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# DEVELOPMENT OF DURABLE PERVIOUS CONCRETE FOR FINLAND’S STORMWATER MANAGEMENT NEEDS

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## ABSTRACT

Pervious concrete is a viable tool for to mitigating impacts of climate changes in urban environments, through their ability to filter high volumes of stormwater. Research has been done in Finland to develop pervious concrete that is durable for arctic environmental conditions. The new materials combined with sub-based design are optimized during design, construction and maintenance, to allow for high filtration to the substrate rather than over-burdening the stormwater collection systems or polluting nearby natural water bodies with urban run-off. The project has conducted laboratory test programs to characterize materials prior to designing concrete recipes that meet Finnish demands and then implemented layer systems where the concrete and subbase layers function for filtration benefits. Performance tests characterize the porous concrete strength, open porosity, microstructure including protective air pores, permeability and freeze-thaw resistance with and without de-icing salt. Several mixes have been prepared and slabs and other specimens have been cast for these studies. The main emphasis has been on ensuring durability for harsh Finnish winter exposure conditions. The results are being used in structural dimensioning tools for stormwater management, combined with computer simulations of future flooding scenarios. Practical guidelines for use of pervious concrete in Finland are being developed for implementation prior to full-scale field demonstrations to be built by municipalities in 2015.

**Keywords:** permeable, pervious, pervious concrete, stormwater, urban, green, modelling, freeze-thaw, de-icing salt, durability, air entrainment.

## BACKGROUND

Worldwide, urban environments are becoming densified, with a greater percentage of horizontal surfacing covered with structures and hard, impermeable surfacing. In Finland, 85% of the population lives in urban environments (European average 72%)[1], with an annual urban population growth rate of 0.9%[2]. The environmental risks of excessive urban sprawl coupled with increasing land-take have been highlighted in the recent EU Soil Sealing Guideline [1], noting that soil sealing as a permanent covering of land area is one of the main soil degradation processes addressed in the EU’s Soil Thematic Strategy [2]. Soil sealing significantly impact water infiltration and thus flooding, while also decreasing green infrastructure. For instance of water management, a Finnish case study has shown that rainwater run-off increases from 18% to 39% when the amount of impermeable material in an urban environment increases from 50% to 69% [3].

Climate forecasts indicate that Finland will be subjected to higher volumes of rainfall and more intense storms. During this century the mean temperature in Finland is expected to rise 3.2 to 6.4°C. As a result of climate change, the annual rainfall is also expected to grow steadily in Finland during this century, at an increase rate of 12-24% depending on the scenario [HSY 2010]. Simultaneously, society aims at having better environment protection and less run-off water carrying pollutants. If surface water can penetrate to the soil faster and in higher volumes, there are many environmental benefits. These include: 1) allowing soil to extract chemicals, oils, metals and other pollutants, while replenishing the ground water level; 2) providing necessary moisture for trees and plants to thrive; 3) improving traffic and pedestrian safety by reducing ice formation associated with melting and re-freezing on surfaces; 4) maintaining lower urban environment temperatures. Governmental directive require municipalities to implement new methods for handling stormwater.

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[1] http://en.worldstat.info/Europe/List_of_countries_by_Population_in_urban_areas
[2] http://www.indexmundi.com/facts/finland/urban-population-growth

The Finnish project entitled “CLASS: Climate Adaptive Surfaces” is providing new material solutions to address these issues identified in the preceding paragraphs. The new materials developed are surfacing layers of pervious concrete (PC), porous asphalt and interlocking concrete (or stone) pavers with open-graded aggregates in joints and openings together with subbase structures of aggregate, pipes, geotextiles and water storage tanks. In CLASS, the Finnish cities’ needs have been identified as gaining information about permeable materials, structures and technical solutions in different soil conditions for the present and future climate. Their main needs are to better understand the functionality in winter conditions, maintenance, slippery and frosty conditions, preventing clogging, service life and life cycle costs. [4]

PC has been widely used since the 1980s in various applications in Japan, USA and Europe because of its multiple environmental benefits: controlling stormwater runoff, restoring groundwater supplies, and reducing water and soil pollution. The PC system must be optimized during design, construction and maintenance, while allowing high filtration of water to the substrate rather than burdening stormwater collection systems or transporting run-off pollutants to local water bodies. Clogging is an inherent property of all the pervious pavements, and proper maintenance actions are therefore essential. Laboratory scale studies by a special Filtration Simulation Rig (FS-Rig) on clogging and maintenance are also included in the CLASS-project though not included here. The overall concrete structures should also be tailored for Nordic environments to ensure their durability and service life. Pervious pavements are also evaluated with respect to secondary benefits of improving water quality and vegetation growth in the surrounding environment. Use of PC in Finland requires that the materials are durable against freeze-thaw cycles as well as designing of the subbase drainage layers to avoid deformations due to frost heave of underlying soils. [5 - 9]

PC is a concrete with interconnected effective pores, typically ranging from 1 mm to 8 mm in diameter, and with a total pore volume of 15 – 30%. Its physical characteristics clearly differ from those of normal concrete, as PC allows for a high water and air permeability. On the other hand, the compressive, tensile, and flexural strengths of PC are lower than conventional concrete due to the high void ratio and low aggregate packing ratio. This is in spite of the low water-cement ratio (w/c), from as low as 0.20 to 0.40, though a typically PC’s w/c is 0.27 – 0.34. In PC a relatively uniform aggregate size is used to ensure good water infiltration rate. The cement paste or fine mortar binds the aggregate particles together and transfers the load between the aggregates. The unit weight of PC is approximately 70 % of conventional concrete, typically from 1600 to 2000 kg/m$^3$. It is usually to have PC with strength less than 17 MPa when used in low traffic areas. For more demanding cases the strength should be higher, for instance in the range of 24 – 28 MPa. A higher effective porosity typically means lower strength (Figure 1). PC shrinks less and has higher thermal insulating values than conventional concrete. Internationally, PC has primarily been used in places with no or minor freeze-thaw exposure. For these cases the technology for PC mix design, casting, compaction and curing is already well known. In the CLASS project the main aim has been to adapt PC to hard Finnish winter circumstances. As PC is not yet available in the Finnish markets, it was necessary to start the research and development from the initial literature reviews [6, 10 – 12], prior to material designs and durability studies.

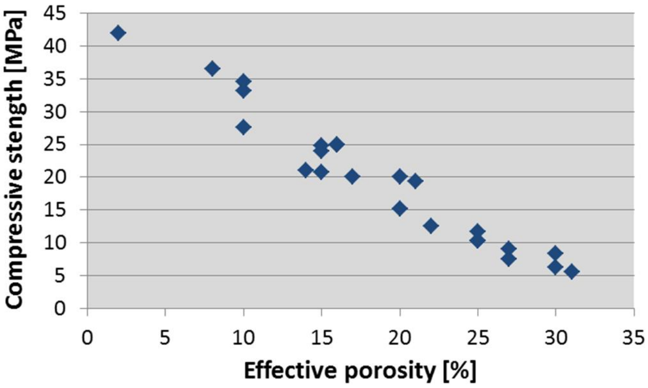

*Figure 1 - Collected values for PC strength as a function of effective porosity. [6]*

Addition of fine aggregate to PC will typically increases strength but decreases the continuous void content. However, in places with severe freeze-thaw exposure, research has shown that up to 7% fines in the mix can provide added durability without losing too much porosity. In addition, air entrainment of the cement paste or fine mortar fraction has been shown to protect the concrete to water expansion on freezing. Fine sand helps to develop the PC’s air entrained air voids during the mixing phase. Entrained air pores are needed for good freeze-thaw durability because although there is a high void content in the PC, the paste is not necessarily protected by these voids everywhere inside the PC microstructure.

According to [13], it appears that the technology to protect PC from the effects of freezing and de-icing salts already exists. Additional research is still needed to determine what should be the demand for the minimum percentage of the entrained air voids and for the maximum spacing of these voids in a low w/c PC. The demands may also be different in different geographic places of use.

There is also a need of new or revised freeze-thaw durability-related testing methods to be used in the production and conformity control to assure a long enough service life for PC. For instance, it has been found that the traditional air content measurement methods (pressure or volumetric) for fresh concrete air content are not applicable to PC. Kevern et al [14] found that the air content is over predicted due to the inability to remove all of the atmospheric air attached inside the water-permeable voids in the measurement of the fresh PC air content. They found also that Air Void Analyzer testing (AVA) is not suitable for PC. The adaptation of this method involved testing mortar obtained from fresh PC through a vibrating screed. Excessive vibration and time were required to obtain sufficient mortar samples. This was also expected to have an effect on the air pores. Overall, the findings in [14] suggested that current test methods for air content and air void systems in fresh concrete did not apply with any reliability to PC.

With regards to hardened PC air pore structure, it was found in [14] that the spacing factor of air pores determined by the RapidAir 457 test method correlated relatively well with the freeze-thaw durability (mass loss). RapidAir 457 is the most widely used automated image analysis method based on the use of plane sections with enhanced contrast between air pores and solid phase. The analysis is according to ASTM C 457 [15]. As hardened PC sample preparation means that installations with inadequate air void systems are not discovered until several days after the placement, methods to determine both fresh and hardened entrained air contents are needed. [14]

The selection of a suitable freeze-thaw testing method for PC is also problematic. The exposure of PC in the pavement includes on one hand water infiltration and on the other hand possibly also high clogging and ice formation in the pores , which both tend to increases PC water saturation and thus also susceptibility to freeze-thaw damage. Methods with high water saturation will be on the safe side but at the same time they may judge PC unnecessary rigorously. Clearly more experience on the correlation of the freeze-thaw testing methods and adapted criterions with the field performance in the place of use, e.g. in Finland, is needed.

Freeze-thaw exposure and related laboratory testing methods with de-icing salt (e.g. NaCl) must be evaluated separately from the case with no salt exposure. In this case the deterioration is known to include surface scaling, and the effect of binding material should also be considered. One additional reason for this is that the microstructural changes of the hardened binding material caused by carbonation and drying (long term ageing) are known to be influential, besides the water-cement ratio and the amount and spacing of small entrained air pores. [16] As a conclusion, all the available knowledge on the traditional concrete freeze-thaw scaling should be adapted to PC. In the Finnish CLASS-project this work was been developed further.

## MATERIALS

Finnish aggregates from Rudus Oy and cements from Finnsementti Oy were used. Admixtures were from Finnsementti Oy and Wacker Chemie AG. Basic materials for the PC-mixes are listed in Table 1, while Figure 2 presents the aggregate gradations.

*Table 1 – Pervious concrete materials used in Finnish PC study.*

Aggregates
- Astrakan SSr 0/1 (Extra fine gravel)
- Karhi SSr 0/4 (Fine gravel)
- Karhi LuoMu 4/8 (Gravel; water sieved)
- Läyliäinen SrM 8/12 (Crushed aggregate)

Cements
- CEM II/B-M (S-LL) 42,5 N (Plussementti)
- CEM I 52,5 R (Pikasementti)

Admixtures
- VB-Parmix (plasticizer; polykarboksylate based)
- Airmix (air entraing agent; syntehetic tenside based)
- Etonis 150 (polymer modifier)

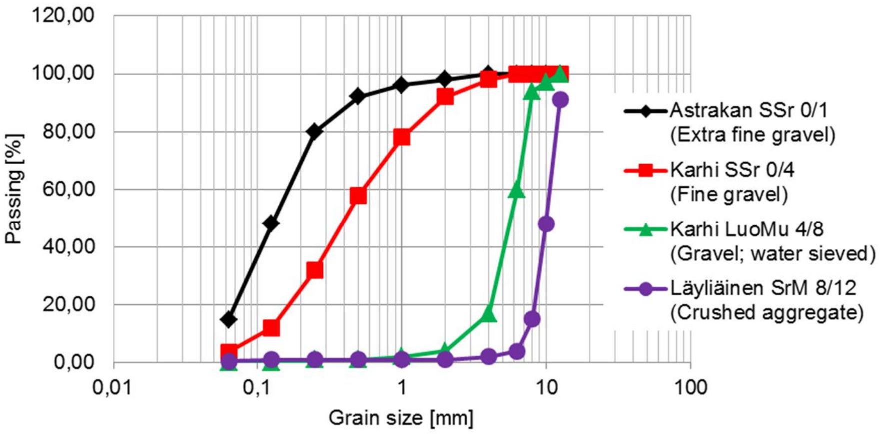

*Figure 2 – Aggregate gradations used in Finnish PC study.*

## MIXES AND MIXING

The final testing program for PC aimed at having four different mixes with different aggregates, cement and admixtures (Table 2). Before these final mixe,s several pre-mixes were made to gain experience and to select the right mix designs, including water-cement ratios (w/c) and admixture dosages, as well as methods for mixing and fresh mix testing and specimen casting. At this early phase also some new methods were created and tested, as presented below. It must be noted that the used air entraining agent was selected because it was known to be especially effective.

*Table 2 – Aggregates, cement and admixtures for the final PC-mixes.*

| PC | Aggregates | | Cement | Admixtures |
|---|---|---|---|---|
| | course | fine | | |
| PC1 | Karhi LuoMu 4/8 | Astrakan SSr 0/1 | CEM II/B-M (S-LL) 42,5 N | VB-Parmix & Airmix |
| PC2 | Läyliäinen SrM 8/12 | Karhi SSr 0/4 | CEM II/B-M (S-LL) 42,5 N | VB-Parmix & Airmix |
| PC3 | Karhi LuoMu 4/8 | Astrakan SSr 0/1 | CEM II/B-M (S-LL) 42,5 N | VB-Parmix & Etonis 260 |
| PC4 | Karhi LuoMu 4/8 | Astrakan SSr 0/1 | CEM I 52,5 R | VB-Parmix & Airmix |

In the pre-testing phase, the consistency of the PC-mixes were adjusted to be suitable. This included the right selection of cement mortar content to cover the all the aggregate particles in the mix, and the right selection of the water, plasticizer and air entraining agent amounts. Based on these studies, the effective w/c for PC was selected to be about 0.27 (water absorbed in the aggregates is not included). The main criterion was to get a mix with enough cohesion to keep the aggregate particles together, but with no visible cement paste drainage. The selection of the right air-entraining agent amount was based on a new method described below. In addition, the, hardened PC entrained air pore structure was studied by thin section analysis to be sure that there was a proper amount of small air pores in the mortar phase of the PC.

Mixing was with a normal planar laboratory concrete mixer having a maximum capacity of 240 kg or 170 litres (Zyklos). In the mixing of the final PC-mixes the full volumetric capacity was used. Some mixes for pre-testing were mixed with a smaller planar concrete mixer. First there was a short pre-mixing with aggregates and a small proportion of the mixing water. The mixing time was then 8 minutes, after the addition of all the water and admixtures. A relatively long mixing time was selected to ascertain the creation of small protective air pores for good freeze-thaw resistance.

## SPECIMEN CASTING AND COMPACTION

Slabs (505x505x150 mm$^3$) were cast by compacting samples with a roller in two layers. In some cases both layers were compacted also by using a Proctor-type hammer (4.5 kg) with a 150 x150 mm$^2$ metal plate. Additional 100 mm and 150 mm cubes were also casted with compaction normally in two layers. Different compaction methods were studied, especially in the pre-testing phase, to get information on the sensitivity of the density and open porosity to compaction. (Figure 3)

*Figure 3 – PC-slab and specimen casting and compaction.*

## TESTING METHODS

Fresh PC-mix testing included the evaluation of workability and the measurement of density and void content of freshly mixed pervious concrete [17]**.** Void content calculation is based on the mix design information and theoretical density. Theoretical density can be calculated based on the amounts and densities of the different constituents in the mix. ASTM C1688 fresh PC void content includes all the voids and pores in fresh compacted PC.

Entrained air consists of small air pores in the cement paste or mortar fraction of PC. Interconnected bigger pores, effective porosity, must not be included. For the evaluation or measurement of fresh PC entrained air amount two new methods were used.

By the first method it is possible to get fast approximate information on the amount of small air pores in PC. A small amount of PC-mix (ca. 1 dl) is introduced on the bottom of a 1 litre measuring cylinder filled with water. The PC sample is carefully mixed with the water on the bottom of the cylinder. By this way small air pores are released and they rise by buoyancy on the top of the water in the cylinder. With a proper air entrainment there will be a clear layer of small air bubbles which form a foamy layer. (Figure 7a)

By the second method (´modified pressure method´) it is possible to measure the amount of entrained air pores (% of PC, or % of cement paste or mortar phase). By this new tentative method only the small protective air pores in the PC paste fraction are measured, excluding the big interconnected voids typical for PC. Air content is measurement itself is as normally by pressure method for mortar (1 litre pot). However, the procedure before the measurement is new. First glycerol-water liquid (ca. 0.5 litre; e.g. Blue AVA-liquid which is normally used in Air Void Analyzer) is poured in the measurement pot. After that PC is carefully introduced to this liquid to almost fill the pot. (Figure 4) At this phase the big pores will disappear. They are not included in the glycerol-water liquid. Only aggregates and the mortar phase around them are introduced for the air content measurement. Subsequently more glycerol-water liquid is added to fill the pressure meter pot. The amounts of glycerol-water liquid and PC must be known (filling of the pot on a digital scale). Finally, theair content is measured as normally by the pressure method. When PC mix composition and all the densities for the PC constituents, as well as for the glycerol-water liquid, are known, it is possible to calculate PC entrained air content excluding the big interconnected voids.

*Figure 4 –Test method for entrained air content of freshly mixed PC by a tentative ´modified pressure method´. Interconnected voids are excluded.*

Thin sections were made for optical studies by direct light, polarized light or fluorescent light microscopy. Thin section consisted of a thin slice of PC impregnated with fluorescent epoxy, glued to an object glass and protected by a cover glass. Fluorescent epoxy penetration is achieved through application of a vacuum to assist epoxy impregnation. The thickness required for analysis of cement-based material is 25 - 30 µm. The area of a thin section was ca. 35 mm x 55 mm. Two thin sections for each PC were prepared.

Compressive strength (normally at 28 d) was measured as for normal structural concrete with 150 mm cubes or 100 mm cores. Density and void content of hardened PC was measured basically according to ASTM C1754 for PC.

a) b)

*Figure 5 – Water infiltration testing. a) Testing equipment for 1) ASTM C1701, 2) EN 12697-40 and 3) ASTM D3385; b) Testing by EN 12697-40 (falling head permeameter for asphalt in situ drainability).*

Hardened PC water infiltration rate was measured by four methods (Figure 5):

- ASTM C1701 (constant head infiltration rate of in place pervious concrete) [18]
- EN 12697-40 (falling head permeameter for asphalt in situ drainability) [19]
- EN 12697-19 (permeability of specimen for asphalt) [20] – no studies included here
- ASTM D3385 (double-ring infiltrometer for infiltration rate of soils in field [21]

The goal was to compare different PC mix infiltration rates as well as to determine the suitability of these methods for PC testing in the laboratory and in situ, and to get the correlation between the methods. Later on these methods will be used for the whole pervious pavement structures. These structures including stone base will be first built in a filtration simulation rig (FS-Rig), for assessing PC clogging and cleaning on the filtration rate. Different water filtration values will be needed for pervious pavement dimensioning and hydrological models.

Freeze-thaw testing with and without salt is also included in the CLASS studies, though not reported here. This testing is essential as the harsh winter season in Finland puts high demands for PC durability. Freeze-thaw testing in water is using different methods to determine the deterioration degree. These methods include determination of the relative dynamic modulus of elasticity (%) by ultrasonic pulse transit time method. Also splitting tensile strength after freeze-thaw and in comparison with the reference specimen in water (+ 20°C) is measured. Freeze-thaw with de-icing salt is with a specimen surface in contact (immersion ca. 5 mm) with 3 % NaCl-solution, after which the surface scaling of the immersed test surface is measured. The PC freeze-thaw testing methods are not exactly according to any standard method. In the CLASS-project the objective is to get experience on the testing methods and to determine what type of methods are most suitable for PC.

## RESULTS

Aggregate gradations for the PC mixes with different maximum aggregate sizes were determined. All the mixes included two aggregate types, the main course aggregate and some fine aggregate to increase durability properties. The optimized aggregate gradations are presented in Figure 6.

Results for a study on the effect of different compaction methods with two specimen sizes are presented in Table 3. It was found that the selected different ways for the compaction did not have a great effect on the PC density or void content. This was presumably because all the methods were relatively effective. Still the void content was in all the cases high enough (22 – 23 %) and the differences were small. In all these cases the void content included entrained air pores (estimated amount 2  % of PC) as the mix was air entrained.

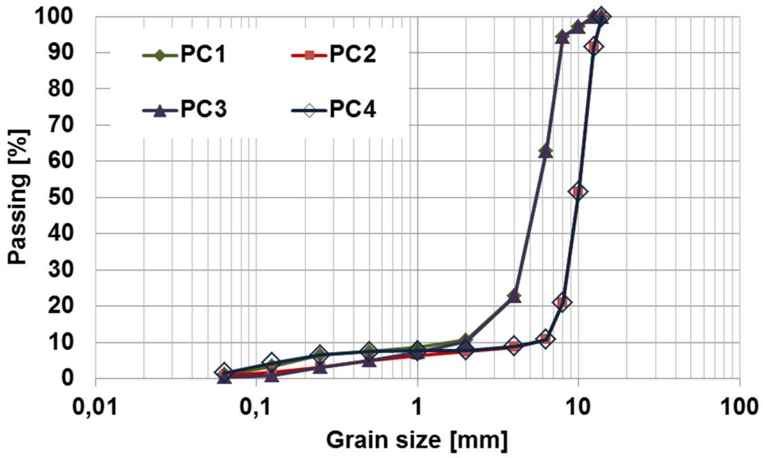

*Figure 6 – Aggregate gradations for the PC-mixes.*

*Table 3 – Effect of different ways for compaction on the PC density and void content.*

| Specimen (cubes) | Compaction (Proctor type method with 4.5 kg ) | Volume [mm$^3$] | Density [kg/m$^3$] | Void content [%] |
|---|---|---|---|---|
| Ia (150 mm) | One layer: 30 drops | 3262500 | 1987 | 22,2 |
| Ib (150 mm) | One layer: 30 drops | 3375000 | 1965 | 23,1 |
| II (150 mm) | Two layers: 5 + 25 drops | 3307500 | 1995 | 21,9 |
| III (150 mm) | Two layers: 15 + 15 drops | 3352500 | 1981 | 22,5 |
| IVa (100 mm) | Two layers. 15 + drops | 1000000 | 1980 | 22,5 |
| IVb (100 mm) | Two layers. 15 + drops | 1000000 | 1969 | 22,9 |
| Average | | | 1980 | 22,5 |
| stdev | | | 11 | 0,4 |
| Minimum | | | 1965 | 21,9 |
| Maximum | | | 1995 | 23,1 |

Fresh PC void content and compressive strength at 28 d was measured to determine if the strength was high enough compared with the high PC void content. For these tests the PC’s cement content was 300 kg/m$^3$, w/c was 0.27, and fresh PC void content was 24 %, including approximately 3 % entrained air pores. The resulting compressive strength (three 150 mm cubes) was 22,5 MPa (stdev 3,1 MPa). This was even more than expected, e.g. compared with the typical values in Figure 1.

The fresh PC entrained air pore content was measured by two tentative methods, as described earlier. Hardened PC thin sections were also made and evaluated for air entrainment (Figure 7b). Two mixes were prepared (PC1-1 and PC1-2). It was found that fresh PC included small air pores in both cases (Figure 7a). The air content in the PC determined by the ´modified pressure method´ was 2.9 % for PC1-1 and 3.8 % for PC1-2. These values had a corresponding mean of approximately 13 and 17 % of air in PC cement paste, respectively. In the optical thin section study it was also found that there were small air pores in these PC-mixes (Figure 7c – e). A quantitative thin section point-count analysis is also possible in future, and air pore spacing factor can also be determined. The new methods for air content and quality analysis can possibly be used in PC quality control to ensure freeze-thaw resistance.

Water infiltration tests were made by three different reference methods (ASTM C1701, EN 12697-40 and ASTM D3385) as earlier shown in Figure 5. One PC-slab (PC1-2) was tested for water infiltration. This PC was with 23.8 % fresh mix void content. If the estimated amount of air pores is not included, the effective porosity for this PC was 20 %. It was found that water infiltration was very high as determined by all the three methods (Figure 8). The summary of the infiltration tests included:

- With the single ring method for PC the average value with 5 subsequent measurements was 6.8 mm/s (from 5.9 to 7.2 mm/s, stdev 0.5 mm/s).
- With the EN 12697-40 falling head method, the relative hydraulic conductivity was measured ($s^{-1}$). Three subsequent measurements were made with this method. The average value was 9.1 $s^{-1}$ (from 9.1 to 9.2 $s^{-1}$, stdev 0.05 $s^{-1}$).
- With regard to the double ring method (ASTM D3385) measurements, the main conclusion was that the PC slab was too pervious compared to the measurement range for this method. It was not possible to make the measurement nicely according to the standard. This was also expected as the method is for soils. According to the standard itself, the method is difficult to use or the resultant data may be unreliable, or both, in very pervious soils (hydraulic conductivity greater than about 0.1 mm/s). The double ring method may be more applicable to PC studies after notable clogging has happened.

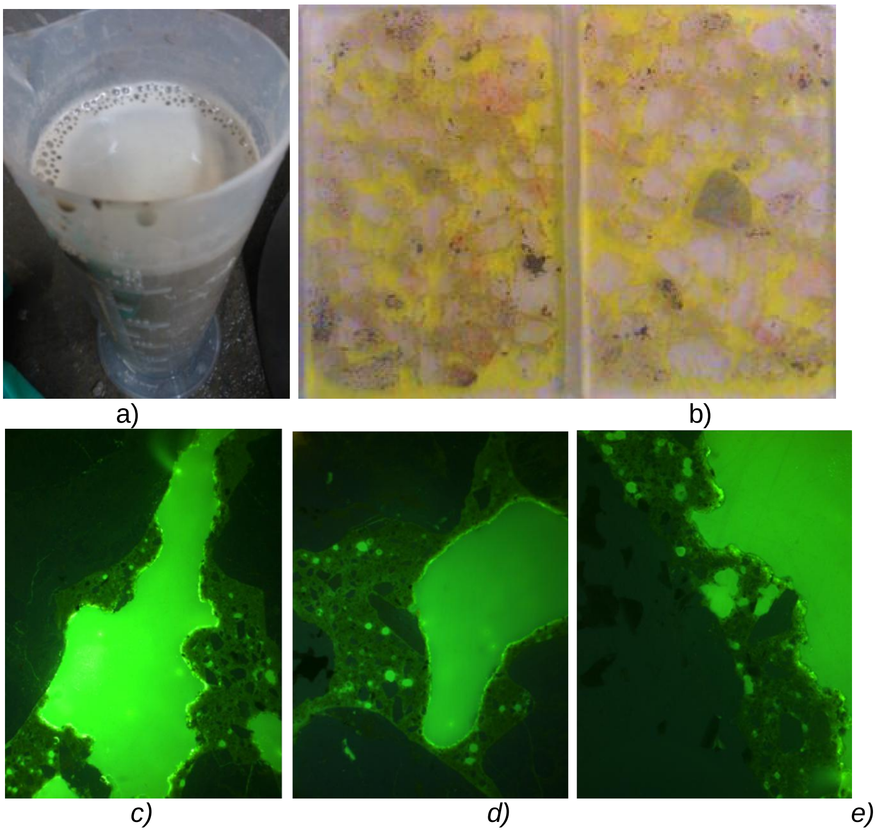

*Figure 7 – Fresh PC pore structure studies. a) A layer of small air bubbles which were released to water from the PC-mix; b) Thin sections with epoxy (yellow) in all the pores (height of the picture is 50 mm); c) – e) This section photos by microscope –interconnected big pores for water infiltration and small spherical entrained air pores for good freeze-thaw resistance (UV-light, height of the picture is 4.5 mm).*

*Figure 8 – PC-slab water infiltration measurements showing high water infiltration rate: a) ASTM single ring method for PC; b) ASTM double ring method (for soil).*

## CONCLUSIONS

The Finnish work on pervious concrete was instigated in 2012 based on the needs of municipalities to have new solutions in their stormwater management programs. Perviuos concrete surfacing combined with sub-surfacing materials has not been utilized in Finland earlier due to the lack of quantitative dimensioning and performance uncertainties for winter durability. New research has been able to evaluate materials and proportion pervious concrete mixtures to meet Finnish codes and the functionality needs for stormwater filtration.

The lab studies have focused evaluation on strength, void content and filtration to ensure performance, with special attention to the freeze-thaw durability for Nordic climates. New test methods have been developed to assess the entrained air properties related to frost resistance. The results to-date have shown that it is feasible to design and later implement pervious concrete in low-volume traffic areas. The pervious concrete can be designed to be frost resistance for arctic conditions and the proper dimensioning with subbase layers can ensure long-term filtration performance. Consistent maintenance actions are needed to sustain the filtration ability, especially with regard to removal of de-icing sand applied that may clog the voids.

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