RESEARCH REPORT

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Pervious pavement winter performance - State-of-the-Art and recommendations for Finnish winter conditions

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Summary

This report concentrates on frost heave, water infiltration and maintenance of pervious pavement during the winter period. Based on the available knowledge, recommendations on frost heave protection and maintenance in the Finnish winter conditions are given.

Pervious pavement surface infiltration capacity in freezing environments will be lowered by the ice formation in the pore structure, but can often maintain a high enough infiltration capacity also during the winter season.

Pervious pavement frost heaving is possible due to the freezing of a frost-susceptible soil below the pavement structure. Normal measures and design methods can be used to avoid too frequent frost heaving events. Uneven subground frost heave must be also considered, especially in the case of having pipes in the pervious pavement system, to maintain the right pipe inclinations. Further studies are needed to clarify more the subgrade frost heave behaviour in a porous pavement, in comparison to the normal pavement structures Thermal conductivity of the new materials should be determined by laboratory testing, both in frozen and nonfrozen state for more accurate calculations on frost depth. The risk for frost heaving of the porous base or subbase itself is very small. The risk is limited because the subbase will seldom hold water long enough to freeze in place, and because of the big open void content of the structure.

The well insulating surface layer will diminish the heat amount coming upwards from the subground. Based on the surface layer thermal conductivity and thickness, it may also be possible to estimate the risk for slipperiness. Because of the lower thermal conductivity in winter, porous asphalt surface may be about 1–2 °C, in some cases even 4 °C, colder than dense asphalt. On the other hand, as pervious pavement is able to infiltrate snowmelt, ponding of melt water and subsequent ice build-up upon the return of freezing temperatures will be reduced. The need for salting is the highest for the events when freezing rain creates icy conditions.

Winter maintenance of pervious pavement is mainly as normal but includes also some additional aspects to consider. Regular plowing is required to maintain good infiltration rate. Modifications which keep the pavement undamaged are advisable. Should the use of salt or salt solution be required, it should be limited as the salts will most assuredly be transmitted into the groundwater. If sanding is necessary, it is better to use coarse grain sand, in some cases preferably as washed, instead of fine sand. In spite of sanding, it is possible to maintain infiltration capacity by adequate cleaning of the porous pavement.

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Preface

This is a WP2 State-of-the-Art and Finnish recommendation 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 Finnish cities, companies and organizations including VTT.

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Summary

Winter performance of pervious pavement consists of several different aspects. This report concentrates on frost heave, water infiltration and maintenance during the winter period. Based on the available knowledge, recommendations on frost heave protection and maintenance in Finnish winter conditions are given.

Porous pavement frost heaving is possible due to the freezing of a frost-susceptible soil below the pavement structure. Normal measures and design methods are in use to avoid too frequent frost heaving events. Complete subgrade frost protection is most costly, and is often considered unnecessary. It has been detected that frost penetration is shallower below permeable pavements than conventional dense construction because of the insulating effect of the porous pavement. Besides, some of the freeze-thaw time period will be reduced because of the rapid thawing caused by the rain events. Also the possibly higher water content in the underlying soil can increase the latent heat available. On the other hand, it has been also found that fast changes in the air temperature are quickly reflected within the system. There is still a need for further in-situ studies to be able to clarify the subgrade frost heave behaviour in a porous pavement, in comparison to normal pavement structures.

The risk for frost heaving of the porous base or subbase is very small, and is normally not anticipated. The risk is limited because the subbase will seldom hold water long enough to freeze in place, and also because of the big open void content of the structure. The most frost susceptible would be a reservoir that is drained very slowly by a very low permeable subgrade, without any other drainage outlet.

In Finland frost heave dimensioning for street structures is typically made based on the statistical once in a 10 year freezing index. Dimensioning is based on the surface layer functional and esthetic demands. Uneven subground frost heave must be also considered, especially in the case of having pipes in the pervious pavement system, to maintain the right pipe inclinations. This may mean that the thickness of the structure must be increased to maintain the right piping slopes.

Porous pavement surface layer thermal conductivity should be determined by laboratory testing, both as in frozen and nonfrozen state. After that, based on the thermal calculations, it will be possible to estimate the effect of the porous pavement on the frost depth, compared to the frost depth in the case of normal dense pavement. Also, based on the pervious pavement thermal conductivity and thickness, it will be possible to estimate the risk for slipperiness during the early winter time. Well insulating pavement will diminish the heat amount coming upwards from the subground. This may lead to colder surface temperatures compared to the normal surface temperatures for normal dense pavements.

Pervious pavement surface infiltration capacity in freezing environments will be lowered by the ice formation in the pore structure. It has been found that pervious pavement often maintains a high enough infiltration capacity also during the winter season. It will clearly decrease surface runoff, and the high porosity stone reservoir normally continues to function as an effective storage unit. As permeable pavement is able to infiltrate snowmelt, ponding of melt water and subsequent ice build-up upon the return of freezing temperatures will be reduced. Anyway, more experiences are needed on the infiltration capacity in the Finnish winter conditions, and under Finnish maintenance practices. Future pilot projects will be useful for this as it is impossible to get authentic results in the laboratory. Different climates as freeze-thaw cycling and rain frequencies will have an effect on the winter and spring snow smelt period infiltration capacity. It is good to have pilot studies in different parts of Finland in the future.

Winter maintenance of pervious pavement is mainly done similar to normal pavements but includes also some additional aspects to consider. These include practices of snow plowing, and can also include de-icing as salting and sanding. Regular plowing is required to maintain

the infiltration rate. Unplowed snow may form compacted snow and ice covers, and the melt water infiltration lags. Some modifications in maintenance are useful, and will keep the pavement undamaged. Plowing can be done so that there is a small distance between the plow and pavement surface, or a plow with a lower edge made of plastic or rubber, or a rotary broom, can be used. Should the use of salt or salt solution be required, it should be limited as the salts will most assuredly be transmitted into the groundwater. If sanding is necessary, it is better to use coarse grain sand instead of fine sand. In spite of the clogging caused by sanding it is possible to maintain the infiltration capacity by taking care of adequate and effective cleaning of the pavement. To detect possible low infiltration, simple water infiltration measurements should be carried on regularly.

The need and the efficiency of salting is different for highways and roads, compared to e.g. parking areas and other areas with lower traffic intensities and traffic speeds. The need of salting on a porous asphalt highway surfaces appears to be ambivalent. Some studies claim that the need of salting is reduced compared to conventional asphalt, the others that the need for salting is increased. Because of the lower thermal conductivity in winter, porous asphalt surface may be about 1–2 °C, in some cases even 4 °C, colder than dense asphalt. On the other hand, melt water does not stand and freeze on the porous surface. The need for salting is the highest for the events when freezing rain creates icy conditions.

Yhteenveto

Vettä läpäisevien pinnoiteratkaisujen talvikäyttäytyminen koostuu kaikkiaan useista tekijöistä. Tämä raportointi keskittyy routimiseen, talvikauden vedenläpäisevyyteen ja talvikauden kunnossapitoon. Käytettävissä olevaan tietoon perustuen annetaan Suomen olosuhteita vastaavat suositukset näiden osalta.

Läpäisevän pinnoiteratkaisun routiminen on mahdollista, jos sen alla on routiva maaperä. Liian usein toistuvaa maaperän routimista, johon liittyy haitallista routanousua, voidaan ehkäistä normaaleilla routimisen ehkäisytavoilla ja suunnittelumenetelmillä. Maapohjan täydellinen routasuojaus on kaikkein kallein menettely eikä sitä yleensä pidetä välttämättömänä. On olemassa havaintoja, joiden mukaan roudan syvyys läpäisevän pinnoitteen alla on pienempi kuin tavanomaisen tiiviin katurakenteen alla. Tämän katsotaan johtuvan huokoisen rakenteen eristävästä vaikutuksesta. Lisäksi sateet voivat sulattaa keväällä jäätynyttä maaperää tavallista nopeammin, kun sadevesi pääsee tunkeutumaan läpäisevien rakennekerrosten läpi maapohjaan asti. Lisäksi, jos vesimäärä muodostuu läpäisevän pinnoitteen alla tavallista suurempi, kasvattaa se lämpömäärää ja hidastaa jäätymistä. Toisaalta on myös havaittu, että ulkolämpötilan nopeat muutokset voivat heijastua nopeasti rakennekerroksiin jolloin niiden lämpötila voi laskea tavallista nopeammin. Läpäisevien rakenteiden routakäyttäytymisen osalta onkin vielä olemassa lisätutkimustarve, jotta pohjamaan routiminen ja sen suhde tavanomaisen rakenteen routimiseen voitaisiin ennakoida riittävän tarkoin.

Suomessa katurakenteiden routamitoitus tehdään tyypillisesti tilastollisesti keskimäärin kerran 10 vuodessa esiintyvän pakkasmäärän perusteella. Päällysrakenteelle sallittava mitoitusroutanousu määritetään päällysrakenteen toiminnallisten tai ulkonäöllisten vaatimusten perusteella. Piha/katurakenteelle tyypillisesti sallittava routanousu kerran 10 vuodessa toistuvalle talvelle on 50–100 mm. Huonosti vettä läpäisevillä pohjamailla käytetään kuivatusputkia läpäisevien päällysteiden yhteydessä. Tällöin, jos rakennuskohteessa on odotettavissa pohjamaan epätasaista routimista, tulee päällysrakenteelle sallittua mitoitusroutanousua pienentää eli päällysrakenteen paksuutta lisätä, jotta kuivatusputkien pituuskaltevuudet säilyvät.

Läpäisevän päällysteen jäätyneen ja sulan tilan lämmönjohtavuus tulisi määrittää laboratoriokokein. Lämpöteknisten laskelmien perusteella voidaan tällöin arvioida päällysteen vaikutusta routimissyvyyteen läpäisemättömään perinteiseen päällysteeseen verrattuna.

Itse läpäisevän rakenteen kantavan ja jakavan kerroksen routimisriski on erittäin pieni. Onkin yleistä olettaa, että näiden kerrosten routimista ei tapahdu. Riski on pieni, koska kerroksissa on suuri huokostilavuus ja huokoset ovat toisiinsa yhteydessä, jolloin rakenne ei pidätä vettä niin kauan, että se ehtisi haitallisessa määrin jäätyä. Periaatteessa näiden vettä varastoivien kerrosten routimisriski on suurimmillaan silloin, kun vesi siirtyy hitaasti erittäin pienen läpäisevyyden maaperään eikä vedelle ole muutakaan poistumistietä kuten putkitusta.

Läpäisevän rakenteen pintakerroksen vedenläpäisevyys pienenee, kun sen huokosrakenteeseen muodostuu jäätä. Kuitenkin on havaittu, että läpäisevän päällysteen vedenläpäisevyys pysyy riittävän suurena myös talvikautena. Päällyste pienentää pintavirtaamia myös talvella ja vesi voi varastoitua alla oleviin huokoisiin rakennekerroksiin. Koska sulava lumi voi siirtyä läpäisevän pintakerroksen läpi alaspäin eikä se jää läpäisevän rakenteen pintakerroksen päälle, pinnalle muodostuu tavallista vähemmän jäätä lämpötilan laskiessa sulamisvaiheen jälkeen. Suomen talvikauden olosuhteissa ja huoltokäytännöissä läpäisevien pinnoitteiden vedenläpäisykyvystä tarvitaan kuitenkin vielä lisää käytännön tietoa ja kokemuksia. Näitä voidaan jatkossa saada in-situ pilot-projekteissa. Todellisia luonnonolosuhteita vastaavaa käyttäytymistä, jossa merkitystä on mm. lämpötilavaihtelulla, sademäärillä ja niiden ajoittumisella sekä auringon säteilylämmöllä, on vaikea jäljitellä täysin laboratoriokokein. Pilot-projekteja on jatkossa syytä käynnistää eri puolilla Suomea ilmastoltaan toisistaan poikkeavissa paikoissa.

Vettä läpäisevien pinnoitteiden talvikauden aikainen huolto on pääosin samanlaista kuin muidenkin vastaavasti liikennöityjen alueiden huolto. Se sisältää kuitenkin joitakin huomioon otettavia lisätekijöitä. Säännöllinen auraus on tarpeen vedenläpäisevyyden ylläpitämiseksi. Auraamaton lumi voi tiivistyessään muodostaa tiiviin jäisen pinnoitteen jolloin sulava vesi ei enää läpäise pintaa ja pääse siirtymään alapuolisiin vettä varastoiviin kerroksiin. Aurauksessa tulee kuitenkin ottaa huomioon tietyt tekijät läpäisevän pinnan vaurioitumisen ehkäisemiseksi; auran ja pinnan välissä tulisi olla pieni rako tai auran alareunassa voidaan käyttää muovi- tai kumireunusta joka pehmentää aurauksen kuluttavaa vaikutusta.

Tietyin edellytyksin myös liukkauden torjuntaa eli suolausta ja hiekoitusta voidaan tehdä. Jos suolausta joudutaan tekemään, sen tulisi olla mahdollisimman vähäistä. Suola siirtyy suurella todennäköisyydellä suoraan alapuoliseen maaperään ja pohjaveteen mikäli vettä läpäisevään pinnoitteeseen ei sisälly putkitusta, joka johtaa veden toisaalle. Jos hiekoitus on tarpeen, tulisi käytettävän hiekoitushiekan olla rakeisuudeltaan mahdollisimman karkeaa ja joissakin tapauksissa mieluiten lisäksi pestyä eli ilman hienoainesta. Joka tapauksessa pinnan vedenläpäisevyyttä on mahdollista ylläpitää huolehtimalla asianmukaisesta, tehokkaasta ja säännöllisestä puhdistuksesta. Vedenläpäisevyyttä ja sen mahdollista alenemista voidaan seurata yksikertaisin pintamittauksin.

Läpäisevän päällysteen lämmönjohtavuuden ja paksuuden avulla voidaan myös arvioida läpäisevän pinnan liukkausriskiä alkutalvesta. Lämmönjohtavuudet tulisi määrittää kokeellisesti. Hyvin eristävä päällyste pienentää maasta vapautuvan lämmön ylöspääsyä, jolloin pinta voi olla selvästi kylmempi kuin perinteisen päällysteen pinta. Toisaalta läpäisevä päällyste reagoi tavallista nopeammin ulkoisiin olosuhteisiin ja erityisesti vesi pääsee sulattamaan sitä ja alapuolista maaperää.

Talvisuolauksen tarve ja sen teho on erilainen vilkkaasti liikennöidyille väylillä ja toisaalta esimerkiksi parkkialueilla ja muilla alhaisen nopeuden ja pienen liikennemäärän alueilla. Esimerkiksi valtateiden, joissa pintana on avoin asfaltti, suolaustarpeesta ja sen tehosta on saatu osin ristiriitaisia tuloksia. Joidenkin tutkimusten mukaan suolaustarve on tavallista pienempi suhteessa tavanomaiseen asfalttiin, mutta joidenkin tutkimusten mukaan se on suurempi. Koska avoimen asfaltin lämmönjohtavuus on tavallista pienempi, voi sen pinta olla 1–2 °C, joskus jopa 4 °C, alhaisempi kuin tavanomaisen asfaltin pinta. Toisaalta sulanut vesi ei jää vettä läpäisevälle pinnalle eikä näin ollen myöskään muodosta jääkerrosta lämpötilan laskiessa. Vettä läpäisevän pinnoitteen suolauksen tarve on tyypillisesti suurimmillaan silloin, kun jäätävä sade muodostaa liukkaan pinnan.

Contents

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 adjacent to the soil. 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.

The use of permeable pavements in cold climates and winter conditions has many challenges, most of which relate to the extreme cold and frost penetration into the porous media. Cold climate and freeze-thaw cycles may potentially affect both the structural and hydrological performance of the permeable pavement system, especially if frost and freeze-thaw effects are not properly considered. [Virginia DCR 2011, Henderson 2012, Ferguson 2005]. Permeable pavement winter performance consist of:

- overall structural performance in freeze-thaw, i.e. the effects of frost heave caused by subgrade performance and pavement reservoir performance,
- surfacing material performance in freeze-thaw, including the effects of possible de-icing chemicals (see Chapter ´Pavement materials´ in [Kuosa et al. 2013])
- water infiltration rates during wintertime and snowmelt period,
- performance in winter maintenance:
    - clogging caused by sanding (see Chapter ´Clogging and maintenance´ in [Kuosa et al. 2013])
    - snow and ice cover,
    - skid resistance and friction,
    - effects of the possible use of de-icing chemicals, widely including also the effects on subsoil and ground-water (see [Loimula & Kuosa 2013]),
    - mechanical effects of snow removal as plowing.

This report includes State-of-the-Art information on the porous pavement winter performance, and also recommendations for Finnish winter conditions.

Pavement surface layer material (Pervious concrete (PC), porous asphalt (PA) and pavers in interlocking pavements (IP)) freeze-thaw durability is not included in this report, but is reviewed in [Kuosa et al. 2013] (in Chapter *´Pavement materials´)* and experimentally studied in [Kuosa et al. 2014]. Anyway, as discussed in [Kuosa et al. 2013], protection of the surfacing materials is also linked to the functioning of pavement reservoir as it has the ability to keep the surfacing material in a not fully water saturated state. This greatly decreases the possibility of freeze-thaw damage of the surfacing materials during the freezing events.

1.1 Freeze-thaw and frost heave

1.1.1 State-of-the-Art and General

The frost susceptibility of pavement subsoil plays a role if located above the freezing line in frost susceptible soil. Frost heaving is possible due to freezing of a frost-susceptible soil having access to water. The risk of frost heaving may be estimated from correlation with soil classification properties (particle size distribution, height of capillary rise and/or fines content). In unclear cases frost heaving tests in a laboratory for the pervious structure and subgrade material are possible. [EN 1997-2: 2007]

Design modifications that provide for an adequate subbase layer reduce frost heave risk. Subgrade frost heave and pervious pavement damage caused by it can principally be limited by several approaches. Complete protection from frost means putting only those pavement structures that are well drained and nonsusceptible to frost damage within the frost penetration zone. A thick layer of paving material insulates well. Thicker material layers may be needed than with regard to bearing capacity only. This kind of complete subgrade frost protection method is most costly, and often considered uneconomical and unnecessary. A less expensive method is to allow limited subgrade frost penetration. This means that some frost penetration is allowed, including penetration in frost-susceptible soils, during e.g. a ten-year freezing event. Different American standards require the upper 50–65% depth of ten-year frost penetration depth being non-susceptible material; the bottom 35–50% may be susceptible. [Ferguson 2005, Stenmark 1995]

Pervious pavement structures incorporating frost heave reducing design features have been used successfully in Nordic countries [Stenmark 1995]. Successful longer term installations of pervious concrete pavements in regions of cold weather also have been documented in North America. [Delatte et al. 2007, NRMCA 2004, Houle 2008].

In a porous structure the water does not pond on the surface; it rather flows downwards and forms ice in the lower layers or recharges away. Reservoirs that are drained soon by highly permeable subgrades or lateral pipes are not considered critical with regards to potential frost damage. They will seldom hold water long enough to freeze in place. Moisture and earth will provide some heat, and there will be such a delay in the freezing of base/subbase that both can drain prior to freezing. Besides, the big void percent of the underlying reservoir layer normally allows expansion of water without heaving, and protection of reservoir layers is far less critical than the protection of the subgrade. Ponded reservoir water is also in a sense self-insulating. When it freezes, it delays freezing temperature from penetrating because of the heat made available from the water´s change of state. The most frost susceptible is a reservoir that is drained slowly by low permeable subgrade, without any other drainage outlet. The addition of lateral drainage pipes at some elevation will decrease the possibility of frost damage event. [Ferguson 2005, Smith 2011]

Because of the low risk, and lack of Nordic experiences, pavement heaving caused by reservoir layer freezing is not anticipated in pavement design manuals, as in e.g. the American Association of State Highway and Transportation Officials (AASHTO) Guide for design of pavement structures (1993), and in the instructions *by U.S. Department of Army and Air Force (1992) for Pavement design for roads, streets, walks and open storage areas*. [Ferguson 2005, Houle 2008, Roseen et al. 2012]

Bäckström (2000) monitored winter temperatures of a porous asphalt and conventional asphalt in Luleå, Sweden. This study was performed in a housing area where there was no sanding nor salting operations during winter. Clogging, maintenance and de-icing effects were not considered. The porous asphalt base (the road was rebuilt by replacing the old subbase with a base of macadam (grain sizes of 16–80 mm) was drained with a pervious pipe and was installed on silty moraine soils with high clay content.

According to Bäckström (2000) the permeable pavement had a lowered risk for frost heave damage. The frost penetration depth was decreased for the permeable pavement, and the frost period was shorter compared to an impermeable pavement. (Figure 1) A greater frost penetration depth was obtained during the cold winter of 1995/1996. The impermeable pavement was frozen to 1.6 m below the asphalt surface (0.6 m below the subgrade) in February and March. The ground was frozen below the subgrade from early December to April. In the porous pavement, the maximum frost penetration depth during 1995/1996 was 1.4 m below the asphalt surface. Thawing of the underlying soil occurred 1 month earlier than in the impermeable pavement.

It must be noted that there was not an acceptable interdependence between frost heave and frost penetration depth. The reason for this anomaly was expected to be the fact that the porous pavement had already started to thaw at the time of the measurement. Consequently, it was perhaps not the maximum frost heave that was measured. [Bäckström 2000]

Higher water content in the underlying soil was detected by Bäckström (2000) in the case of permeable pavement. Infiltration of stormwater most likely increased the soil water content in the porous pavement, which increased the amount of latent heat available. Studies by Hogland & Wahlman (1990) of porous pavements and impermeable pavements in Lund in southern Sweden also showed that the water content increased in the soil below the subgrade of a porous pavement [Bäckström 2000].The porous asphalt surface also thawed earlier because infiltration of melting snow and ice helped to warm the underlying stone reservoir. The thawing process in a comparable impermeable pavement was clearly slower. The shallower frost penetration beneath the porous asphalt was expected to be attributed also to the heat insulating effect of air in the porous pavement. More rapid infiltration of melt water has the additional benefit of reducing the potential for slip hazards as there is less water on the surface that can freeze during cold nights. The study included measurements of ground temperature, frost penetration depth, frost heave, groundwater levels and also runoff measurements. It was found that the snowmelt runoff volumes could be reduced by 50–60% by the use of permeable pavement.

A conclusion by Bäckström (2000) was that there is a need for further studies to be able to clarify the mechanisms of frost heave in a porous pavement, and also further investigations of porous pavement performance during thaw are needed, as studies of bearing capacity. [Bäckström 2000]

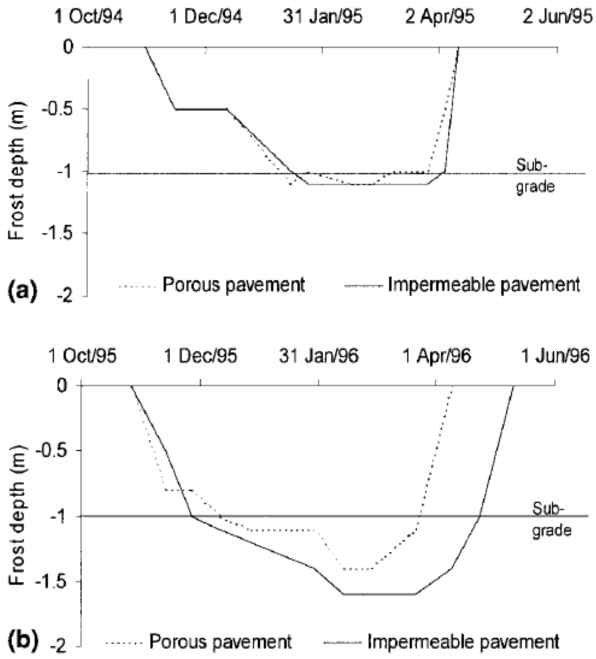


Figure 1. Frost Penetration in Porous Pavement and Impermeable Pavement during: (a) 1994/1996; (b) 1995/1996 ("cold winter"). [Bäckström 2000]

According to [Virginia DCR 2011] and [Henderson 2012] in maintaining the structural durability of pervious pavement in cold climates the following design adaptations may be helpful:

- Designs should not allow water to pond in or above the permeable pavement.
- Complete drainage of the permeable pavement system within 24 hours following a rainfall event should be ensured.
- The filter bed and under-drain pipe should be extended below the frost line and/or the under-drain should be oversized by one pipe size, to reduce the freezing potential.

In the study by Houle (2008) frost depth penetration within the PA system was measured using a "field assembled frost gage". In this case, the maximum frost depth was 0.7 m. It was found that PA exhibited normal maximum frost penetration to soil, even with several inches of open graded surface material. The data showed that frost depth penetration in PA was highly influenced by the air temperature and abrupt changes in the temperature were quickly reflected within the system. As in the study by Bäckström (2000), the PA thawing correlated with rain events. The rapid thawing of the PA was considered a significant finding. If the system is thawing weeks earlier than expected, much of the freeze-thaw time period is reduced, helping to decrease the risk of pavement failure. After four winters of observation (2004–2008), no noticeable heaving of the porous asphalt surface was witnessed. [Houle 2008]

Comprehensive studies by Ferguson (2005) undertaken in the U.S.A into the performance of permeable pavements failed to find an example of a permeable pavement in a cold climate that had failed due to frost damage. This included one example of a 550 mm deep pavement in an area with frost penetration up to 1800 mm that had not experienced any objectionable distortion over 10 years. It was also found that frost penetration was shallower below permeable pavements than conventional dense construction because of the insulating effect of the pavement. [Interpave 2007, Ferguson 2005]

1.1.2 Recommendations for Finnish winter conditions

In Finland the most common soil is moraine, which is very susceptible to frost heaving, as also silty soils. Frost heaving may widely and severely break road structures which are exposed to alternating temperature and freeze-thawing.

In Finland local freezing index (h °C) values are used to estimate for instance the ground frost depths. For the whole winter season this value is calculated based on the daily average temperatures, as presented in Equation 1. Here both the negative and positive differences from the freezing point (0 °C) are counted. There are also some other more minor detailed rules for this calculation which are presented in [RIL 261 2013].

$$F = 24 \cdot \sum_j (T_f - T_{d,j}) \tag{1}$$

where

F	is	freezing index for the whole winter season, h °C
T_f		freezing point 0 °C
$T_{d,j}$		average daily temperature for the day j, °C.

The yearly average freezing index (h °C) is different for Southern Finland and Northern Finland. For Southern Finland this value is 11000 h °C, and for the Northern Finland it is 44000 h °C. For very frost susceptible silty grounds the frost depth in a courtyard/street structure is for an average winter ca. 1.2 m in Southern Finland, and ca. 2.3 m in the Northern Finland. Once in 10 years freezing index for Southern Finland is 22000 h °C and for Northern Finland this statistical once in a 10 year value is 58000 h °C (see also Figure 2). Based on these 10 year statistical values, the corresponding frost depths are about 1.7 m and 2.7 m. For frost susceptible moraine grounds the frost depths are typically even more than the preceding values for the silty grounds.

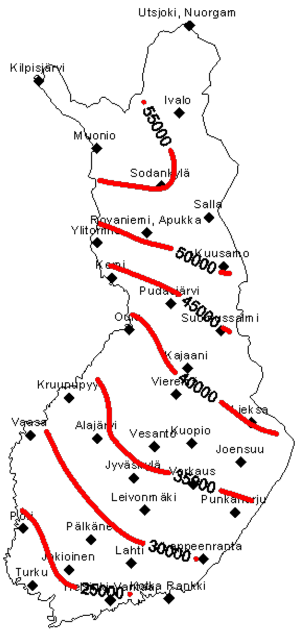


Figure 2. Once in a 10 year freezing index value (F10, h °C) [RIL 261 2013].

The thickness of a courtyard/street structure pavement layer is determined based on the frost heave suspectibility, local dimensioning freezing index and the allowed frost heave amount (mm). Structural bearing capacity demands must also be fulfilled.

In Finland frost heave dimensioning for street structures is typically made based on the statistical every 10 year freezing index. [RIL 261 2013] The allowable dimensioning frost heave amount for the pavement structure is based on the surface layer functional and esthetic demands. The typical allowable frost heave amount for a courtyard/street structures is 50–100 mm calculated based on the statistical every 10 year freezing index.

When the subground water infiltration capacity is low, piping is normally used in the pervious pavement structure. In this case, if uneven subground frost heave is expected, allowable dimensioning frost heave must be lower than normally in the case of even frost heave. This means that the structure must be thicker to maintain the right piping inclinations.

The porous pavement surface layers thermal conductivity should be determined by laboratory testing, both as in frozen and unfrozen state. For trusty calculations, these values are needed also for the open graded base and subbase. After that, based on the thermal calculations, it will be possible to estimate the effect of the porous surface layer on the frost depth, compared to the frost depth in the case of normal dense surface layer. Also, based on the pervious surface layers´ thermal conductivity and thickness, it will be possible to estimate the risk for slipperiness during the early winter time. The well insulating surface layer will diminish the heat amount coming upwards from the subground. This may lead to colder surface temperatures compared to the normal surface temperatures for normal dense surfaces.

1.2 Water infiltration

Frozen soil, sand and gravel

Numerous studies have investigated the effect of frozen ground on the meltwater runoff in cold regions. Catchment runoff studies in areas with permafrost or seasonal soil frost have demonstrated the hydrological effects of frozen ground at the large scale. Local process studies showed that the soil infiltration capacity is normally reduced by the presence of pore ice, which may generate considerable surface runoff and decrease the underlying groundwater recharge. But it has also been demonstrated that meltwater is able to percolate through the frozen layer through air-filled pores. [Bayard et al. 2005, Nyberg et al. 2001]

Drainage through frozen soils is affected by the formation and presence of ice in the porous matrix in comparison to similar unfrozen soils. As water added to the soil by rain events or by melting snow drains through a frozen soil, a fraction of the water will be retained in the pore space and eventually freeze. With repeated infiltration of water, the pore space will become saturated with ice, restricting any additional infiltration of water. [Fourie et al. 2006] This ice formation is a dynamic process affected by the environment, as especially temperature fluctuation, rain and also smelting snow. Ice formation can be different at different depths, or in different layers of the pavement.

There are several studies on the permeability of frozen sand, gravel or other course soils that may give information adaptable also to pervious pavements. Komarov (1957) measured permeability of frozen sand that had a porosity of 40%, water content oven dry weight from 2 to 17% and pore ice saturation of 3 to 60%. The permeability reduced from 0.1×10^{-3} m/s at 3% of ice to 0.001×10^{-3} m/s at 27% of ice. Temperature prior to infiltration was -5 °C, and temperature of water infiltrating into the frozen sand was 0 °C. During infiltration, the soil temperature increased to -0.2 °C. [Fourie et al. 2007]

Mukhetdinov (1984) studied the change in permeability in gravel (14/43 mm), and the formation of infiltration ice. In these experiments, the ice formed mainly in vertical veins. [Fourie et al. 2007]

Olovin (1993) studied the permeability of frozen coarse soils using air as fluid. Results from over 3000 tests generally showed that permeability decreased by approximately two to three orders of magnitude with an increase in saturation of up to 50%. In many of these tests the permeability of soil with pore ice saturations up to 20% was greater than the permeability of dry soil. Kaliuzhnyi and Pavlova (1981) also noticed this effect. It was hypothesized that the ice formation at the soil particle interfaces pushes the soil particles away from one another, thus increasing the size of pore at low enough water content. [Fourie et al. 2007]

As the amount of pore ice present impacts the strength characteristics of the soils as well as the flow of fluid through soil, Fourie et al. (2007) studied the impact of gradation, temperature, compaction and initial moisture content on the formation of pore ice in coarse grained soils. The aim was to prepare a conceptual model of the freezing mechanism in coarse grained soils, and to qualify the parameters that influence the ice formation. Infiltration columns and X-ray computed tomography were used for this investigation. Well graded soil, a uniformly graded pea gravel with average particle diameter of 6.25 mm, and a uniformly graded coarse gravel with average particle diameter of 25 mm were studied. The gradation proved to be an important parameter as to the location of the initial ice layer. Infiltration of melt water into both gravels resulted in an ice layer forming at the bottom of the column, where there was a small sized mesh. The mesh openings retained water which eventually froze, blocking drainage pathways for subsequent additions of melt water. The process of pore ice formation in a uniformly graded soil is shown in Figure 3.

In contrast, in the well graded gravel, a frozen barrier was rapidly created near the top of the column. Already, the addition of relatively smaller soil particles to an otherwise uniform coarse grained soil reduces the individual pore size in the soil, and a greater amount of soil–water is retained in the soil after drainage. In freezing, the retained water eventually freezes to ice further reducing pore size and eventually blocking drainage pathways for subsequent additions of melt water (see Figure 4).

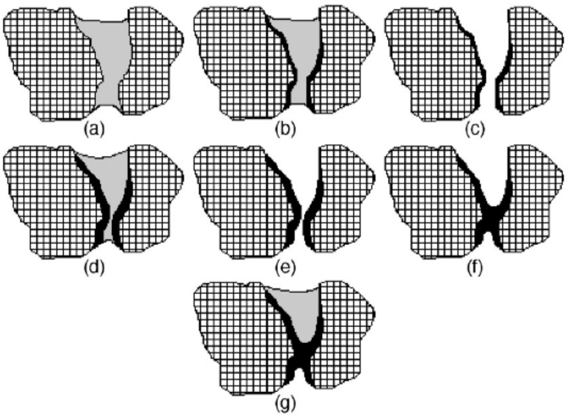


Figure 3. The hypothetical freezing of coarse grained soils from infiltration of meltwater. In (a) the pore is filled with melt water. As water drains through the pore, a fraction of the water freezes to the pore walls (b) and then drains (c). Successive infiltration causes additional freezing to the pore walls (d) and (e) until the pore has been closed off (f). Thus the pore throat has become a dead end that will eventually fill with ice (g). [Fourie et al. 2007]

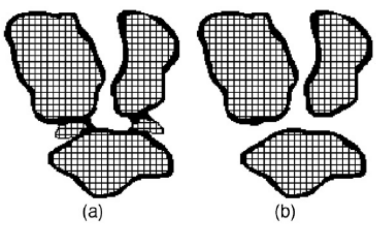
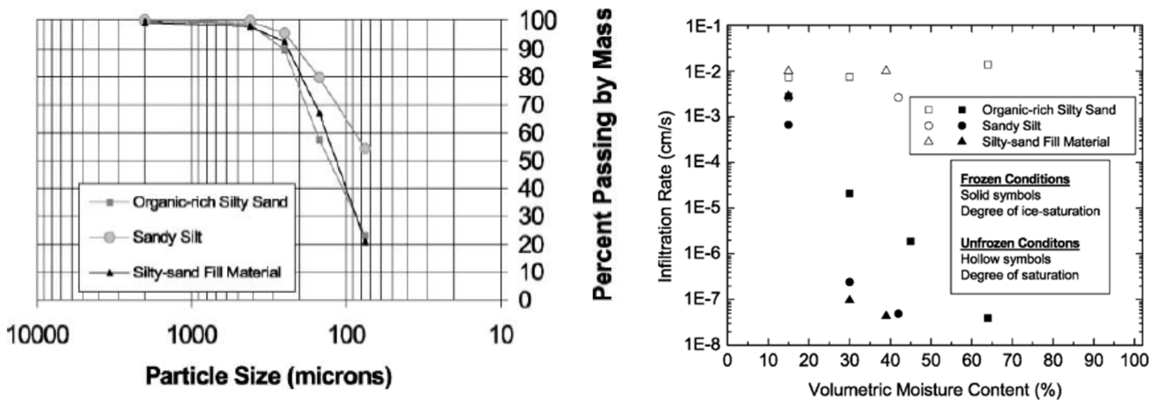


Figure 4. Pore ice formation in coarse grained soils with (a) and without (b) the presence of smaller particles. Further additions of water to the pore space shown in (a) will result in the pore becoming either filled with ice or entrapped air. [Fourie et al. 2007]

The purpose of a study by McCauley et al. (2002) was to investigate the potential for frozen soil to serve as a barrier for depth penetration of spilled fuel. Laboratory tests quantified hydraulic conductivities, permeabilities and also fuel infiltration rates for three soil types collected at a fuel storage facility in Bethel, Alaska. These soil types were organic-rich silty sand, sandy silt and silty sand. Figure 5a shows the grain size distribution for the three soils. Tests for frozen samples were conducted in a cold room at -4 °C. Figure 5b displays average infiltration rates versus moisture content, both as frozen and unfrozen. Moisture content reflects volumetric soil moisture prior to freezing. Hydraulic conductivity rates in frozen and unfrozen soils were within an order of magnitude for each soil type prepared at a volumetric moisture content of 15%. Soil samples prepared at higher soil-moisture contents exhibited higher ice contents when frozen. Increased ice content resulted in a considerable decrease in hydraulic conductivities. Infiltration rates measured in the laboratory were comparable with the in situ infiltration rates measured in situ on ice-saturated soils by [ASTM D5093 2008].



a) b)

Figure 5. a) Grain size distribution for the soils; b) Infiltration rate relationship with volumetric soil-moisture content for frozen and unfrozen soil specimens. [McCauley et al. 2002]

Pervious pavement

Several studies have also been made on pervious pavement surface filtration capacity in freezing environments, or more extensive winter performance studies including also studies on water infiltration. [Houle 2008, Houle et al. 2009, Stenmark 1995, Bäckström & Bergström 2000]

Holue (2008) made a comparative study of porous asphalt, pervious concrete, and conventional asphalt in a northern climate. Frost penetration was observed to reach depths of 0.46 m. However, surface infiltration capacities remained in excess of 1.4×10^{-3} m/s. In the case when pervious pavement pores are clogged, and infiltration capacity is reduced, water may form ice covers. Ice may also clog the surface layer in some cases so that e.g. spring snowmelt runoff may increase temporarily.

Stenmark (1995) and Bäckström & Bergström (2000) found that infiltration capacity reduced in winter period but remained “sufficient functioning” (ca. 3×10^{-7} – 1×10^{-6} m/s) in snowmelt conditions. The main focus in a study by Bäckström & Bergström (2000) was to evaluate the function of porous asphalt (PA) in cold climates. The draining function of PA was measured in a climate room with adjustable temperature in the range of -10 °C to +20 °C. At the freezing point, the infiltration capacity of PA was ca. 50% of the capacity at +20 °C. To study the effect of snowmelt period, PA was exposed to alternating melting and freezing during 2 days. In this case the infiltration capacity was reduced by ca. 90%. Even at this rate, however, the pavement still infiltrated at a rate of between 1.6×10^{-5} m/s and 8.3×10^{-5} m/s, which is similar to that of a relatively well drained agricultural soil. (Figure 6)

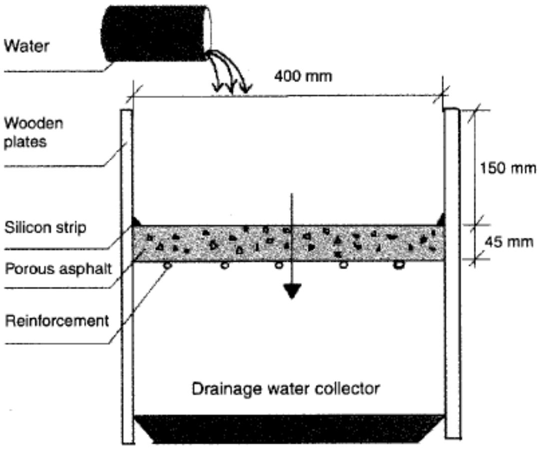


Figure 6. Measurement of PA drainage in a climate room with adjustable temperature. [Bäckström & Bergström 2000]

Favourable performance of a permeable interlocking concrete paver system during winter was also observed in an installation in King City, Ontario, Canada. Even with above ground air temperatures as low as -25 °C, the stone reservoir continued to function as an effective storage unit. Because the permeable pavement was able to infiltrate snowmelt, ponding of melt water and subsequent ice build-up upon the return of freezing temperatures, was reduced. [TRCA 2009, TRCA 2007]

Roseen et al. (2012) investigated the performance of porous asphalt (PA) in coastal New Hampshire, U.S.A, where 6 months of subfreezing temperatures typically occur. Studies were during two years and the area was subject to the normal winter maintenance actions of sanding and salting. The PA system performed impressively despite the cold-climate challenges. The porous pavement system function remained strong for hydraulics and water quality during the coldest periods of the year. Surface infiltration capacity remained high throughout the year despite substantial frost penetration (maximum 71 cm). No consistent statistical difference was observed for seasonal hydrologic performance with mean infiltration capacity ranging from 4.1–7.5 × 10^{-3} m/s. According to Roseen et al. (2012), the persistence of infiltration capacity during periods of prolonged frost penetration indicated that the coarse open-graded materials retained significant porosity and remained well-drained throughout the year.

Figure 7 presents some results by Roseen et al. (2012). Frost under PA clearly followed changes of air temperature compared to nonpermeable reference site. At the reference site the frost depth remained very even and thawing lasts about one month longer than in PA during spring. Frost penetration was also deeper in PA than in the reference site, but this did not affect the hydrological performance. There were not any observable frost heaving, no runoff occurred and peak flow was reduced significantly. In this study there were no statistical differences in the seasonal hydrologic performance and the mean infiltration capacity. Infiltration capacity followed the air temperature, but remained sufficient high to maintain the performance of the pavement also during the winter periods. [Roseen et al. 2012]

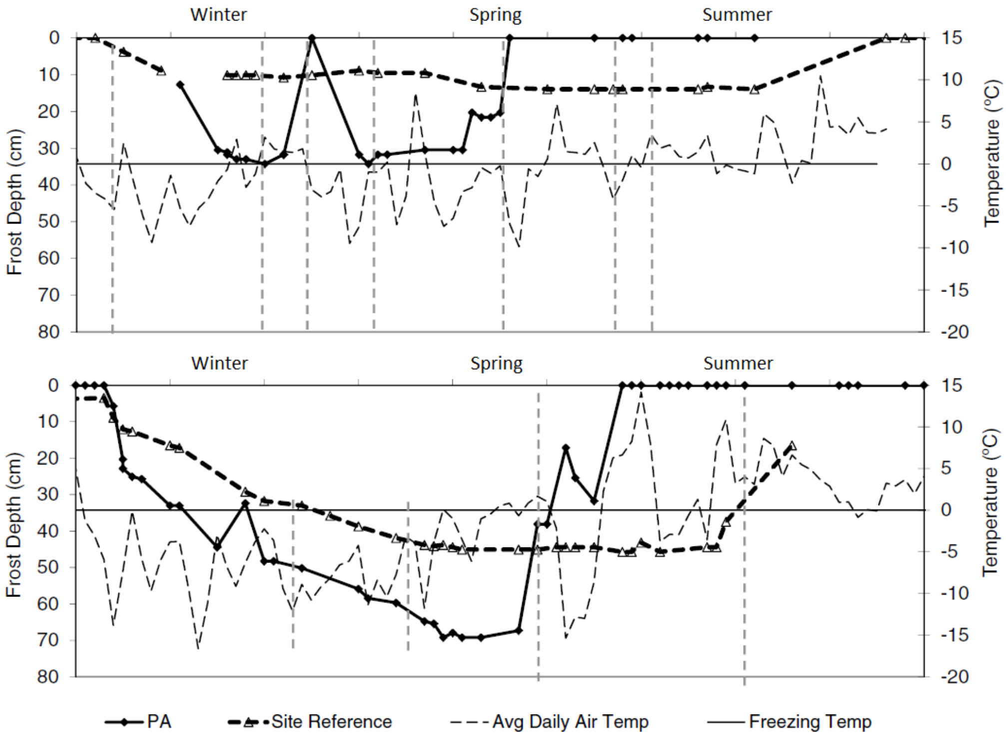


Figure 7. Frost depth in winter 2006-2007 (bottom) and 2007–2008 (top). Vertical dashes are rain events. In accordance to Roseen et al. (2012) (edited figure).

1.3 Winter maintenance

1.3.1 General and State-of-the-Art

Winter maintenance of PA includes snow plowing, de-icing as salting and sanding. Other actions are washing and vacuuming of the clogged surface. According to Houle (2008) the PA does not collect as much snow as conventional asphalt, but regular plowing is required for remaining the infiltration rate. Unplowed snow may form compacted snow and ice covers and the meltwater infiltration lags. [Houle 2008, Roseen et al. 2012]

According to [Henderson 2012] and [Virginia DCR 2011] snow removal with conventional ploughing equipment has been deemed to be suitable for all kind of pervious pavements (PP). The ideal winter maintenance scenario would involve the removal of snow and allow any remaining ice or snow to melt and drain through the PP.

According to [CRMCA 2009] interlocking pavement snow removal should be accomplished using a rotary broom. If use of a rotary broom is not possible, snow should be cleared using a plow with a lower edge made of plastic or rubber. Metal plows should be avoided as their blades tend to catch stones (particularly at joints) and cause raveling. It is also possible to do the plowing so that there is a small distance between the plow and the pavement surface, for instance to keep the plow 1 cm above the pavement surface.

Large snow storage piles should be located in adjacent grassy areas so that sediments and pollutants in snowmelt are partially treated before they reach the permeable pavement. Sand should not be applied, or only limited sand, over permeable pavement or areas of impervious pavement that drain toward permeable pavement, since it can increase clogging of the system. Also, owners should be educated about winter maintenance of PPs. Owners should be judicious when using chloride products for de-icing over all permeable pavements designed for infiltration, since the salts will most likely be transmitted into the groundwater. Salt is also a risk for durability (scaling of concrete pavers and pervious concrete). Should the use of salt or salt solution be required, it should be limited. [Henderson 2012, Virginia DCR 2011]

According to Yildrim et al. (2007) salting or other de-icing chemicals may be an alternative to sanding to prevent frost, black ice and slipperiness. Sometimes it is recommended that limited sand should be applied to the surface. The sand will not lead to the pervious concrete becoming fully clogged, assuming that maintenance is performed in the spring season. If sanding is necessary, it is better to use coarse grain sand instead of fine sand [Stenmark 1995]. Sometimes sanding is not recommended, because it can lead to pore clogging. The dust caused by studded tyres may have the same effect.

In the U.S.A, Greater Kansas City area, according to [CPG 2013], snow less than 75 mm disappears quickly from pervious PC once walked or driven on. The snow and meltwater goes below the surface and there is no standing water on the surface. This is also why there is no big reason to use deicing chemicals. There is no refreezing of melted snow at night since the water has moved down below into the base. The base layer is usually 8 to 10 °C warmer than the surface as the air voids are great insulators. [CPG 2013]

Winter performance experiences on porous asphalt, when used to reduce highway noise, is presented in [Danish Road Directorate 2012]. According to this information mainly on highway experience, collected form Bavaria in Germany, Switzerland, France and the Netherlands, with appropriate monitoring, managing, salting and snow removal it is possible to service porous pavements in the winter periods. None of the countries had new statistical information on special traffic safety problems during the winter periods.

In all, the need of salting on the porous asphalt surface appears to be an ambivalent thing. Some studies claim that the need of salting is reduced compared to conventional asphalt [Houle 2008], while others claim that the need for salting is increased in the case of PA [Bendtsen 2011, Poulikakos et al. 2006]. It must be noticed that the need and the efficiency of salting is different for highways and roads, compared to e.g. parking areas and other areas with lower traffic intensities and traffic speeds. This may also be an explanation for the different results and experiences on porous asphalt winter performance, and need for salting. Some examples on the different research results and recommendations are presented below.

Porous asphalt (PA) highway winter maintenance has been studied for instance in Switzerland. In general, PA mixtures exhibited lower thermal conductivity and reduced heat capacity compared with dense-graded hot mix. Elevated air voids contents in PA reduce the flow rate of heat through the material. In fact, the thermal conductivity of PA can be 40% to 70% of that for dense-graded mix, making PA operate as an “insulating course” at the surface. Because of the lower thermal conductivity in winter, PA surface may be about 1–2 °C, in some cases even 4 °C, colder than dense asphalt (Figure 8). Therefore, on the PA surface, snow tends to settle earlier and remain longer. Also ice forms earlier when the roads are wet. [Estakhri et al. 2008, Poulikakos et al. 2006, Huber 2000]

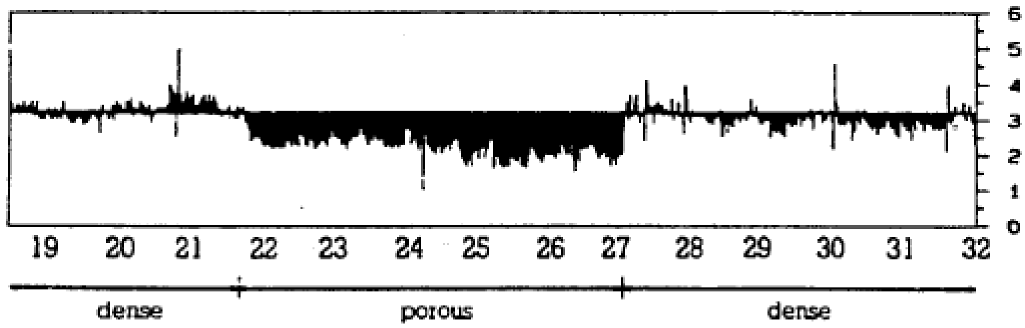


Figure 8. Surface temperature of asphalt mixtures under clear sky conditions. Dense and porous mixtures. [Huber 2000]

It was found in Europe, based on the experiences of the road administrators, that the need of salting is greater on highways made of PA [Bendtsen 2011]. The salting frequency was higher and the amount of salt need was 30–50% more than for the roads with a conventional asphalt layer. Sometimes it has been necessary to close the roads or reduce allowed speed in winter time. There has also been some durability problems and shortened service life in some countries because of frost and winter damages [Bendtsen 2011]. Dooley et al. (2009) reports also up to 100% increase in the need of salt on porous asphalt. This may occur when car wheels push the salt into the voids of the asphalt.

A recommendation in [Danish Road Directorate 2012] is that a more frequent salting process (60 to 90 minutes) and 30 to 50% more salt per year are needed for porous pavements than dense pavements. According to [Danish Road Directorate 2012], situations with black ice can occur on porous pavements, which can be more complicated to remove than on dense pavements. Also situations can occur where snow is pressed down in the pores and this can result in an icy surface, which can be more complicated to remove. Also according to Bendtsen (2011) and Yildrim et al. (2007), porous asphalts are not free of black ice, which makes the surface slippery. Also according to [Yildrim et al. 2007], the problem with PA has been the uncertainty regarding their performance under winter weather conditions, especially in rapid freezing conditions where some moisture may be trapped in the open mixes – conditions that might cause black ice. PA may be problematic during rapidly advancing freeze conditions and especially during rapid freeze-thaw cycles (i.e., a nightly freeze with daily thaw).

Research conducted in Belgium by Heystraeten & Diericx (2002) found that under winter conditions PA surfaces do not behave like conventional closed surfaces. This is because moisture is entrapped almost permanently in the pores in winter and may in some cases lead to solid condensation at the road surface. Also, the porosity of PA prevents salts spread for an anti-icing or de-icing purpose from staying active on the surface, and PA lower thermal conductivity causes their surface temperature to drop more sharply and severely under certain climatic conditions. As a result, this study also found that larger amounts of conventional de-icing salts have to be spread to keep the roads clear from ice. The study cites the need for de-icing salts that are more appropriate on open-graded road surfaces. The report goes on to present possible solutions, such as to use a mixture of 1/3 calcium chloride and 2/3 coarse sodium chloride grains that are up to 5 mm (0.2 in) in size.

In the U.S.A. formation of black ice and extended frozen periods are considered the main problems associated with PA highway maintenance. Because of the different thermal properties, the winter maintenance of PA highways differs from that of dense asphalt highways. It is necessary to adjust the practices for winter maintenance often and to react quickly to the actual weather conditions. Timing of the application of salt is very important because when the snow depth increases it is harder to solve the freezing problem. Furthermore, more salt should be applied in the first application of the season, and salt application should be repeated regularly to maintain the permeability of the wearing course. [Estakhri et al. 2008, Poulikakos et al. 2006, Huber 2000, Yildirim et al. 2007]

Instead, analysis of snow and ice cover and pavement skid resistance by Houle (2008) demonstrated that up to 72% less salt was needed for porous asphalt to maintain equivalent or better surface conditions as impermeable asphalt. Houle (2008) widely studied the performance of porous asphalt at a field site in winter circumstances. His results show that the skid resistance of the parking lot made of porous asphalt remains as good as the conventional asphalt although there is 72% less salt on PA, because meltwater does not stand and freeze on surface. Salt crystals may also remain on the surface when melted water drains thorough the surface and they will melt the new raining snow instead of being washed away by the runoff water. When the amount of salt was reduced to 0%, the skid resistance of PA reduced only 4%, while in conventional asphalt skid resistance reduced 27%. According to Houle (2008), if PA is plowed regularly, salting is need only for events when freezing rain creates icy conditions. [Houle 2008].

Porous asphalt pavement is widely used on expressways in Japan. Iwata et al. (2002) describes how the Japan Highway Public Corporation conducted an on-site study in order to quantitatively evaluate PA winter performance. In this study it was found that there is no significant difference between porous asphalt and dense-asphalt pavement in terms of road surface characteristics. Therefore, according to Iwata et al. (2002), no major modifications are required to the existing road maintenance method for winter. This research conducted in Japan compared the performance of PA with conventional asphalt pavement under winter conditions. It was found that porous asphalt pavement is effective in preventing freezing of the road surface. The study concluded that accidents may be reduced under snowy and icy conditions due to the higher friction found on the surface of the PA.

Also, for instance the road agency of canton Vaud in Switzerland has noted a significant decrease in the number of accidents occurring on PA under snowy conditions as compared to dense courses. Canton Vaud in western Switzerland is known as one of the leaders in promoting and using PA. Currently, 1/3 of the Vaud motorways are covered with porous asphalt, and the use of PA is planned to be extended to most of the motorway surfaces in the canton Vaud up to an altitude of 600 m. [Estakhri et al. 2008, Poulikakos et al. 2006, Huber 2000]

Huber (2000) compared the PA highway winter maintenance practices in use. Typically these practices differ from the winter maintenance and de-icing of normal dense asphalt highways, and also vary from place to place:

- In Texas U.S.A., de-icing agents are currently considered the most effective winter treatment for PA, followed by liquid de-icer agents and sand.
- However, the U.S. Federal Highway Administration (FHWA) recommends developing snow and ice control using chemical de-icers and plowing and avoiding the use of abrasive materials to improve traction. This is because spreading of sand to enhance friction and hasten de-icing contributes to the clogging of voids.
- Since the de-icer can flow into a PA, instead of remaining at the surface, Oregon Department of Transportation (Oregon DOT) has suggested research on organic deicers with higher viscosity and electrostatic charge technology (similar to that employed in emulsified asphalt) to improve bonding of de-icers to the surface.
- Intensive application of liquid de-icing salts has allowed Belgium to obtain similar conditions between dense and porous asphalt mixtures subjected to snowy weather.
- Higher frequency of application and 25% more liquid salting are reported in the Netherlands to address winter maintenance difficulties in PA highways.
- The use of liquid chloride solutions was reported in the cold Alpine regions of Italy, Austria, and Switzerland as more effective than the use of solid salt.
- Britain practices preventive salting just before snowfall and more frequent application of salt in comparison with dense graded mix. They recommend increasing the amount of salt applied on dense graded sections that are adjacent to PA segments. This recommendation is due to the reduction in the transfer of salt from the PA to the dense-graded mix and the differences in response of each material.
- Also in Britain, greater control in the homogeneous supply of de-icing chemical is required in PA, as the traffic has minimal contribution in its distribution over the surface. [Huber 2000]

The problem of using salt is the chloride pollution effect to underlying soil and groundwater. Dissolved anionic contaminants, such as chloride, remain in the filtrate fluid. If the pavement surface is salted in winter, the amount of chloride in underlying soil and water would increase immediately. The asphalt structure can also hold the chloride loads for months so that the chloride “leaking” may continue after the actual salting period. The only way to reduce the chloride loads is to reduce salting. [Roseen et al. 2012, Houle 2008, Ferguson 2005, Toronto and Region Conservation 2009]. A common guideline for constructing permeable pavement structures is that the structure should be constructed with an impermeable membrane if there is any concern about filtration pollutants migrating to groundwater. The impact of permeable pavements on water quality, including the effects of winter periods, is reviewed in the Finnish CLASS-project State-of-the-Art Report [Loimula & Kuosa 2013].

1.3.2 Recommendations for Finnish winter conditions

1.3.2.1 Additional analysis with regard to Finnish winter conditions

Clogging caused by sanding and snow piling

Clogging will decrease water infiltration rate, and may also fill with time some of the pore volume designed for water filtration, retention and detention. Clogging is caused by all kind of urban pollutant loading, and is very much dependant on the environmental circumstances, i.e. the total urban pollutant loading. [Mata 2008]

In Finland, during the winter season, sanding is an additional cause for clogging. Sanding may decrease the infiltration rate, and it may also fill the pore volume designed for water retention. Anyway, by using course enough sand, the risk for clogging and filling of the pores is significantly lowered.

Clogging by sanding can be studied for instance based on the fine material migration through a porous material according to [Locke et al. 2001]. Figure 9 presents the calculated minimum grain sizes for the sanding material in the case of different joint material gradations. The calculation in Figure 9 was made for fully compacted joint materials. If the compaction degree is lower, also bigger grains, than those presented in Figure 9, are able to enter the joint material. Thus it is advisable to use a somewhat coarser material than the calculation in Figure 9 gives.

After all, it is recommended to select the gradation for the sanding material so that less than 10% of the sand is able to penetrate in the pavement or joint material. For pervious block pavements, with fairly single sized pervious sand in the joints/openings, a rule of thumb is that the minimum grain size for the sanding material should be bigger than 10% of the grain size at the 50% passing for the joint material (≥ d_{50}/10). This means that for the typical joint materials (with d_{50} = 2.5–6.0 mm) the minimum grain size for the sanding material should be 0.25–0.6 mm. This means also that the generally acceptable minimum grain size for the sanding material is ca. 1 mm.

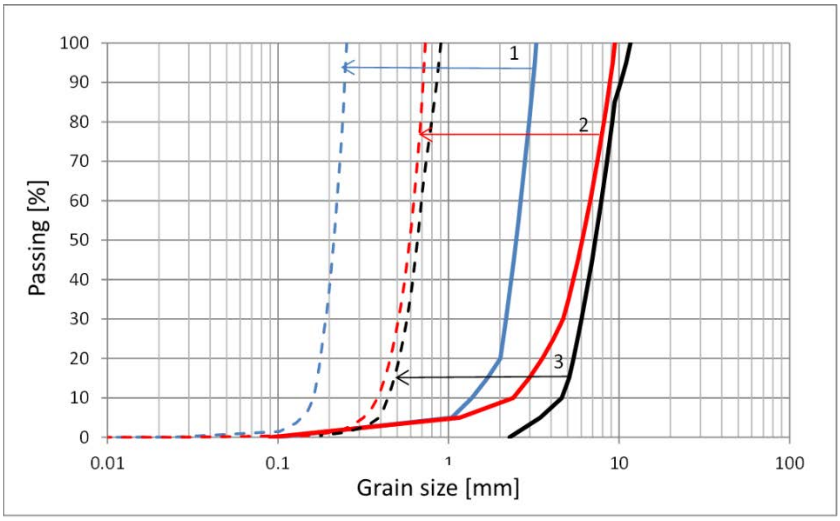


Figure 9. Selected joint material gradations 1, 2 and 3, and the corresponding sanding material gradations which will not migrate through the fully compacted joint material. Calculation is according to [Locke et al. 2001].

The same principles, as for the block pavement joints, will apply to the monolithic pervious pavement materials. The sanding material should not include small grains that can enter and clog the pores mainly responsible for the hydraulic conductivity. Most significant for the hydraulic conductivity are the biggest interconnected pores. This is as hydraulic conductivity is in relation to the 4^{th} power of the channel size. If the channel size is doubled, hydraulic conductivity will be 16-fold ($16 = 2^4$). This means that it is important to take care that the biggest interconnected pores, mostly responsible for the water infiltration rate, will not be clogged.

For monolithic pervious surfacing materials, as for porous asphalt and pervious concrete, up to the surface open pore sizes are 5–10 times larger than the minimum channel sizes. This means that large sanding material grains will stay on the surface, and the hydraulic conductivity of the material will not be essentially diminished.

Figure 10 gives a rough estimation of the dominating channel sizes as a function of hydraulic conductivity, in the case of different total porosities (2%, 5%, 10%, 15% and 20%). Figure 10 is only meant to support the selection of the finer portion in the sanding material. The initial total porosity and hydraulic conductivity of the surfacing material is first determined. After that the minimum grain size for the sanding material is selected. In Figure 10 this minimum grain size is the dominating channel size for conductivity. This method is not suitable for all the pervious materials. Anyway, for the present, this method can be applied as a general rule, as there is a lack of more detailed knowledge or observations on the effect of clogging by sanding.

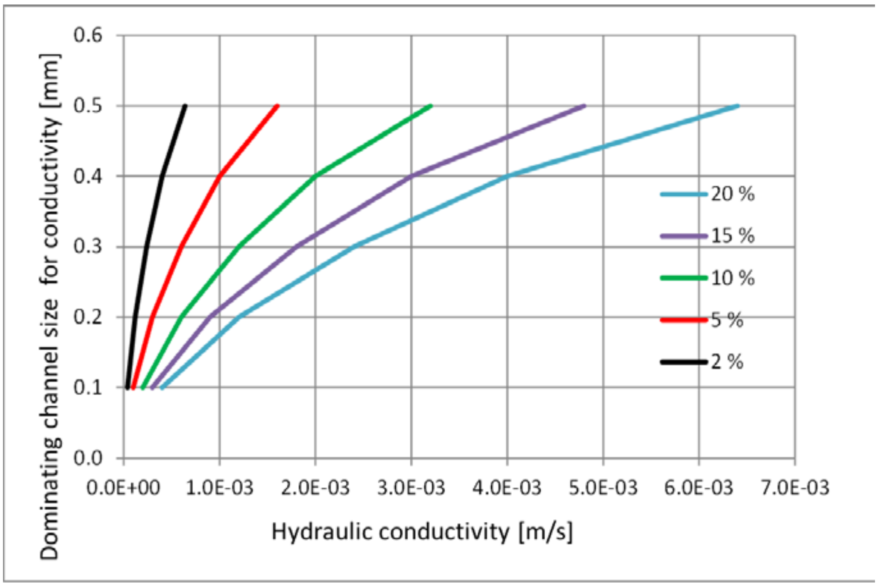


Figure 10. A simple interdependency between the total porosity, hydraulic conductivity and the dominating channel size for hydraulic conductivity.

<u>Effect of fines and organic material</u>

Fines, grains ca. <0.1 mm, in the aggregate material for sanding, are not as problematic for the surface layer hydraulic conductivity as the coarser materials. Fines will sooner or later be transported through the pervious pavement surface layer, will be removed by cleaning, or will block only the finest channels which are not especially significant for the hydraulic conductivity. This means that it is not necessary for the sanding material to be washed. More important is to make sure that the sanding material does not include, according to Figure 10, problematic grain sizes.

If there is a geotextile under the pavement surface layer, fines may enter it, fill the pores in it, and decrease water infiltration. [Kuosa et al. 2014] In this case, the use of washed material for sanding may be useful over the long term.

Also, if there are a lot of fines entering the pavement, from all the sources, including sanding, the fines may with time fill a portion of the pore volume designed for water retention in the pavement bottom layer, or especially decrease the infiltration rate to the soil subgrade. A conservative approach is recommended regarding the soil subgrade infiltration rate over the long term, e.g. a safety factor of 2 or even higher, can be used. [Smith 2011, Kevern 2008, Kuosa et al. 2013]

Leming et al. (2007) estimated conservatively (depositions were estimated to be 1125 kg/ha/year or higher) that fine grained sediments deposited in the pervious pavement will most likely occupy less than 12 mm of the depth of the aggregate base in 20 years of service, resulting in only a few percent loss in storage capacity. An extra 25 mm of aggregate base was estimated to be adequate to supply sufficient storage capacity. Anyway, it was concluded that additional research on the effects of sedimentation on permeability and porosity would be useful. [Leming et al. 2007, Kuosa et al 2013]

Besides the mineral material, also organic materials such as grounded leaves, catkins, fir needle, seeds, etc. together with the mineral material may increase clogging. As a result of the microbial activity, organic material will usually disintegrate in the pores into soluble form in a few years. However, in unfavourable circumstances the organic material may also bind with the mineral material, and build difficultly degradable blockages in the pavement surface layer pores. This risk is the highest in areas close to forests and parks, where there is high amount of organic materials beside the pavement, and this material can be windblown to the pavement, and can be accumulated on the pavement surface.

<u>Effect of snow piling</u>

Snow piling on the pervious pavement surface will also increase the risk for clogging. This risk is caused by the aggregate particles accumulated in the snow pile, after plowing the snow including these particles after sanding. These particles will be released fast on the pavement while the snow pile is melting in the springtime. These aggregate particles may also include fine particles. This is because the original material for sanding may become crushed, especially if there is traffic in the area. For this kind of fractionated sand there is a higher risk to be trapped in the pervious pavement pores, than for a material including only a single sized fine material.

<u>Clogging by freezing water after snow melting beside the pavement, melting snow piles</u>

Snow piling on or near the pavement surface is also a presumable risk for clogging by ice, especially during the late spring period. The melting snow will first enter the pavement surface. The temperature of this water, and the pavement surface, will maintain near the freezing temperature, as in Finland the days are still short during the early spring time, and the sun will maintain at low position. During the daytime, the pavement will reach temperatures above +0 °C only very close to the pavement surface. Thus there is a risk that the melted water will eventually freeze in the frozen zone below the near surface layer of the pavement, and will thus block the pores under the near surface layer. As a result, water infiltration will be decreased beside the melting snow pile. Anyway, this kind of period will not be long, presumably only a few weeks in the springtime. Salting, if it is considered a suitable method, will enhance melting water to enter the pavement layers for water retention below the surface layer.

1.3.2.2 Recommendations

There is no experience on the winter maintenance of pervious pavements in Finland. At the moment, the above State-of-the-Art information (Chapter 1.3.1), and the information based on the additional analysis (Chapter 1.3.2.1) can be adapted. Recommendations for the pervious pavement winter maintenance in Finland are presented below.

Snow clearance as plowing

Unplowed snow may form compacted snow and ice covers especially during the spring time, and the melt water infiltration lags. Regular snow clearance such as plowing is required to maintain the infiltration rate. Snow clearance and plowing is mainly done in a manner similar to normal pavements but includes also some additional aspects to consider. To protect the pavement surface from mechanical damage and ravelling, plowing should be done so that there is a small distance between the plow and pavement surface, or a plow with a lower edge made of plastic or rubber, or a rotary broom, can be used.

Sanding

If sanding is needed, coarse grain sand instead of fine sand should be used. It is recommended to select the gradation for the sanding material so that only a small portion (<10%) is able to enter the pavement surface layer. Tentative instructions for the selection of the sanding material are given above in Chapter 1.3.2.1 (*Additional analysis with regard to Finnish winter conditions*). Normally a safe selection is to use a sanding material with a minimum grain size ≥1 mm.

Fines, grains ca. <0.1 mm, in the aggregate material for sanding, are not especially problematic for the surface layer hydraulic conductivity. This means that it is not normally necessary for the sanding material to be washed. Anyway, if geotextile is used under the surface layer, there is a risk that fines may fill the pores in it, and decrease water infiltration rate.

There is a small risk that also the sanding materials fines, together with other fines, will with time fill a portion of the pore volume designed for water retention in the pavement bottom layer, or especially decrease the water infiltration rate to the soil subgrade.

Ice build-up on the surface, slipperiness

Because of the lower thermal conductivity, the porous surface during winter time may be about 1–2 °C, in some cases even 4 °C, colder than dense pavement surfaces. On the other hand, as permeable pavement is able to infiltrate snowmelt, ponding of melt water and subsequent ice build-up upon the return of freezing temperatures will be reduced.

More experiences in the Finnish winter conditions are needed to know if pervious pavements, or some types of pervious pavements, are more than usually prone to icy surfaces and slipperiness. It is important to collect also this kind of comparative information in the future Finnish pilot projects.

De-icing, salting

For pervious pavements, the need for salting is the highest for the events when freezing rain creates icy conditions. Should the use of salt or salt solution be required for a pervious pavement, it should be limited.

It is a generally accepted recommendation that salting is not recommended for no or low traffic areas, and especially if it will be a risk for ground water. Salts will most assuredly be transmitted into the groundwater, or will be a corrosion risk for the draining systems. Salt will also increase freeze-thaw deterioration risk, i.e. surface scaling, of cement based pavement materials.

The need and the efficiency of salting is different for highways and roads, compared to e.g. parking areas and other areas with lower traffic intensities and traffic speeds. The need of salting on porous asphalt highway surfaces appears to be ambivalent. Some studies claim that the need of salting is reduced compared to conventional asphalt, the others that the need for salting is increased.

Snow piling on or beside the pavement

Snow piling beside or on the pervious pavement is not at all advisable.

Snow piling on the pervious pavement will increase the risk for clogging. This risk is caused by the aggregate particles, and also fine crushed particles, accumulated in the snow pile because of wintertime sanding in the area for plowing.

Snow piling on or near the pavement surface is also a presumable risk for clogging by ice, especially during the late spring time. There is a risk that the melted water will eventually freeze in the frozen zone below the warmer near surface layer of the pavement, and will thus decrease water infiltration rate. This kind of spring time period will not be long, presumably only a few weeks in the springtime. Salting, if it is considered a suitable method, will enhance melting water to enter the pavement layers below the surface layer.

Cleaning and infiltration measurements

In spite of winter time sanding, in addition to all the other clogging material entering the pavement, it is possible to maintain the infiltration capacity by taking care of an adequate cleaning of the pavement.

To detect the possibly lowered infiltration rate, water infiltration measurements should be carried out regularly. In the beginning once or twice a year, later on based on the infiltration measurement results for the pavement, environment and cleaning practises in question.

More information on clogging and cleaning is presented in [Kuosa et al. 2013], in Chapter "*Clogging and maintenance*", including some information on the recommended cleaning methods. Laboratory testing results on the effect of clogging and cleaning on the water infiltration rate for different pervious surfaces are presented in [Kuosa et al. 2014].

Future Finnish pilot projects will help to estimate more closely the needed cleaning degree in different kind of urban areas, under different sanding and maintenance practises.

1.4 Winter performance cases

Additional examples from field studies on pervious pavement winter performance are hereby reviewed shortly.

PC sites located in the northern U.S.A.

According to Delatte et al. (2007) pervious concrete pavement has an excellent performance history in the areas with no freeze-thaw, but it has limited use in environments with significant freeze-thaw cycles. Long term, over 10 years, field experience was missing. That is why the assessment of the actual field performance was considered important.

The project by Delatte et al. (2007) included field observations, and non-destructive testing results of PC pavement sites located in northern U.S.A. (states of Ohio, Kentucky, Indiana, Colorado, and Pennsylvania). Most often PC was used as a pavement for parking lots. The field investigation plan encompassed a thorough visual inspection for signs of distress, especially as cracking, surface ravelling and areas with clogging. Two types of surface infiltration measurements and ultrasonic pulse velocity (UPV) testing was also performed. In addition to field observations, laboratory testing on cores removed from some of the test sites were performed. In this research many PCs were relatively new (age 1–4 years). Because of this it was concluded that they should be examined again in the future, probably at 5 and 10 years from the publication of the report. [Delatte et al. 2007]

Generally, the PC installations had performed well in northern U.S.A. freeze-thaw environments, with little maintenance required. Field performance was dependent on the quality of the mixture as well as proper control of construction and curing. The installations did not show any signs of freeze-thaw damage. Some pavements had surface raveling, which generally had stopped after a few months of use. Saw cut joints had less raveling than tooled joints. A few pavements had cracks, which were expected to be attributed to overloading or long spaces between joints. Some of the pavements had very poor infiltration capability, and this was due to improper installation. [Delatte et al. 2007]

Observations by Delatte et al. (2007) suggest that providing sufficient drainage under PC to keep them from becoming saturated in freezing weather, as recommended by the U.S. NRMCA (National Ready Mixed Concrete Association), is likely to be effective.

Pervious concrete in Canada

Henderson (2012) evaluated in his thesis the behaviour of pervious concrete (PC) pavements in winter conditions in Canada. This research was the first in Canada to consider the use of pervious concrete pavement. According to Henderson (2012) additional research into each aspect of the life cycle of a PC pavement will be required in the long term. In his research the durability of the PC was not satisfactory. No information on the cement type in these PC mixes, or information on the hardened paste air content was given in [Henderson 2012]. The true reasons for the deterioration of the PC slabs with freeze-thaw exposure with salt remain unclear. Based on the low durability with freeze-thaw exposure with salt it was concluded that PC pavement winter maintenance in Canada should preferably not include salt or salt solutions.

Permeable pavements in Sweden

According to Westerlund (2007), Hogland & Wahlman (1990) reported that permeable pavements are more resistant to freezing and to frost actions than conventional roads. The thawing process was found to be faster for a permeable pavement due to the snowmelt infiltration. Indications that roads with porous asphalt become free from snow and ice earlier than conventional roads was observed during several inspections in different parts of Sweden. (Figure 11) [Hogland & Wahlman 1990, Westerlund 2007]

Figure 11. Comparison of porous pavement (left) and a nearby impermeable pavement (right) during the snowmelt period. [Hogland & Wahlman 1990, Westerlund 2007]

Winter performance study in New England, U.S.A.

Figure 12 demonstrates a theme that was commonly observed in the study by Houle (2008) in New England, U.S.A., during cyclical freezing-thawing conditions. The photos were taken at 9AM, one-day after a snow event. Any precipitation that remained on the porous asphalt immediately drained through the pavement (Figure 12a). The opposite was true on the standard asphalt (Figure 12b). Meltwater refroze overnight creating icy conditions in the morning.

Figure 12. Instantaneous pavement conditions after thawing and refreezing of meltwater. a) Porous asphalt; b) Dense asphalt. [Houle 2008]

European experiences on porous asphalt highways

Bendtsen (2011) collected European winter condition experiences on porous asphalt as a highway surfacing material. In the Netherlands 90 percent of the highways are made of porous asphalt for noise reduction. In other countries the use of PA has declined, because of higher winter maintenance costs, experiences on reduced durability and lifetime compared to conventional asphalts [Bendtsen 2011]. Some slippery conditions were reported, as black ice, condensation of freezing mist and icy surfaces when plowed snow is pressed down into the pores. On the other hand, it was reported that the driving comfort is increase, and splashes and noise are reduced. Traffic safety was not reported to be worse than with conventional asphalts. With proper maintenance, PA was considered to be a usable alternative. [Bendtsen 2011]

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