTO T 283-07 (*Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage).* According to this standard the test is performed by compacting specimens to an air void level of six to eight percent. Three specimens are selected as a control and tested without moisture conditioning, and three more specimens are selected to be conditioned by saturating with water undergoing a freeze cycle, and subsequently having a warm-water soaking cycle. The specimens are then tested for indirect tensile strength by loading the specimens at a constant rate and measuring the force required to break the specimen. The tensile strength of the conditioned specimens is compared to the control specimens to determine the tensile strength ratio (TSR). This test may also be performed on cores taken from the finished pavement. In this method the degree of saturation in freezing is selected to be between 70% and 80%, and is achieved by a vacuum procedure.

Strictly speaking, AASHTO T 283 is not appropriate for porous specimens (e.g. void content 20%). AASHTO T 283 recommends discarding a specimen once its saturation is more than 80 percent. Question remains on how to choose an appropriate degree of saturation for porous asphalt. In the study by Wang & Wang (2011) the degree of saturation ranged from 55% to 65%.

In Finland the PANK 4306 (*Asfalttimassan jäätymis-sulamiskestävyys. Asphalt mix freeze-thaw durability*) method is for the HMA freeze-thaw testing. In this method freezing can be in water or in air. Thawing is always in water. There is no experience on the suitability of this method to porous asphalt. The evaluation of the deterioration degree is based on the splitting tensile strength testing.

8. Methods for supplementary materials and products

8.1 Geosynthetics

The International Geosynthetics Society (IGS, in Finland IGS-FIN) is a learned society dedicated to the scientific and engineering development of geotextiles, geomembranes, related products and associated technologies (founded in Paris (1983)). The Society brings together individual and corporate members from all parts of the world, who are involved in the design, manufacture, sale, use or testing of geotextiles, geomembranes, related products and associated technologies, or who teach or conduct research about such products. In the www-page of the IGS there is a lot of information available on all the geosynthetics, and on the proper use of these products. The IGS promotes the dissemination of technical information on geosynthetics through a newsletter (IGS News) and though its two official journals (*Geosynthetics International* – www.geosynthetics-international.com and *Geotextiles and Geomembranes* – www.elsevier.com/locate/geotexmem). [IGS 2014, IGS-FIN 2014]

The Geosynthetic Institute (GSI) is a consortium of organizations interested in, and involved with, geosynthetics. All types of polymeric geosynthetic materials are involved. [GSI 2014]

Geosynthetica is an online source for information on geosynthetic engineering and technology. Geosynthetica's Library section tracks relevant publications for professionals who utilize geosynthetics. [Geosynthetica 2014]

In Europe, CEN/TC 189 develops the necessary standards to assess the desired level of performance of geosynthetics. The scope of the standardisation related to geosynthetics includes terminology, sampling before testing, identification and marking rules, test methods, and requirements related to the intended used. Standardisation of hydraulic test methods for geosynthetics is included in CEN/TC 189/WG 4 - Hydraulic testing. [CEN/TC 189 2014]

8.1.1 Geotextiles

A filter should prevent excessive migration of soil particles, while at the same time allowing liquid to flow freely through the filter layer. Filtration is therefore summarised by two seemingly conflicting requirements:

- The filter must retain soil, implying that the size of filter pore spaces or openings should be smaller than a specified maximum value.
- The filter must be permeable enough to allow a relatively free flow through it, implying that the size of filter pore spaces and number of openings should be larger than a specified minimum value. [Tengate 2014, Rathmayer & Juvankoski 1992]

Due to the conflicting nature of filter requirements, in the selection of the numerical criteria, it is necessary to decide whether retention or permeability is the favored filter characteristic. This must be based on all the information on the design case, including application of the filter, filter boundary conditions, properties of the soil being filtered, and construction methods used to install the filter subgrade properties. [Tengate 2014, Rathmayer & Juvankoski 1992]

<u>European standardisation and testing methods</u>

European geotextile standards can be roughly divided in product specifications (related to applications) and test methods. A summary of the content of the product specifications and a short description of the test methods is presented in [Foubert 2009]. In all there are 11 European geotextile product standards (EN). Each of them specify the requirements for geotextiles (and geotextile-related products) used in a given application.

The relevant characteristics of geotextiles and geotextile-related products required for use in the construction of roads and other trafficked areas (excluding railways and asphalt inclusion) are presented in EN 13249:2000 (*Geotextiles and geotextile-related products – Characteristics required for use in the construction of roads and other trafficked areas (excluding railways and asphalt inclusion)*). Appropriate test methods to determine these characteristics are also defined.

The intended use of geotextiles or geotextile-related products is to fulfil one or more of the following functions:

- Filtration (F),
- Drainage (D),
- Reinforcement (R),

- Separation (S),
- Protection (P) when used in combination with a geosynthetic barrier and
- Interlayer barrier (B) stress relief (STR) in conjunction with a bitumen layer for asphalt reinforcement.

The separation function is always used in conjunction with filtration or reinforcement, accordingly separation will never be specified alone. [EN 13249, Foubert 2009, Rathmayer & Juvankoski 1992.

According to Foubert (2009) the manufacturer shall provide data on a set of properties, which are related to each function, as claimed in the manufacturer's product information. These properties may be either imposed by the Mandates M/107 and M/386 of the European Commission (H-properties, for regulatory purposes; for Harmonization), or be of a voluntary nature to be used in all conditions of use (A-properties) or some conditions of use (S-properties). The H-properties are directly related to the function and independent from the application. The A- and S-properties may vary with the application and the actual conditions of use. Their relevance is specified in the individual standards. Typical A- and S-properties are strength of seams and junctions, tensile and compressive creep, abrasion, damage during installation and friction. Table 1 presents H-properties and test methods vs. functions. [Foubert 2009]

Table 1. H-properties and test methods vs. functions. [Foubert 2009]

Property	Test method	F	D	R	S	P	STR	B
Tensile strength	EN ISO 10319	X	X	X	X	X	X	X
Elongation (at break)	EN ISO 10319		X	X		X	X (**)	X
Static puncture (CBR) resistance	EN ISO 12236 (*)			X	X	X	X	X
Dynamic perforation resistance	EN ISO 13433	X	X	X		X		X
Water permeability (perpendicular to the plane)	EN ISO 11058	X						
Characteristic opening size	EN ISO 12956	X						
Water flow capacity (in the plane)	EN ISO 12958		X					
Durability (to be assessed in accordance with guidelines specified in annex to the standards- applicability of test methods dependent on materials and conditions of use)	EN 12224 EN 12225 EN 12447 EN 14030 EN ISO 13438	X	X	X	X	X	X	X

(*) for a product fulfilling a protective function EN 13719 shall be used.
(**) both elongation at breaking load and bitumen retention (according to EN 15381, annex C) shall be assessed

Appendix C includes information on the European geotextile testing standards for the harmonization (H-properties) [EN 13249].

NorGeoSpc (2013) presents a Nordic system for the certification and specification of geosynthetics and geosynthetic related products for separation, filtration and/or reinforcement in all applications, as e.g. in Pavements and asphalt overlays which are included in EN 15381: 2008 (*Geotextiles and geotextile-related products. Characteristics required for use in pavements and asphalt overlays*). [NorGeoSpc 2013]

Other testing methods

ASTM D4751-12 (*Standard Test Method for Determining Apparent Opening Size (AOS) of a Geotextile*) is the ASTM-standard for the opening size. AOS is defined by O_{95} which indicates the approximate largest particle that would pass through the geotextile. The AOS testing method provides only one opening size value; a pore size distribution cannot be obtained.

According to [TenCate 2011] the most obvious issue encountered in the AOS test is the high probability of smaller sized test beads passing through larger sized openings in the fabric, rather than passing through the openings that are the same size as the specific test bead diameter. Other AOS testing problems include electrostatic effects, testing beads sticking together, and beads becoming trapped in the material from friction. According to [TenCate 2011], with so many potential problems with the AOS test method, an improved test must be developed.

The Capillary flow porometer is a test that provides a great deal of geotextile opening size information accurately and precisely (ASTM D6767 (*Test Method for Pore Size Characteristics of Geotextiles by Capillary Flow Test*). According to [TenCate 2011] The porometer test method is not limited to one opening size and will measure opening values between O_0 and O_{98}. Each test has a range opening sizes which are reported as an average for a sample. One would have to run countless AOS tests to provide the same amount of information provided from one porometer test. The test comparison is impractical because the AOS test only measures O_{95}. Using the values obtained for the porometer testing of the geotextile, one can accurately predict the way the material will perform during both AOS testing and water flow testing (ASTM D4491 (*Standard Test Methods for Water Permeability of Geotextiles by Permittivity)*). The porometer test method is more accurate and defines a material's drainage and filtration characteristics. The porometer will let one know if there are any pores larger than the O_{95}, such as O_{98}, while AOS testing will report the O_{98} falsely as the O_{95} value. [TenCate 2011]

The results obtained by ASTM D5101-12 (*Standard Test Method for Measuring the Filtration Compatibility of Soil-Geotextile Systems*) may be used as an indication of the compatibility of the soil-geotextile system with respect to both particle retention and flow. The results obtained may be used as an indication of the compatibility of the soil-geotextile system with respect to both particle retention and flow capacity. This test method is intended to evaluate the performance of specific on-site soils and geotextiles at the design stage of a project, or to provide qualitative data that may help identify causes of failure (clogging, particle loss). It is not appropriate for acceptance testing of geotextiles. It is also improper to utilize the results from this test for job specifications or manufacturers' certifications. For soils with a plasticity index lower than 5, the systems compatibility shall be evaluated per this standard. For soils with a plasticity index of 5 or more, it is recommended to use ASTM D5567-94 (2011) (*Standard Test Method for Hydraulic Conductivity Ratio (HCR) Testing of Soil/Geotextile Systems*) instead of this test method.

Geotextile selection and testing can also include the assessment of the clogging potential. According to Bhatia & Smith (1996) the existing clogging criteria are generally based on: soil/geotextile filtration tests, geotextile porosity measurements or on relationships between a characteristic pore size of the geotextile, such asO_{95}, O_{90} ,O_{50} or O_{15} and the grain-size distribution of the surrounding soil. The clogging potential of a geotextile may be evaluated by performance tests, such as the long-term flow test, the gradient ratio test (ASTM D 5101), or the hydraulic conductivity test (ASTMD 5567). These performance tests are generally not carried out because they are time consuming, expensive, and only provide information for a specific soil/geotextile system. The porosity of a geotextile is important; however, almost every geotextile passes the given criterion that a geotextile should have a porosity greater than 30–40% (most geotextiles have a porosity in the range of 80–90%). Clogging criterion are thus evaluated by considering the permeability and the opening size of the geotextile. Although this approach is commonly accepted, it has been determined that the permeability and the largest opening size of nonwoven geotextiles do not indicate clogging. However, for woven geotextiles, the open area is directly related to clogging potential. [Bhatia & Smith 1996]

Bailey et al. (2008) developed a rapid method for clogging potential of geotextile filters by finer grained soils by using the flexible wall gradient ratio (FWGR) test. This test is a combination of a flexible wall permeameter and the standard gradient ratio test. Because the test allows for backpressure saturation, the time required for stabilization during a clogging test is greatly reduced. FWGR test was able to obtain accurate results within a week, compared with times of two months for the same trials with the conventional gradient ratio test. According to Bailey et al. (2008) the FWGR seems to be an improvement over current test methods for performance testing of geotextile filters in fine-grained soils.

8.1.2 Geosynthetic barriers

Barriers are used in earthwork construction to control movement of water, other liquids and sometimes vapours. Barriers are used to waterproof structures, to prevent moisture changes beneath roadways, to contain water and wastes, and to support other applications in transportation works. The function of these barriers is to either prevent damage to highway pavements and structures or to contain water or waste materials. Barriers must be engineered to perform their intended function for the particular application and project being designed. [Holz et al. 1998, Rathmayer & Juvankoski 1992]

EN 15382: 2013 (*Geosynthetic barriers. Characteristics required for use in transportation infrastructure)* presents the requirements for geosynthetic barriers used as fluid barriers in infrastructure works, and the appropriate test methods to determine these characteristics. It defines requirements to be met by manufacturers and their authorised representatives with regard to the presentation of product properties. There are three different product types, i.e. polymeric (GBR-P), bituminous (GBR-B) and clay (GBR-C, i.e. bentonite carpets) geosynthetic barriers.

The properties to be tested are divided to physical properties (such as thickness and unit weight (kg/m^2)), hydraulic properties (such as water penetration/tightness), mechanical properties (such as tensile strength, strain, puncture resistance, resistance to tearing, friction characteristics) and thermal properties (such as flexibility at low temperature and linear thermal expansion). These testing methods for these testing are not reviewed here, but are presented in the relevant testing standards. [EN 15382: 2013]

CEN/TS 14416: 2014 (*Geosynthetic barriers - Test method for determining the resistance to roots*) defines a method for testing the resistance of a geosynthetic barrier to penetration by roots. Such resistance is a requirement for many uses of geosynthetic barriers. This standard describes a laboratory procedure for the rapid testing of the resistance of polymeric, bituminous or clay geosynthetic barriers to root penetration. It is suitable for testing of welded seams or other areas of potential weakness. A longer test that may be more suitable for testing the long-term resistance of geosynthetic barriers is described in EN 13948:2007 (*Flexible sheets for waterproofing. Bitumen, plastic and rubber sheets for roof waterproofing. Determination of resistance to root penetration*).

8.2 Piping systems

Plastic pipes and fittings have achieved a strong market position in storm and foul water systems over the past decades. Stiffness, flexibility, impact strength, leak tightness, ease of installation, and durability are some of the essential properties of the plastic systems to be tested. [TEPPFA 2014, EN 14758-1, EN 13476- 1, EN 13476-2, EN 13476-3]

Load carrying capacity, material properties and long term durability of pipes used in connection with the pervious structures is essential. Information on the Nordic certification is presented in Chapter 9 (*Requirements, type testing and quality control*). Testing methods and standards are not reviewed here.

The European Plastic Pipes and Fittings Association (TEPPFA) is the trade association representing manufacturers and national associations of plastic pipe systems in Europe. Information on the European standardisation can be found at the TEPPFA homepage. [TEPPFA 2014]

As an example, the key aspects and the main performance characteristics of the standard for structured wall piping systems (EN13476) are presented in [Teppfa-EN13476. 2104]:

- ring stiffness of pipes and fittings and available classes,
- required ring flexibility of pipes,
- dimensions and tolerances,
- impact strength, resistance to dynamic loading,
- demonstration of leak tightness of the system,
- resistance to high temperatures,
- recommendation for sewer pipe cleaning, jetting,
- demonstration of the durability of the used thermoplastic materials,
- chemical resistance of the used thermoplastic materials,
- recycling of thermoplastic pipes and fittings.

8.3 Water harvesting systems

There are a number of permeable sub-base replacement and water harvesting systems on the market that can be incorporated into permeable pavement, as lattice plastic cellular units, chambers, cisterns, vaults and tanks. A sub-base replacement and water harvesting system should have a technical approval, to fit for the use in infrastructure constructions. [Interpave 2007, Virginia DCR 2011, Kuosa et al. 2013a]

As an example, Pipelife´s storm water boxes comply with load resistance requirements of [BRL 52250] (Netherlands), which specifies a 3 days vertical load of 200 kN/m^2 and a lateral load of 85 kN/m^2. The high load resistance and quality of the boxes has been confirmed by the Kiwa N.V. KOMO Certificate. [Pipelife 2114]

As another example, StormTech chambers are subjected to full scale testing to verify the AASHTO safety factors for live load and deep burial applications. Chambers are designed to adapt to the requirements of ASTM F2418 (polypropylene chambers) and ASTM F2922 (polyethylene chambers) and design requirements of ASTM F2787. [StormTech 2104]

ASTM F2418 (polypropylene chambers) specification covers requirements, test methods, materials, and marking for polypropylene, open bottom, buried chambers of corrugated wall construction used for collection, detention, and retention of stormwater runoff. According to the standard, applications include commercial, residential, agricultural, and highway drainage, including installation under parking lots and roadways. Chambers are produced in arch shapes with dimensions based on chamber rise, chamber span, and wall stiffness. They are manufactured with integral feet that provide base support. They may include perforations to enhance water flow and must meet test requirements for arch stiffness, flattening, and accelerated weathering. The successful performance of the product depends upon the type and depth of bedding and backfill, and care in installation. The ASTM-specification includes requirements for the manufacturer to provide chamber installation instructions to the purchaser. [ASTM F2418: 2013]

The evaluation of conformity of the specific products used as a part of water harvesting systems is also possible. For instance parameters of PVC foil used in the construction of underground retention tanks can be determined and evaluated for conformity according to appropriate standards or guidelines. Table 2 presents an example on the parameters and testing standards for PVC foil when used in the construction of underground retention tanks [Pipelife 2014].

BS 8515:2009+A1:2013 (*Rainwater harvesting systems. Code of practice)* is applicable to systems supplying non-potable water in the UK for domestic use (such as laundry, WC flushing and garden watering). This standard is for the design, installation, testing and maintenance of these rainwater harvesting systems.

Also DIN-standards are available for the rainwater harvesting systems:
- DIN 1989-1: 2002 (Planning, installation, operation and maintenance),
- DIN 1989-2: 2004 (Filters),
- DIN 1989-3: 2003-08 (Collection tanks for rainwater),
- DIN 1989-4: 2005-08 (Components for control and supplemental supply).

Table 2. Parameters of PVC foil used in the construction of underground detention tanks in [Pipelife 2014].

No.	Properties	Unit	Test method	Parameters
1.	Thickness	mm	EN 1849-2	1.5 ± 10%
2.	Dimensions (L x W)	m	EN 1848-2	2 x 20 ± 5%
3.	Tensile strength -longitudinal -transverse	MPa	EN 527-1/3	14 12
4.	Static puncture	kN	EN ISO 12236	2.5
5.	Compatibility with asphalt	-	EN 1548 EN 1928	compatible with bitumen
6.	Resistance to root penetration	-	PR-CEN/TS 14416	no perforation
7.	Reaction to fire	-	EN 13501-1	Class E

9. Requirements, type testing and quality control

This Chapter includes some examples on pervious pavement requirements, pavement material type testing and quality control. There are several specifications and specifier´s guides providing more such details for pervious pavements. [CRMCA 2009, UNHSC 2009, ACI 522R-10, ACI 522.1-13]

Specifications include instructions for pervious pavement construction, and also more specific requirements and quality control demands for the materials and methods. These general specifications can be sited in pervious pavement projects. In different countries there are different demands for the pervious pavements, as well as different general practices and demands. This is why different specifications are needed in different countries or places of use.

9.1 Subgrade

Prior to placement of the surfacing layer the subgrade can be evaluated for compaction or infiltration rate. [Ferguson 2005]

BS EN 1997-2:2007 (Eurocode 7. Geotechnical design. Ground investigation and testing) is intended to be used in conjunction with EN 1997-1 (Eurocode 7. Geotechnical design General rules).

BS EN 1997-2:2007 provides rules supplementary to EN 1997-1 related to:
- planning and reporting of ground investigations,
- general requirements for a number of commonly used laboratory and field tests,

- interpretation and evaluation of test results,
- derivation of values of geotechnical parameters and coefficients.

In addition, examples of the application of field test results to design are given.

9.2 Test area

It is a good practice to make, and to approve, first a small test panel, before proceeding with a full project. This will assure that all the materials and the placement procedures are correct and compatible. After the test panel has been fully cured, it can be evaluated for [CRMCA 2009]:

- infiltration rate,
- raveling and
- general condition.

According to [CRMCA 2009] PC test panels shall be constructed in accordance with the plans and specifications and shall be placed a minimum 30 days prior to construction. Regardless of qualification, the contractor is to place two test panels, each a minimum of 20 m^2 at the required project thickness. Test panels shall be consolidated, jointed and cured using materials, equipment, and personnel proposed for the project, to demonstrate to the Architect/Engineer's satisfaction that in-place densities can be achieved and a satisfactory pavement can be installed at the site location. In addition, the proposed ready-mix supplier must be used during the construction of the test panels to ensure proper delivery of a satisfactory pervious concrete mixture.

Also, according to [CRMCA 2009] satisfactory performance of the PC test panels shall be determined by:

- compacted thickness of no less than specified thickness minus 6.4 mm (Tcompacted ≥ Tspecified – 6.4 mm),
- voids: 15% minimum; 25% maximum,
- density ± 80 kg/m^3 of the design weight,
- compressive strength equal to or greater than design strength.

In the case of PC, pressure washing is a practical way to see if any fraction is poorly cemented or slowly infiltrating [Ferguson 2005]. This can be adapted also to PA.

9.3 Pavers

In the U.S.A, concrete pavers should conform to ASTM C936/C936M-13 (*Standard Specification for Solid Concrete Interlocking Paving Units*).

In Europe, there are no harmonized standards for concrete interlocking paving units to be used in pervious pavements. Harmonized standards for concrete tiles and concrete paving flags are partially applicable also to interlocking paving units to be used in pervious pavements:

- EN 1338: 2003 (Concrete paving blocks. Requirements and test methods)
- EN 1339: 2003 (Concrete paving flags. Requirements and test method).

In Finland there is also a national application standard:

- SFS 7017: 2009. *("Betonista tai luonnonkivestä tehdyille ulkotilojen päällystekiville, -laatoille ja reunakiville eri käyttökohteissa vaaditut ominaisuudet ja niille asetetut vaatimustasot". The demanded properties, and the standard levels, for the concrete and natural stone paving stones, slabs and curbs in different use)*

For setts and slabs of natural stone there are harmonized standards:

- EN 1342:2012. Setts of natural stone for external paving. Requirements and test methods.
- EN 1341:2012. Slabs of natural stone for external paving. Requirements and test methods.

Testing methods for paving blocks, paving flags and for setts and slabs of natural stone are not reviewed here.

In Belgium there is a technical specification [PTV 122 2009] for water pervious concrete paving blocks and tiles, including requirements for the raw materials used, the production and the finished products. PTV 122 (2009) is based on the above standards for normal concrete paving blocks and flags but it gives additional requirements specific for blocks for pervious concrete surfaces. It does not apply to grass paving clinkers.

Paving products in PTV 122 (2009) are classified as:

a. Water pervious paving products with drainage openings; these are paving products provided with continuous openings and/or half openings in the sides as a result of which the ground covering shows vertical openings,
b. Water pervious paving products with widened joints; these are paving products provided with wide spacers and/or grooves in the sides, as a result of which the ground covering shows continuous or locally widened joints,
c. Water pervious paving products; these are paving products made of porous concrete with an open grain construction.

The method for the determination of the water perviousness is included in PTV 122 (2009). This test is carried out on complete porous paving products. For pervious concrete blocks the demand for average permeability is $\geq 5.4 \times 10^{-5}$ m/s, and in the case of pavement blocks with enlarged joints or drainage holes the demand for an open surface area is ≥ 10%. [PTV 122 2009]

9.4 Pervious concrete

The American Concrete Institute (ACI) has prepared a summary of recommended inspection and testing activities that should be performed during construction of pervious concrete pavements [ACI 522R-10], as well as a specification for pervious concrete construction [ACI 522.1-13]. Acceptance testing for pervious concrete is typically limited to density (ASTM C1688) and thickness (ASTM C42).

The workability and consistency of pervious concrete may be determined for each ready mixed truck to ensure high quality construction. Typically workability is adjusted on-site for the first load and then readjusted during batching for all subsequent loads. [CPG 2013]

Consistency determination can be made by unit weight measurement [ASTM C1688] and comparison against required values. Typically unit weight for PC is 1600 – 2000 kg/m^3. Unit weight (density) values greater than 80 kg/m^3 different from the desired values may be an indication of an incorrect mixture. [ACI 522R-10, Bury et al. 2006]

Unit weight of porous concrete decreases linearly with void content, and the permeability of the concrete increases exponentially with the concrete void content. As a result, the unit weight test can serve as a simple, quick quality control test in field to ensure proper void content or permeability of the concrete. Figure 24 presents one example of that. [Schaefer et al. 2006] For different mix designs and compaction degrees, these relations are of course somewhat different.

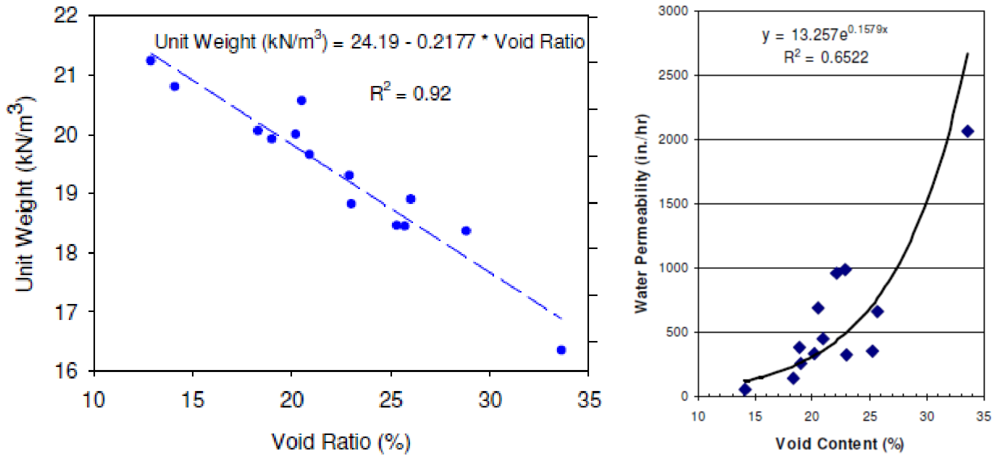


Figure 24. a) An example of pervious concrete properties: a) Relationship between unit weight and void content. b) Relationship between permeability and void content. [Schaefer et al. 2006]

After hardening of porous concrete cores can be taken. Testing of these cores can include:

- thickness,
- void content and
- compressive strength.

Comparison can be made with the possible pre-project test panel properties.

Delatte & Cleary (2006) presented that one possible way of reconciling the difficulty of controlling quality and determining pavement design properties for PC might be to specify different grades of pervious concrete. They presented three grades of pervious concrete:

- Hydraulic – low strength, high permeability, for non-structural applications.
- Normal – intermediate strength and permeability, for light duty parking lots.
- Structural – higher strength and lower permeability, for parking lots, streets, and roads with heavy trucks (with small amounts of fine aggregate added).

9.5 Porous asphalt

Material specifications and requirements of porous asphalts are listed in the European standard EN 13108-7 + AC *Material specifications: Porous Asphalt* and national Annex *Finnish asphalt specifications* (PANK, Finnish Pavement Technology Advisory Council, 2011).

Type testing of asphalt material is defined in standard EN 13108-20 (*Asfalttimassat. Materiaalivaatimukset. Osa 20: Tyyppitestaus;* In Finnish), and testing method standards of asphalt mixtures are collected in EN 12697 standard series (1–43). Some testing methods used in Finland are presented in PANK technical procedure guidelines. All standards presented in this Chapter are listed in Appendix D. Some other countries have also their own standards and testing routines.

Standard EN 13108-7 + AC and national annex PANK (2011) used in Finland sets requirements for raw materials, asphalt mixtures and asphalt pavements. These requirements are depended on the target site and final use of pavement. Raw materials are divided to aggregates, binders and additives. Aggregate properties are geometrical, mechanical, physical and chemical, and they must meet the standard EN 13043 (*Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas*). Binders and additives have several physical and chemical properties, which must meet the requirements in standards EN 12591 (*Bitumen and bituminous binders. Specifications for paving grade bitumens*), EN 14023 (*Bitumen and bituminous binders.*

Specification framework for polymer modified bitumens) or other standard/approval/ document depending on material (additive). Also the use of crushed asphalt is possible, if it meets the requirements in EN 13108-8 (*Bituminous mixtures. Material specifications. Part 8: Reclaimed asphalt*).

An asphalt mixture is designed using either empirical or performance-based mix design depending on the target application. In case of less challenging applications (as the porous asphalt is usually used) the empirical design is sufficient. Then the designed properties are binder content and grading. The performance-based mix design includes in addition to the above compactability, voids in mineral aggregate (VMA), voids filled with binder/asphalt (VFB/A), voids in total mix (VTM), resistance to wear by studded tyres, resistance to deformation and water sensitivity.

The designed asphalt mixture needs a type testing for proving the properties meet standards before getting the CE mark (PANK 2011). The type testing includes the following studies in the case of porous asphalt:

- Binder content (standard: EN 12697-1)
- Grading (standard: EN 12697-2)
- Void content (standard: EN 12697-8)
- Voids filled with binder/asphalt (standard: EN 12697-8)
- Void content of gyratory compacted specimen (standard: EN 12697-31 and -8)
- Resistance to wearing by studded tyres (standard: EN 12697-16)
- Water sensitivity (standard: EN 12697-12)
- Resistance to deformation (standard: EN 12697-22 or EN 12697-25, procedure A).

In standard SFS-EN 13108-20 there are also some testing procedures more:

- o Bitumen-aggregate affinity (standard: EN 12697-11, part C)
- o Resistance to fuel (standard: EN 12697-43)
- o Resistance to de-icing fluids (standard: EN 12697-41).

A final type testing report includes some additional information, such as temperature of mixture. Depending on the application area there may also be information about binder drainage, particle loss and permeability. Also fire burning behaviour and notification of hazardous substances can be studied if needed. The quality control properties and allowed deviations of asphalt production according to standard EN 13108-21 (*Bituminous mixtures. Material specifications. Part 21: Factory Production Control)* have also been determined in PANK 2011 specification. [PANK 2011, EN 13108-20]

In PANK asphalt specifications (2011) there are guidelines for grading and binder percentage for different asphalt types. There are also guidelines for different features of layers of road structure. Grading curves are presented by basic test sieve series (according to standard SFS-EN 933-2 (*Tests for geometrical properties of aggregates. Part 2: Determination of particle size distribution. Test sieves, nominal size of apertures*): 0.063; 0.125; 0.25; 0.5; 1; 2; 4; 8; 16; 31.5 and 63 mm) and additional test sieve serie no. 1 (5.6; 11.2; 22.4 and 45 mm). There are four different grading mixture compositions for porous asphalts: AA 5, AA 8, AA 11 and AA 16. Each of them can include bitumen as either road bitumen 35/50…70/100 or rubberized bitumen KB65 or KB75. Additional material could be cellulose fibres or natural asphalt. Binder percentage (vol.-%) and mass amount of standard thickness pavement plate (kg/m^2) vary depending on the composition. A binder mixture must be homogenous.

Figure 25 presents an example grading curve guideline for AA 5 asphalt mixture. The binder content of this mixture is 5.0–6.0% and mass amount of standard thickness pavement plate 50–75 kg/m^2.

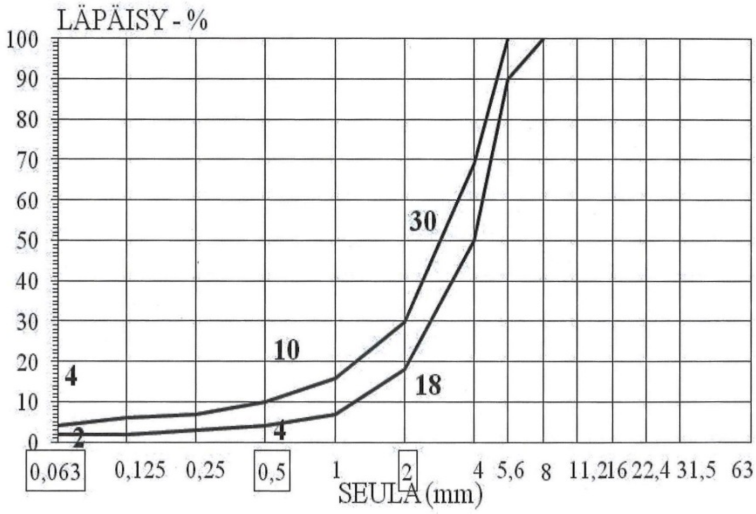


Figure 25. AA 5 grading curve (PANK 2011). The passing % is on the vertical axis and the sieve size (mm) on the horizontal axis.

The customer may set the quality requirements for functional features of asphalts in a contract document. Requirements may be focused to the quality of the asphalt mixture or quality of the final asphalt pavement. Quality control testing of the asphalt mixture is done in laboratory and testing of final pavement is done an in situ or by using the samples drilled from in situ structure. These functional features are wear resistance, deformation resistance, water sensitivity, freezing/frost resistance and compactability. Quality of functionality testing can be done at the same time as the type testing as the test methods and standards are the same.

Testing the final pavement may include, in addition to the tests mentioned above, some in situ tests. Void content can be measured with a laboratory method according to standard EN 12697-8 (*Bituminous mixtures – Test methods for hot mix asphalts – Part 8: Determination of void characteristics of bituminous specimens;* core samples taken from pavement surface) or in situ methods which do not break the pavement such as PANK 4113 (*Päällysteen tiheys, DOR-menetelmä* (in Finnish); Density), PANK 4122 (*Asfalttipäällysteen tyhjätila, päällystetut-kamenetelmä* (in Finnish); Void-% by radar method) or PANK 4123 (*Dielektrisyyteen perus-tuva pistekohtainen asfalttipäällysteen tiheyden mittaus* (In Finnish) Thickness and void-% by dielectricity).

Other measurable features are e.g. friction (PANK 5201, Päällysteen sulan kelin kitka, sivu-kitkamenetelmä (in Finnish)), freeze-thaw resistance (PANK 4306, Asfalttimassan jäätymis-sulamiskestävyys (in Finnish)) and noisiness (PANK 5210, Päällysteen meluominaisuuden mittaaminen (in Finnish)).

Porous asphalts are applicable to e.g. fields, yards and light trafficked roads and areas (PANK 2011). For the pavement of these areas a general instruction is to test the gradation and bitumen content. The volumetric ratio, wearing/abrasion, deformation and water resistance may be also tested if needed depending on the target use on pavement. All test mentioned in this Chapter are not necessary for porous asphalts. For instance, if the planned speed limit is high, the pavement must be more resistant to wearing and this feature must be tested.

In the case of PA pavements, permeability properties are especially important. Information on these methods was presented in Chapter 2 (*Hydraulic properties – materials and pavement*).

9.6 Piping systems

The CE mark is intended to show that a product fulfils the legal requirements in the EU´s Construction Products Directive. The requirement level in the CE mark for pipes does not correspond to the previous type approvals or products certified to the Nordic national standard. Specifying a quality level equivalent to the ´Nordic Poly Mark´ ensures that plastic pipe products will continue to have the previous level of quality. The intention is to implement certification on the basis of standards or corresponding documents, taking into account the Nordic conditions and to give manufacturers and buyers the possibility for certification with a high quality level in an established system in the Nordic countries. [Nordic Poly Mark 2014]

Specific rules for Nordic certification done in accordance with:

- EN 14758-1 (Plastic piping systems for non-pressure underground drainage and sewerage PP-MD) is presented in [INSTA SBC 14758-1 2011], and
- EN 13476- 1, EN 13476-2 and EN 13476-3 (Structured wall sewage PVC, PP, PE) in [INSTA SBC 13476 2011].

The issuing of a certification license requires that the applicant commits himself to follow the general rules for certification [NSTA-CERT GRC 2012] and the specific rules, but also to make sure that the products mentioned fulfil the requirements in the European standard in question. Register of approved products can be found on the INSTA-CERT homepage www.insta-cert.com.

The Nordic conformity mark for products according to [INSTA SBC 13476 2011] is presented in Figure 26. [Inspecta 2014, Nordic Poly Mark 2014, INSTA-CERT 2011]

Nordic Poly Mark

Figure 26. Nordic conformity mark for plastic pipes. [Inspecta 2014, Nordic Poly Mark 2014, INSTA SBC 13476 2011]

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ASTM C1688/C1688M. 2013. Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete. 4 p.

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ASTM C1701/C1701M. 2009. Standard Test Method for Infiltration Rate of In Place Pervious Concrete. 3 p.

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ASTM C1754/C1754M. 2012. Standard Test Method for Density and Void Content of Hardened Pervious Concrete. 3 p.

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ASTM C496/C496M. 2011. Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. 5 p.

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ASTM C78/C78M. 2010e1. Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). 4 p.

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ASTM D4751. 2012. Standard Test Method for Determining Apparent Opening Size (AOS) of a Geotextile. 7 p.

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Appendix A – Test methods for pervious concrete

ASTM C1688/C1688M-12. Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete. [CPG 2013]


Equipment & materials needed


A proctor hammer


First lift compacted


Second lift compacted


Striking off the surface


Weighing & final calculations

ASTM C1701/C1701M-09 Standard Test Method for Infiltration Rate of In Place Pervious Concrete [CPG 2013]


Equipment & Materials Needed


Calibrated markings in the rim


Secure the rim with putty


1 gallon of water into apparatus


(Step 2 if needed) 5 gallons into apparatus


Final calculations

The Inverted Slump Cone Test (for pervious concrete)

Filling the inverted slump cone | Checking workability | Workable mix | Over-worked mix

Picture credit: Kevern, Schaefer, Wang [CPG 2013]

Workability or mouldability assessment for pervious concrete. [Tennis et al. 2004, Aoki 2009]

(a) too little water | (b) proper amount of water | (c) too much water

Appendix B – Freeze-thaw testing methods with and without chlorides

Reproduced from [Kuosa et al. 2013a]:

When assessing the durability of pervious concrete pavements in cold climates, there are two aspects that should be considered:

- durability of the pervious concrete material itself, and
- durability and winter performance of the whole system.

Winter performance of pervious pavements as the whole structure is reviewed more closely in a Finnish CLASS-project State-of-the-Art Report concentrated on the winter performance of pervious pavements [Kuosa et al. 2013b]

In all there are several testing methods for assessing conventional concrete freeze-thaw resistance with de-icing salt solution. In these methods specimens are in contact with salt solution during the testing. There is a solution layer on or below the specimen surface, or the specimens are immersed in the salt solution. Solution contact is needed for scaling. Most typically a 3% salt (NaCl) solution is used as it normally is the most critical for the surface scaling degree. Specimen surface scaling (g/m^2) or volume change (vol.-%) is normally measured. Internal deterioration caused by cracking can also be determined, e.g. the change of relative dynamic modulus of elasticity.

For instance in the European testing specification for concrete [CEN/TS 12390-9:2006(E)] there are three testing methods for concrete freeze-thaw scaling with de-icing salt: slab-test, CDF-method and cube-test. The slab-test is normally used in Finland (Figure 1b). This method is based on the earlier Swedish standard SS 13 72 44 (1992), so called “Borås-method”. In this test there is one freeze-thaw cycle per one day. For structural concrete normally 56 cycles are needed. In the testing of paving units the demand (in Finland) is presented based on the scaling degree after 28 cycles (average <1 kg/m^2). The minimum temperature is -20±2 °C, maximum temperature is +20±4 °C, and cooling is from +0 °C to -20 °C in 12 hours (1.7 °C/h).

For the estimation of the freeze-thaw resistance of structural concrete with regard to internal structural damage, there are three different methods in the European testing standard [CEN/TR 15177 (2006)]. No single test method is established as a reference test method as these methods produce relatively consistent results. These methods are:

- Slab-Test,
- CIF-method and
- Beam test.

In Finland mostly Slab-Test is used. Besides SFS 5447 (1988) is still in use (Freeze-thaw durability; normally with beams 500×100×100 mm^3). This method essentially includes freezing in air (-20 °C) and thawing in water (water temperature less than 40 °C, and end of thawing cycle temperature is +20 °C). SFS 5447 is a very loosely defined method. Besides, thawing by the relatively warm water (<40 °C) is a harsh method especially for relatively brittle high strength concrete, and at the same time for low w/c paste. Thus it is also a harsh method for PC with typically very low w/c (< 0.25…0.30).

In [By 50 2012] this method (SFS 5447) is an optional quality control method in addition to CEN/TR 15177 Slab-Test and air pore analysis (Spacing factor). Based on the demanded design service life and exposure class, the amount of freeze-thaw cycles is 100 or 300. The acceptance criterion is based on either the relative dynamic modulus of elasticity (RDM) as measured by ultrasonic pulse transit time (UPTT) (≥75%) or relative flexural or splitting tensile strength (≥67%). [By 50 2012]

In North America the most commonly used testing standard for freeze-thaw resistance is ASTM C666/C666M-03(2008). This standard includes two methods:

- rapid freezing and thawing in water (Procedure A), and
- rapid freezing in air and thawing in water (Procedure B).

The open structure of PC allows free ingress of water into the specimen. Subsequent freezing of saturated PC could cause rapid deterioration. Anyway, freeze-thaw damage has been reported to develop in pervious concrete primarily as paste deterioration of lower porosity pervious concrete. [Mata 2008]

The general recommendation for pervious concrete systems in freeze-thaw environments is to install a layer of aggregate base below the PC pavement to store stormwater in order to avoid saturation of the pervious concrete during freeze-thaw events. According to Kevern et al. (2008) there are no documented cases of freeze-thaw failures of existing installations when these recommendations are followed. However, there is still some potential for saturation of the pervious concrete layer and it is therefore necessary to design pervious concrete mixtures to be freeze-thaw resistant in case the pervious concrete does become saturated during freeze-thaw events.

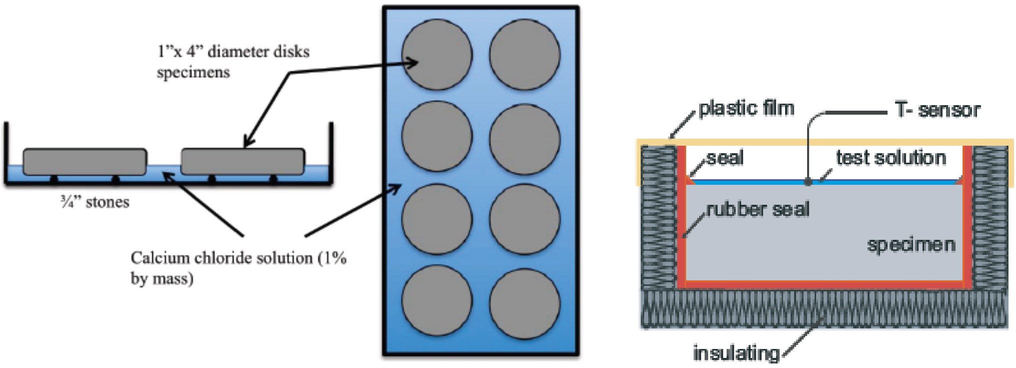
Testing of concrete by freezing and thawing while submerged in water is a harsh performance test method. This is because cement paste water saturation will get high during the testing. However, a PC mixture that passes this kind of testing will have a high probability of performing well in the field. If the pavement system drains well enough to keep the PC from being saturated, then the harsh conditions represented by for instance the ASTM C 666 (Procedure A) test do not apply. This is, therefore, the goal of the system design. [Delatte et al. 2007]

According to [Mata 2008] the de-icer salt test described in ASTM C672 [ASTM C672/C672M-12] may be better suited for evaluation of durability of concrete in paving applications because it involves slower, more realistic freezing cycles in the presence of a de-icing salt solution (4% NaCl) and attempts to more realistically simulate frost exposure conditions in a pavement. In this test minimum temperature is -18 ±2 °C, maximum temperature is +23 ±2 °C and there is one freeze-thaw cycle per one day.

In his work Mata (2008) used a modification of the ASTM C672 method. (Figure 1) Evaluation was based on mass loss and changes in dynamic modulus of 25 mm thick concrete disks with 100 mm diameter. The results of this study indicated that small disks, tested at realistic freezing rates, could be successfully used to evaluate frost resistance of paving mixtures. To get information on the effect of PC microstructure on the frost resistance, Mata (2008) used one additional disk specimen to assess qualitatively the entrained air void system by stereoscopic microscope. The entrained air void system could be interpreted as “inadequate”, “acceptable,” or “excellent” by an experience analyst.

Mata (2008) concluded that the cement paste alone, i.e. without any fine sand, is not sufficient to develop the air entrained air voids during the mixing phase, required to protect the concrete to water expansion on freezing. The results of the freezing and thawing tests confirmed that the addition of 7% sand by weight as replacement for coarse aggregate increases the frost resistance of pervious concrete significantly and, when used with an adequate amount of air entraining agent can provided adequate frost resistance as measured by the modification of ASTM C672 method used in this study. According to Mata (2008) additional research is still needed to determine the percentage of entrained air voids related to air entraining admixture and sand content in a low w/c PC mixture.

For concrete surface scaling the binding material and also the microstructural changes caused by carbonation and drying in it (long term ageing) are known to be essential, in addition to water-cement ratio and amount (vol.-%) and spacing (mm) of small (<0.3 mm) entrained air pores. [Kuosa et al. 2012a]



a) b)

Figure 1. a) ASTM C672 modified pervious concrete freeze-thaw testing with salt solution [Mata 2008]; b) CEN/TS 12390-9:2006(E) Slab-Test for the determination of surface scaling and internal deterioration caused by freeze-thaw with de-icing salt solution.

Partially saturated pervious concrete in air has demonstrated substantially higher durability than those subjected to freezing and thawing under water. This means that a good way to increase freeze-thaw durability is to take care of good drainage, i.e. bv using a good subbase system. Caution should be exercised when using pervious concrete in a situation where complete saturation may occur. [ACI 522R-10]

The NRMCA (National Ready Mixed Concrete Association) in the U.S.A. has defined four exposure climate categories based on moisture (wet or dry) and temperature (freeze or hard freeze). Below is some basic information on the expected performance of PC in these exposure climates. [Delatte et al. 2007]

Dry freeze and hard dry freeze

- As there is little precipitation during the winter (´dry´) PC is unlikely to be fully saturated in these environments. No special precaution is necessary for successful performance of pervious concrete but a 100 mm to 200 mm thick layer of clean aggregate base below the PC is recommended.

Wet freeze

- Since the ground does not stay frozen for long periods in ´wet freeze´ it is unlikely that the PC will be fully saturated, because of drainage. No special precaution is necessary for successful performance of pervious concrete but a 100 mm to 200 mm thick layer of clean aggregate base below the PC is recommended.

Hard wet freeze

- These areas may have situations where the pervious concrete becomes fully saturated. The following precautions organized in the order of preference, are recommended to enhance the freeze-thaw resistance of PC:
    - Use an 200 mm – 600 mm thick layer of clean aggregate base below the PC.
    - Attempt to protect the paste by incorporating air-entraining admixture in the PC mixture.
    - Place a perforated PVC pipe in the aggregate base to capture all the water and let it drain.

Laboratory study by Yang et al. (2006) give detailed information on the effects of moisture conditions on the damage development in PC during cyclic freeze-thaw. The degree of saturation of the paste played an important role in the damage development in PC. Both the fundamental transverse resonant frequency and the mass of each specimen were monitored during freeze-thaw testing. In the beginning of the freeze-thaw testing, mass change included possible water absorption (if freezing was in water). Vacuum saturation was used in some cases to get all the pores water saturated, including capillary and air pores in the paste fraction of PC. It was found that:

- PC specimens that were vacuum-saturated and then frozen and thawed in water exhibited the lowest freeze-thaw durability.
- The vacuum saturated specimens that were sealed and frozen and thawed in air showed a relatively higher freeze-thaw resistance. (Figure 2a)
- The highest freeze-thaw resistance occurred on the PC specimens without vacuum saturation, which were frozen and thawed in air under sealed conditions.
- When PC specimens without vacuum saturation were frozen and thawed in water, a drastic decrease in the freeze-thaw resistance was observed.
- Vacuum-saturated and sealed conventional concrete exhibited very low resistance to freezing and thawing cycles (completely failed at about 13 cycles), whereas PC with the same pre-treatment and test conditions showed higher freeze-thaw durability (lasted for 100 cycles). (Figure 2a)
    - The slow damage development in PC can be attributed to the lower internal pressure generated during freezing in a thin layer of paste in PC.
- Instead, when PC was partially saturated and exposed to a wet environment, it was found to deteriorate much more rapidly than conventional concrete.
    - For PC a drastic increase in weight occurred during the first few cycles. This was because of the rapid water uptake that occurred at the beginning of the test. (Figure 2b)
    - PC specimens with air-entraining admixture could resist more than 300 cycles implying that air entrainment had significant impact on the freeze-thaw durability in partially saturated PC. (Figure 2b)
    - Conventional concrete (with 5.5% air) was able to resist more than 2000 freeze-thaw cycles. The primary reason for the relatively poor PC freeze-thaw resistance in water (for PC 300 cycles, and for conventional concrete 2000 cycles) was the fast saturation of air void system in the thin PC paste layer. (Figure 2c)
    - Partially saturated (water-cured specimens, no vacuum saturation) air entrained PC was found to be very durable when freezing and thawing was in air. (Figure 2d)

It should be noted that the rapid freezing and thawing (ASTM C666, with 6 to 7 cycles per day) was used in the study by Yang et al. (2005). This is significantly differed from field conditions. Higher freezing rate typically leads to faster damage development. According to [Yang et al. 2006] and [Mata 2008] using a fast freezing rate may not be suitable for evaluating the freeze-thaw durability of field PC.

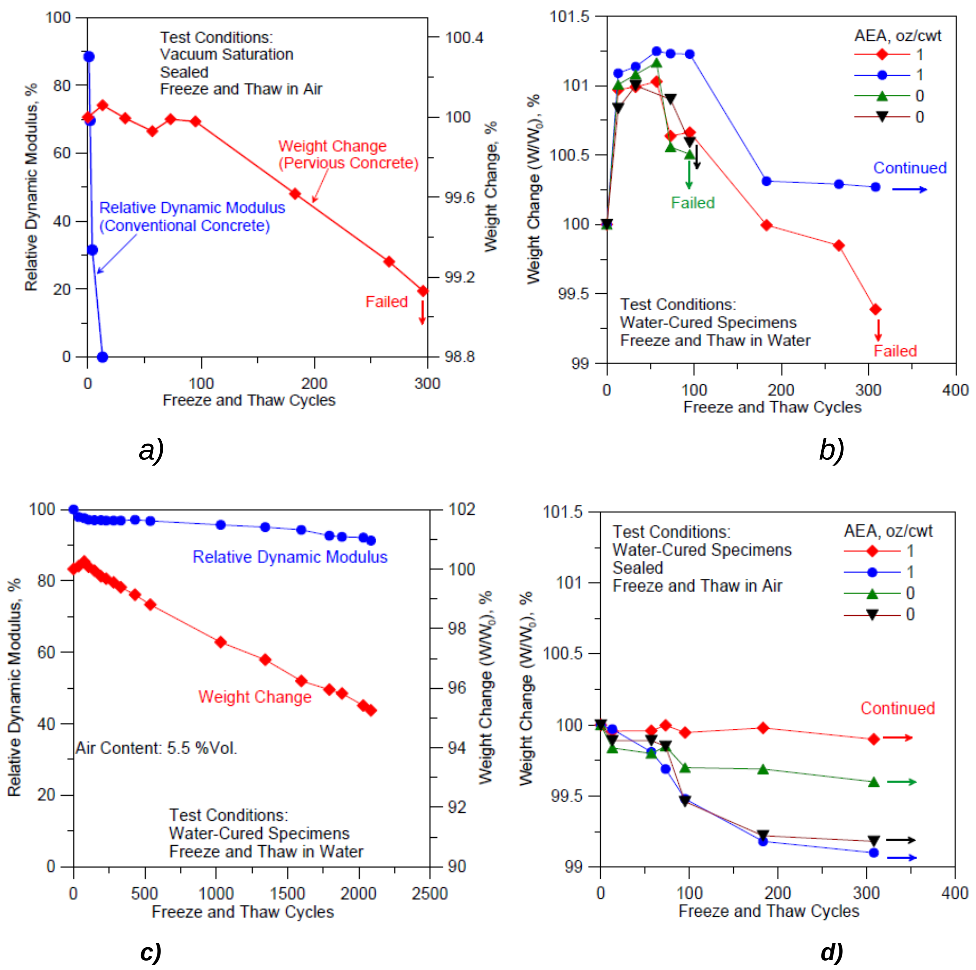


Figure 2. a) Comparison on freeze-thaw damage development between PC and conventional concretes with vacuum saturated and sealed specimen (no water uptake); b) Variation of specimen weight (water uptake + volume loss) as a function of freeze and thaw cycles for PC with water cured specimen (no vacuum saturation) subject to freeze-thaw in water; c) Typical slow freeze-thaw damage development in water for conventional concrete; d) PC specimen weight as a function of freeze-thaw cycles with water cured specimen (no vacuum saturation) subject to freeze-thaw as sealed (no water uptake). [Yang et al. 2006]

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Appendix C – European geotextile testing standards for the harmonization

H-properties [EN 13249]

EN ISO 10319: 2008. Geosynthetics – Wide-width tensile test.

- The tensile properties of the material should be verified in accordance with this method.
- The tensile test method covers the measurement of load elongation characteristics and includes procedures for the calculation of secant stiffness, maximum load per unit width and strain at maximum load. Singular points on the load-extension curve are also indicated.

EN ISO 12236: 2006. Geosynthetics – Static puncture test (CBR test).

- Specifies a method for the determination of the puncture resistance by measuring the force required to push a flat-ended plunger through geosynthetics.
- The test is normally carried out on dry specimens conditioned in the specified atmosphere. The test is applicable to most types of products, but not to materials with apertures greater than 10 mm.

EN ISO 13433: 2006. Geosynthetics. Dynamic perforation test (cone drop test)

- Specifies a method to determine the resistance of geosynthetics to penetration by a steel cone dropped from a fixed height. The degree of penetration is an indication of the behaviour of the geosynthetic when sharp stones are dropped on its surface. The method is generally applicable to geosynthetics. However, the validity of this test for some types of products should be considered carefully, as the test principle may not be applicable.

EN ISO 11058: 2010 – Geotextiles and geotextile-related products – Determination of water permeability characteristics normal to the plane, without load.

- This standard specifies two test methods for the determination of the water permeability characteristics of a single layer geotextile (or geotextile-related product) normal to the plane:
    - Constant head method: a flow velocity in m/s (volume per unit of time and area: $m^3/m^2 \cdot s$), and
    - Falling head method: a flow velocity in m/s (hydrostatic head difference divided by time).

EN ISO 12958: 2010. Geotextiles and geotextile-related products. Determination of water flow capacity in their plane.

- Specifies a method for determining the constant-head water flow capacity within the plane of a geotextile or geotextile-related product.
- The compressibility of the product over time will substantially influence the in-plane water flow capacity. Test methods for assessing the compressive creep behaviour of geotextiles or geotextile-related products are described in ISO 25619-1. The test report is judged in conjunction with the long-term compressive creep behaviour in order to assess the long-term flow capacity.

ISO 12956:2010. Geotextiles and geotextile-related products – Determination of the characteristic opening size.

- Specifies a method for the determination of the characteristic size of the openings of a single layer of a geotextile or geotextile-related product using the wet-sieving principle.

- A quantity of graded granular material (usually soil) is brought on the surface of the geotextile and washed through with water. The geotextile acts as a sieve and the granular material, which passes the geotextile, is analysed. The characteristic opening size (O90) of the geotextile corresponds to a specified size of the granular material passed (d90). d90 = particle size for which 90% (by mass) of the particles is smaller than that particle.

Long term durability verification is also needed for harmonization. This is according to the EN 13249 Annex B. There are different ways to demonstrate the needed long term durability. From EN 13249 the appropriate type of durability testing can be derived.

An informative flow chart for the assessment of the long term durability is presented in EN 13249 Annex D. [EN 13249] Long term durability is linked to a number of parameters:

- Duration of exposure to sunlight on site,
- Soil conditions (pH, temperature, contamination),
- Expected lifetime of the construction, and
- Composition and structure of the geotextile.

From the [EN 13249] the appropriate type of durability testing can be derived.

Appendix D – Standard (EN) and Finnish PANK methods for asphalt

Method	Name
EN 12591	Bitumen and bituminous binders. Specifications for paving grade bitumens
EN 12697-1	Bituminous mixtures - Test methods for hot mix asphalts - Part 1: Soluble binder content
EN 12697-2	Bituminous mixtures - Test methods for hot mix asphalts - Part 2: Determination of particle size distribution
EN 12697-3	Bituminous mixtures - Test methods for hot mix asphalts - Part 3: Bitumen recovery: Rotary evaporator
EN 12697-4	Bituminous mixtures - Test methods for hot mix asphalts - Part 4: Bitumen recovery: Fractionating column
EN 12697-5	Bituminous mixtures - Test methods for hot mix asphalts - Part 5: Determination of the maximum density
EN 12697-8	Bituminous mixtures - Test methods for hot mix asphalts - Part 8: Determination of void characteristics of bituminous specimens
EN 12697-11	Bituminous mixtures - Test methods for hot mix asphalts - Part 11: Determination of the affinity between aggregate and bitumen
EN 12697-12	Bituminous mixtures - Test methods for hot mix asphalts - Part 12: Determination of the water sensitivity of bituminous specimens
EN 12697-16	Bituminous mixtures. Test methods for hot mix asphalt. Part 16: Abrasion by studded tyres
EN 12697-17	Bituminous mixtures - Test methods for hot mix asphalts - Part 17: Particle loss of porous asphalt specimen
EN 12697-18	Bituminous mixtures - Test methods for hot mix asphalts - Part 18: Binder drainage
EN 12697-19	Bituminous mixtures - Test methods for hot mix asphalts - Part 19: Permeability of specimen
EN 12697-22	Bituminous mixtures. Test methods for hot mix asphalt. Part 22: Wheel tracking
EN 12697-25	Bituminous mixtures. Test methods for hot mix asphalt. Part 25: Cyclic compression test
EN 12697-31	Bituminous mixtures - Test methods for hot mix asphalts - Part 31: Specimen preparation by gyrator compactor
EN 12697-40	Bituminous mixtures - Test methods for hot mix asphalts - Part 40: In situ drainability
EN 12697-41	Bituminous mixtures - Test methods for hot mix asphalts - Part 41: Resistance to de-icing fluids
EN 12697-43	Bituminous mixtures - Test methods for hot mix asphalts - Part 43: Resistance to fuel
EN 13043	Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas
EN 13108-8	Bituminous mixtures. Material specifications. Part 8: Reclaimed asphalt
EN 13108-20	Bituminous mixtures. Material specifications Part 20: Type testing.
EN 13108-21	Bituminous mixtures. Material specifications. Part 21: Factory Production Control
EN 14023	Bitumen and bituminous binders. Specification framework for polymer modified bitumens
EN 933-2	Tests for geometrical properties of aggregates. Part 2: Determination of particle size distribution. Test sieves, nominal size of apertures
PANK 4113	Päällysteen tiheys, DOR-menetelmä (5-2011) (thickness)
PANK 4122	Asfalttipäällysteen tyhjätila, päällystetutkamenetelmä (void %)
PANK 4123	Dielektrisyyteen perustuva pistekohtainen asfalttipäällysteen tiheyden mittaus (thickness, void %)
PANK 4306	Asfalttimassan jäätymis-sulamiskestävyys (freeze-thawing)
PANK 5201	Päällysteen sulan kelin kitka, sivukitkamenetelmä (friction)
PANK 5210	Päällysteen meluominaisuuden mittaaminen (noisiness)