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Porous Pavement in a Cold Climate

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PREFACE

This thesis is presented as a partial fulfilment of the requirements for the degree of Licentiate. The work was carried out at the Division of Sanitary Engineering, Luleå University of Technology. Financial funding was provided by the Swedish Council for Building Research (BFR), the Swedish Association of local Authorities (KF) and the local authority of Luleå, which are gratefully acknowledged.

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Luleå in April 1999

Magnus Bäckström

ABSTRACT

Major stormwater issues today concern runoff control, pollution control, and how to sustain the urban water resources on a long-term basis. A number of alternative stormwater management techniques have been developed during the last decades. Most of the research on these techniques has so far been carried out in regions with relatively warm weather. Thus, there is a need for more knowledge about the performance of the alternative stormwater facilities in cold climate regions. Local disposal of stormwater can be achieved by using porous pavements instead of impermeable pavements with conventional stormwater pipes and manholes. The objective of this thesis was to analyse the performance of porous pavements during freezing, thawing and snowmelt conditions in order to evaluate if the porous pavement is suitable for stormwater management and road construction in cold climate regions. Another purpose of the thesis was to study the differences in winter performance of porous pavement and impermeable pavements.

A full-scale porous pavement construction was built in 1993/1994 in a residential area on the outskirts of Luleå, Northern Sweden (N:65°36′, E:22°13′). The construction consisted of a layer of porous asphalt placed on top of a sub-base of coarse macadam or blast furnace slag. A geotextile separated the sub-base from the underlying soil and a drainage pipe was laid at the sub-grade. The thickness of the porous asphalt, the adjustment layer and the macadam sub-base was 45 mm, 30 mm and 600-1000 mm respectively. For comparison, one stretch of road in the area was surfaced with impermeable asphalt and one stretch of road was constructed with a sub-base of blast furnace slag. The width of the grassed roadside swales was increased to create a larger area for stormwater infiltration.

In situ-measurements of ground temperature, frost heave, groundwater levels and runoff were performed between 1994 and 1997. Climatic conditions, including air temperature, precipitation and snow-pack thickness, were monitored during the same period. The infiltration capacity and draining behaviour of the porous asphalt at different ambient air temperatures in the range -10 °C to +20°C were investigated in the laboratory.

It was found that porous pavements have a potential to reduce meltwater runoff, avoid excessive water on the road surface during the snowmelt period and accomplish groundwater recharge by local disposal of stormwater. The porous pavement was more resistant to freezing than the impermeable pavement, probably due to higher water content in the soil below the sub-grade of a porous pavement and due to the insulating effect of the air in the porous pavement. Thawing of porous pavement was a rapid process, which was explained by meltwater infiltration during the beginning of the snowmelt period.

The full-scale porous pavement construction was not damaged by frost heave and the frost heave of the porous pavement was less or equal to the frost heave of the comparable impermeable pavement. This behaviour can be explained by the decreased frost penetration and by the fact that the porous pavement was a homogenous road construction due to the elimination of conventional stormwater pipes and manholes. A sub-base depth of 1.0 m is recommended in regions with similar climate conditions as Luleå. No clear differences in frost penetration and frost heave between porous pavement with macadam sub-base and porous pavement with blast furnace slag sub-base were observed.

SAMMANFATTNING

Dagvattenhantering inbegriper idag flödeskontroll, föroreningsreduktion och bevarande av stadens vattenresurser. Under de senaste decennierna har ett flertal alternativa dagvattenmetoder utvecklats. Forskning kring funktionen av dessa alternativa dagvattenanläggningar har i huvudsak bedrivits i regioner med varmt/milt klimat. Det finns därför ett behov av mer kunskap kring hur kallt klimat påverkar funktionen av dessa anläggningar. En metod för lokalt omhändertagande av dagvatten är den s.k. enhetsöverbyggnaden som består av dränerande asfalt lagd ovanpå en vägkropp av grovt material (t.ex. makadam). Syftet med denna avhandling var att studera hur frysning, tining och snösmältning påverkar enhetsöverbyggnadens funktion. Ett annat syfte med studien var att jämföra enhetsöverbyggnad med konventionell, tät gatukonstruktion med avseende på funktion under vinterförhållanden.

1993/1994 anlades en enhetsöverbyggnad i full skala i ett bostadsområde i utkanten av Luleå. Konstruktionen bestod av ett lager av dränerande asfalt lagd ovanpå en vägkropp av makadam eller slagg (hyttsten). Undergrunden separerades från vägkroppen medelst en permeabel geotextil och ett dräneringsrör lades i botten av vägkroppen. Den dränerande asfalten hade en tjocklek av 45 mm och vägkroppens tjocklek var 600-1000 mm. Mellan asfalt och vägkropp lades ett utjämningslager med en tjocklek av 30 mm. En delsträcka av vägen konstruerades med tät asfalt och på en sträcka anlades en vägkropp bestående av slagg. Vägdikena breddades för att skapa en större yta för dagvatteninfiltration.

Mellan 1994 och 1997 mättes marktemperatur i och under vägkropp, grundvattennivåer i ett antal vägsektioner, tjälhöjning av vägytan samt avrinning från vägkroppen. Dessutom registrerades lufttemperatur, nederbörd och snötäckets tjocklek under samma period. Temperaturens inverkan på den dränerande asfaltens infiltrations kapacitet och dräneringsförlopp undersöktes i klimatrum.

Undersökningarna visade att enhetsöverbyggnaden reducerade smältvattenavrinningen och att den genomsläppliga beläggningen behöll sin dränerande funktion under snösmältningsperioden. Enhetsöverbyggnaden var mer motståndskraftig mot frysning jämfört med den traditionella (täta) gatukonstruktionen. Detta förklarades av ett högre markvatteninnehåll i underliggande mark under den genomsläppliga beläggningen samt att luften i enhetsöverbyggnaden isolerade undergrunden och fördröjde frysförloppet. Gatukonstruktionen med enhetsöverbyggnad tinade snabbare än den traditionella gatukonstruktion på grund av att smältvatten infiltrerade genom den dränerande asfalten i början av snösmältningsperioden och påskyndade tiningsprocessen.

Inga tjälskador observerades på vägytorna med dränerande asfalt. Tjälhöjningen av enhetsöverbyggnaden var mindre eller jämförbar med tjälhöjningen av den traditionella gatukonstruktionen. Orsakerna till detta var den minskade tjälnedträngningen och att enhetsöverbyggnaden var en homogen gatukonstruktion utan dagvattenledningar och brunnar.

Vägkroppens tjocklek bör vara 1.0 m i områden med klimat likande Luleås. Studier av vägkroppsmaterialets inverkan på frysförloppet visade att makadam och slagg var jämförbara i detta hänseende.

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1. BACKGROUND

Urbanisation has led to a rapid increase of impermeable surfaces. As a consequence of this, problems associated with stormwater quantity and quality have increased in urban areas. The conventional approach to deal with these problems is to build large-scale conveyance systems. In these systems, stormwater is transported to a sewage treatment plant or directly to receiving waters by a network of combined or separate pipes. It has become clear that this approach is in conflict with the environment (Marsalek *et al.*, 1993). Stormwater pollutants cause a degradation of receiving waters and reduced infiltration leads to a reduced groundwater recharge. It is common that sewage treatment plants receive increased inflows during wet weather, which have negative effects on the treatment efficiency (Bengtsson *et al.*, 1980). With a continuing urbanisation, the capacity of the sewer system becomes insufficient and the risk for surface flooding increases.

The urban hydrological cycle during cold weather is different from the hydrological cycle for warm-weather conditions (Marsalek, 1991; Viklander and Bäckström, 1998). Precipitation falls as snow or rain, snow is accumulated in the snowpack and air temperatures could be very low. The critical runoff volumes occur during the snowmelt period because the surfaces that normally are permeable, for example grassed areas, have a reduced infiltration capacity when the soil is frozen. All these aspects make the design of stormwater facilities more complicated in cold climate regions. Furthermore, cold climate conditions affect stormwater quality. The amounts of pollutants are higher in the winter season and the pollutants accumulate in the snow during wintertime which makes the meltwater more polluted than rain runoff (Viklander, 1997).

The cold climate has detrimental effects on many components in the urban environment. For example, roads are damaged by frost heave. A large part of the frost damage on paved areas in the cities occurs in conjunction with the stormwater system (figure 1). Stormwater manholes and pipes are chilled by air during wintertime, which cause ground freezing in the surrounding soil and uneven frost heave (Sellgren, 1983). Another frequent problem is ice-blockages in stormwater pipes, which cause flooding during the snowmelt period.

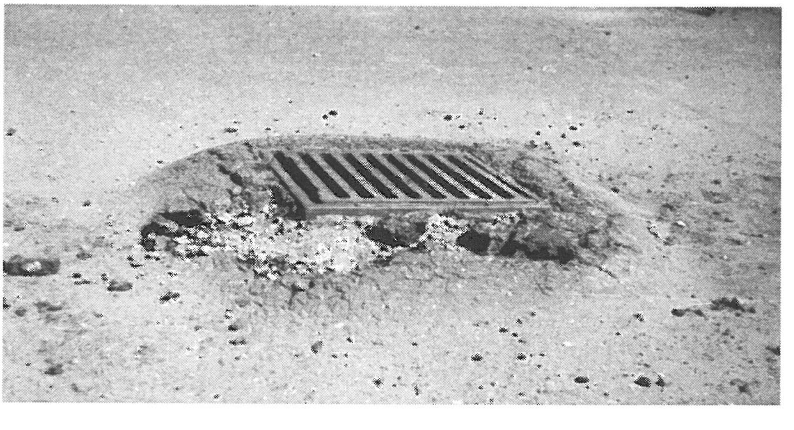


Figure 1. Stormwater inlet damaged by frost heave.

The major stormwater issues today concern not only stormwater flows, but also how to sustain the urban water resources on a long-term basis (Rowney *et al.*, 1997; Fujita, 1998). This has led to the development of a number of alternative techniques for conveyance, detention, infiltration and re-use of stormwater. Examples of these alternative stormwater techniques are grassed swales, filter strips, wetlands, ponds, percolation trenches, infiltration basins and porous pavements. Most of the research on these techniques has so far been carried out in regions with relatively warm weather. Thus, there is a need for more knowledge about the performance of the alternative stormwater facilities in cold climate regions.

2. OBJECTIVES

The objective of this thesis was to analyse the performance of porous pavements during freezing, thawing and snowmelt conditions in order to evaluate if the porous pavement is suitable for stormwater management and road construction in cold climate regions.
Another purpose of the thesis was to study the differences in winter performance of porous pavement and impermeable pavements.

3. PREVIOUS STUDIES OF POROUS/PERMEABLE PAVEMENTS

In stormwater infiltration structures, the urban runoff is forced away from surface discharge and into the underlying soil. Porous and permeable pavements have been used for this purpose in different parts of the world (Thelen and Howe, 1978; Hogland and Wahlman, 1990; Fujita, 1994; Ferguson, 1994; Raimbault, 1997; Pratt, 1997).
For example, in Tokyo, Japan, approximately 494 000 sq. m. of porous and permeable pavements have been installed during a 12-year period between 1983 and 1995 (Fujita, 1997). In Sweden, 240 000 sq. m. of porous pavement were constructed between 1981 and 1986 and approximately 300 porous pavement facilities were built during the 1980's (Hogland and Wahlman, 1990).

A porous pavement construction is surfaced with materials which allow the immediate infiltration of stormwater into the underlying construction across the total surface of the pavement (Pratt, 1997). Stormwater flows through the interconnected pores of the surfacing material. A common surfacing material of this sort is porous asphalt.
A similar construction is the permeable pavement, that is surfaced with materials which are not themselves porous, but which provide inlets in the surface to allow the stormwater to enter the underlying construction. The surfacing of a permeable pavement may consist of grass-concrete blocks (Pratt, 1997). Raimbault (1997) defines porous and permeable pavements as reservoir structures. The reservoir structure has both a mechanical and hydrological function. The mechanical function enables the construction to withstand traffic loads and the hydrological function allows stormwater to be stored temporarily and infiltrated into the underlying soil.

A reservoir structure that has been widely used in Sweden is the 'Unit superstructure' shown in figure 2. The construction was first presented by Larson (1982) and a comprehensive research program was carried out at Lund University of Technology during the 1980's (Hogland and Wahlman, 1990).

The construction consists of a layer of porous asphalt placed on top of a sub-base of coarse macadam or blast furnace slag. A geotextile separates the sub-base from the underlying soil. A drainage pipe may be laid at the sub-grade in order to eliminate the risk for permanent water storage in the sub-base.

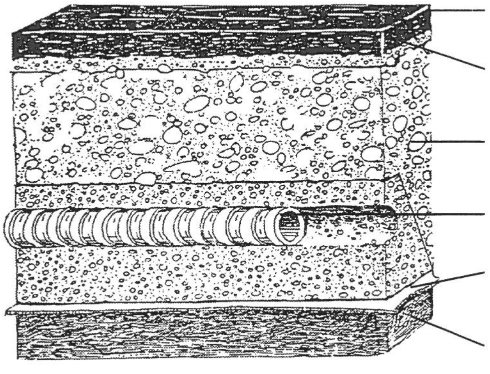


Figure 2. Porous pavement construction – 'Unit superstructure' (Larson, 1982)

3.1 Porous/permeable pavements for runoff control and groundwater recharge

In runoff simulations in a residential area in Mölndal, Sweden it was found that porous pavements have a great potential for runoff reduction. By using porous pavements instead of a separate pipe system, peak flows and total runoff volumes were reduced by 80% and 77-81 % respectively (Niemczynowicz *et al.*, 1985). In-situ measurements of a porous pavement construction in Lund in Southern Sweden revealed that the infiltration capacity of the underlying soil is the only limitation in respect of groundwater recharge (Hogland and Niemczynowicz, 1986).

Raimbault (1997) presented measurements of runoff reduction in an area with porous pavement in the town of Rezé south of the Nantes urban area, France. The porous pavement construction consisted of porous asphalt (6 cm), two layers of bitumen-stabilised porous materials (10 cm each), a 35-cm thick sub-base of crushed materials, road drains and a geotextile at the sub-grade. The underlying soil in the investigated area was a clay which had a permeability of less than $5 \cdot 10^{-8}$ m/s. During the studied 3 year period, a minimum of 87% of all rainwater seeped into the sub-grade and contributed to the groundwater recharge. It was found that the ability of water to infiltrate into the sub-grade depended on the water content of the soil.

Runoff control using a permeable pavement with concrete block paving laid on top of a sub-base of coarse material has been investigated in the U.K. (Pratt *et al.*, 1989, 1990, 1995). A geotextile was placed between the block paving and the sub-base stone. The sub-grade was sealed with an impermeable plastic membrane. Thus, infiltration into the sub-grade was hindered. The runoff during storm events was delayed because of a larger initial loss on the permeable surface compared with traditional impermeable surfaces. The start of the first discharge was 25-50% into the rainfall duration, hence runoff was prolonged well after rainfall ceased (Pratt *et al.*, 1995). The peak flow was decreased and only 30-50 % of the rainfall was discharged within the storm duration (Pratt *et al.*, 1990). The runoff reduction during a 30-day period was 25-45 % due to evaporation of stored water within the structure.

3.2 Porous/permeable pavements for pollution control

Long term studies of a porous pavement structure in the town of Rezé, France showed that a large part of the heavy metals (Pb, Cu, Cd and Zn) was accumulated in the deposited particles in the top 2 cm of the porous asphalt layer (Legret and Colandini, 1998). After 8 years of operation, there was no significant contamination of the underlying soil with respect to Pb, Cu, Cd or Zn. The observations from these in-situ studies and additional laboratory experiments have been compared with a model based on the convection-dispersion transport equation (Legret *et al.*, 1998). The model confirmed the filtrating capacity of porous asphalt. Heavy metals that flow through the porous asphalt are well retained in the first 20 cm of the underlying soil and do not migrate to a level 35 cm below the sub-grade. However, the migration of Cd into the underlying soil was more pronounced than for Pb, Cu and Zn. When clogging particles are evacuated from the porous asphalt it is recommended to collect the particles and treat them as toxic waste (Colandini *et al.*, 1995). The heavy metal content is higher in particles of small sizes.
In-situ measurements of pollution retention in permeable pavements situated in Bordeaux, France, showed that 50% to 60% of heavy metals (Pb, Cd and Zn) and suspended matter were retained in the construction (Baladès *et al.*, 1995). The permeable pavement proved to be very effective in reduction of lead, due to its affinity with suspended matter.
Mass balances for heavy metals in a porous pavement have been calculated on basis of 7 years of in-situ measurements (Legret and Colandini, 1998). Less than 3% of the heavy metals (Pb, Cu, Cd and Zn) ended up in the drain effluent. Approximately 10% of Pb, 60 % of Cu and Zn and 85% of Cd follow the infiltrated water to the geotextile and soil (figure 2).

The drainage water from porous pavements in Sweden that had been in operation for several years showed drinking water quality for most constituents, except Fe and Al (Hogland *et al.*, 1990). The highest pollution concentrations were found in the geotextile layer and there was no obvious accumulation of pollutants in underlying soil.
Snow was applied and melted on a test road with porous pavement in Lund and the drainage water quality was analysed (Hogland and Niemczynowicz, 1986). The calculated reduction of pollutants in snowmelt runoff is shown in table 1.

Table 1. Pollution reduction in porous pavement receiving snowmelt runoff (Hogland and Niemczynowicz, 1986)

	SS	P_{TOT}	Pb	Cu	Cd	Zn
Reduction (%)	95	71	50	42	33	62

Pratt *et al.* (1995) showed that a permeable (reservoir) pavement, surfaced with concrete block paving, reduced the pollutant loading in discharges compared with traditional impermeable surfaces. Sediments were trapped in the upper layer of the construction, which minimised the throughput of pollutants.

Laboratory studies of mineral oil bio-degradation within a permeable pavement were performed in Coventry, UK (Pratt *et al.*, 1998). The pavement comprised pre-formed concrete blocks bedded on clean gravel. A geotextile separated the block bed from the sub-base and the effluent was collected at the base of the 780 mm deep pavement structure. Slow-release fertiliser was applied to increase the microbiological activity. The long-term observations (300 days) showed that the permeable pavement can act as an aerobic bio-reactor, reducing petroleum contamination in the effluent to 2.4% of the oil applied to the pavement.

Berbee et al. (1999) showed that runoff from highways surfaced with porous asphalt was less polluted with a number of heavy metals, PAHs, mineral oil, suspended solids, and oxygen-consuming substances than runoff from highways surfaced with impermeable asphalt. It is imprtant to note that the porous asphalt was laid on a foundation of impermeable asphalt in this case. Thus, the stormwater was not infiltrated through the sub-base and down to the underlying soil.

3.3 Experiences with porous/permeable pavements in cold climates

The ice and snow conditions during mid-winter are similar on both a porous asphalt surface and an impermeable asphalt surface, according to Ferguson (1994). However, there are indications that roads with porous asphalt become free from snow and ice earlier than conventional roads. This has been observed in several ocular inspections in different parts of Sweden (Hogland and Wahlman, 1990). Meltwater infiltrated immediately through the porous asphalt, which gave fewer problems with slipperiness, as there was no water on the road surface that could refreeze during cold nights. Fujita (1994) suggested that porous pavements situated in cold climate districts should be constructed with drainage pipes in order to avoid the risk for damage during freezing.

Hogland and Wahlman (1990) reported that porous pavements were more resistant to freezing and frost actions than a conventional (impermeable) road construction. As a consequence, the risk for frost damage was decreased.
Stenmark (1995) has previously presented some preliminary investigations of the full-scale porous pavement presented in this thesis. It was found that porous pavement was less susceptible to irregular frost heave causing damage on the road surface than conventional road constructions. The major reason why the frost damage decreased was the absence of stormwater pipes and manholes within the porous pavement construction.

3.4 Maintenance of porous/permeable surfaces

Different methods for cleaning porous surfaces have been tested in Bordeaux, France (Balades *et al.*, 1995). A high-pressure water jet combined with simultaneous suction proved to be the most effective method, and this has been confirmed in other studies (Hogland and Wahlman, 1990; Fujita, 1994). Methods using sweeping operations did not give satisfactory cleaning results. Suction alone was recommended as preventative cleaning operation (Balades *et al.*, 1995).

Experiences of the clogging of porous asphalt pavements in Japan have shown that clogging normally occurs at a depth of around 3 cm from the surface (Fujita, 1994).

A porous pavement, which had been in operation for 4 ½ years, had a (sufficient) infiltration rate of 65 mm/min (Hogland *et al.*, 1987). In Haparanda, in Northern Sweden, a porous pavement construction with porous asphalt has been functioning for 9 years. No maintenance operations were carried out during this period (Bäckström and Forsberg, 1998).

Pratt *et al.* (1995) suggest that a permeable pavement construction may need to be renovated after 15 to 20 years of operation. A permeable pavement situated in a parking area in the UK had infiltration rates in excess of 1000 mm/hour after 9 years of operation.

3.5 Porous asphalt as road surfacing material

Porous asphalt has been used as road surfacing material on highways and urban roads in many countries. In the case of roads with high traffic density, porous asphalt is often placed on top of an impermeable base. Camomilla *et al.* (1990), Isenring *et al.* (1990), Wågberg (1991), Swedish National Road Administration (1994) and Noort (1996) have reported the main advantages and disadvantages of porous asphalt.

The main advantages of porous asphalt are traffic noise reduction, reduction of hydroplaning and spray, absence of reflection from road surface, good skid properties, and good resistance to permanent deformation. The main disadvantages are high maintenance costs for unclogging operations, sensitivity to oil spills, and different winter maintenance strategies are needed (i.e. specialised use of salt and friction material for slipperiness control).

4. FULL-SCALE POROUS PAVEMENT IN LULEÅ, SWEDEN

A full-scale porous pavement construction was built in 1993/1994 in a residential area on the outskirts of Luleå, Northern Sweden (N:65°36´, E:22°13´) (figure 3). A description of the field site can be found in Stenmark (1995). The structure that was built was similar to the porous pavement construction shown in figure 2. The thickness of the porous asphalt, the adjustment layer and the macadam sub-base was 45 mm, 30 mm and 600-1000 mm respectively. The porosity of the porous asphalt and the sub-base material was 15-20% and 35-40% respectively. The width of the grassed roadside swales was increased to create a larger area for stormwater infiltration. For comparison, one stretch of road in the area was surfaced with impermeable asphalt and one stretch of road was constructed with a sub-base of blast furnace slag. The underlying soil consisted of silty moraine (frost susceptible) with a permeability of $1 \cdot 10^{-6}$ to $4 \cdot 10^{-5}$ m/s. A view of the road area after construction is presented in figure 4.

Figure 3. The full-scale porous pavement during construction.

4.1 Field studies

Measurements of ground temperature, frost heave, groundwater levels and runoff were performed between 1994 and 1997. Climatic conditions, including air temperature, precipitation and snow-pack thickness, were monitored during the same period. Details on the methodology of the in-situ measurements were presented in **Paper I-II**.

4.2 Laboratory studies

Two 0.4 x 0.4 m^2 pieces of porous asphalt were cut out from the field site road in December 1996. Each asphalt piece was mounted on a grid of reinforcement steel in a test box. Infiltration capacity and draining behaviour of the porous asphalt were measured at different ambient air temperatures in the range -10 °C to +20°C. The methodology of the laboratory experiments was described in **Paper III**.

Figure 4. A view of the field site during rainfall in September 1994. The road in the foreground is surfaced with porous asphalt. A wet impermeable road surface can be seen in the background of the picture.

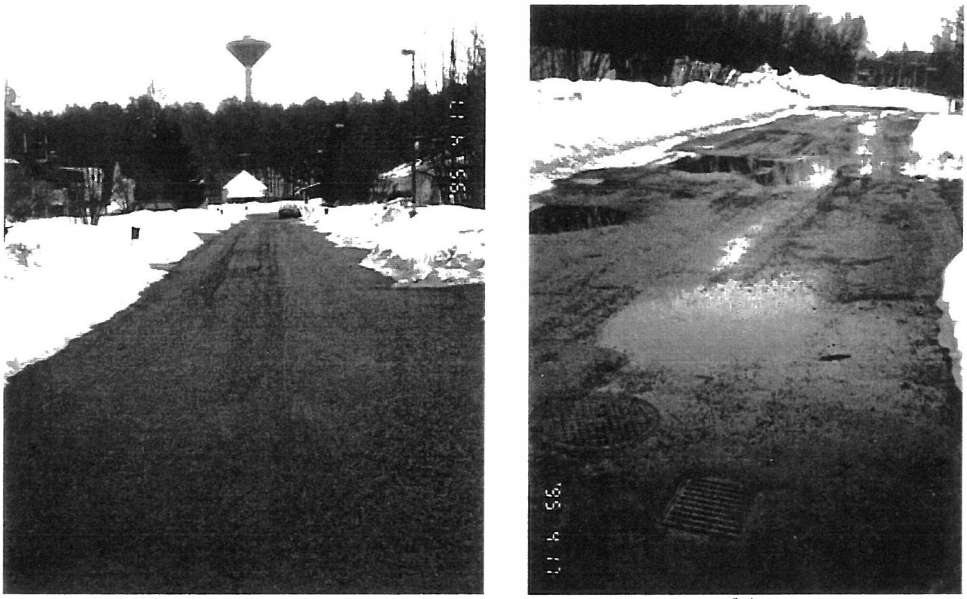
5. MAJOR RESULTS

5.1 Runoff control

The critical runoff volumes arose when the snow melted during a few weeks in late March and April (**Paper I**). At this time, the runoff reduction by the porous pavement was 50-60%. The typical runoff hydrograph during the snowmelt period had its highest peak at the beginning of the runoff event. The highest flows from the porous pavement occurred during the first part of the snowmelt period. Between 1994 and 1996 only two rainfall runoff situations were observed. The rainfall intensity was high in both cases. Long periods of rain with low intensity did not cause any runoff.

The porous asphalt retained its draining function during the snowmelt period, even though the infiltration capacity was decreased at low temperatures (**Paper III**). The results from the laboratory studies showed that the infiltration capacity at freezing point was approximately 50 % of the infiltration capacity at +20°C. Simulation of melt-freeze cycles for 2 days showed that ice clogging of the porous asphalt reduced the infiltration capacity by approximately 90%.

Ocular inspections revealed that the porous pavement became free from ice and snow on the surface earlier than impermeable asphalt surfaces. No water ponding or puddles occurred, as shown in figure 5. Due to the absence of water on the porous asphalt surface, no ice layer was formed during cold nights in springtime.



Porous pavement **Impermeable pavement**

Figure 5. A comparison of porous pavement and a nearby impermeable pavement during the snowmelt period (17th April 1995).

The groundwater level below the porous asphalt pavement rose one month earlier during spring, compared with the groundwater levels under the impermeable asphalt and the grass-covered ground (**Paper I and II**). Furthermore, the infiltration of stormwater seemed to produce a groundwater recharge in the porous pavement in summer and autumn. The groundwater level was higher below the porous pavement than below the impermeable pavement.

5.2 Ground temperature

During the winter months, normally October to February, ground temperatures in the porous pavement decreased linearly with time in the first 1.0 m of soil below the sub-grade (**Paper II**). Temperatures in the sub-base were sensitive to changes in ambient air temperature, especially at a point 0.2 m below the asphalt surface (figure 6). The sub-base temperatures responded even more quickly to variations in air temperatures when the layer of ice and snow on the porous asphalt surface disappeared in the spring. The ground temperature at 4.0 m below the asphalt surface varied between 3°C in mid-spring and 8°C in autumn.

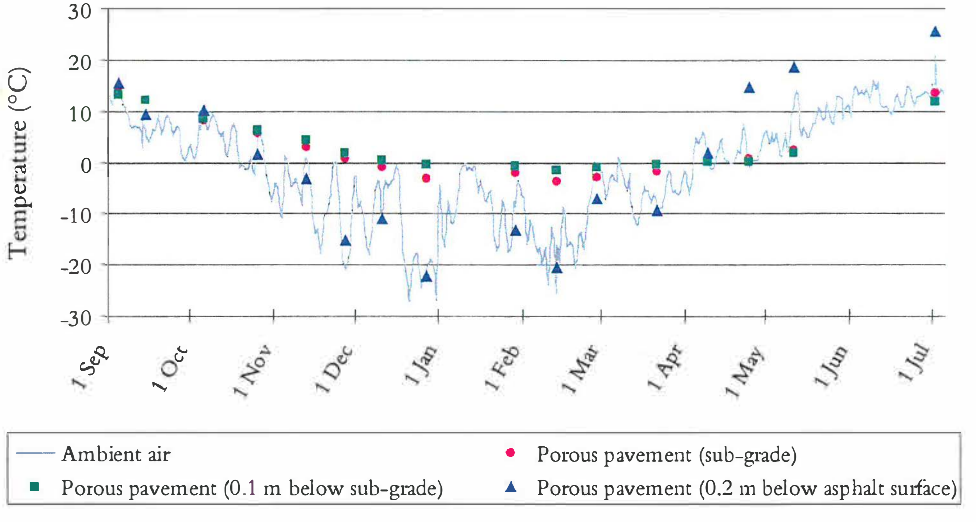


Figure 6. Comparison of ambient air temperatures and ground temperatures at three different levels in the porous pavement construction (September 1995 to July 1996).

The porous pavement was more resistant to frost penetration (i.e. downward movement of the 0°C-isothem) than the impemeable pavement during the cold winter of 1995/1996 (**Paper I and II**) (figure 7). The porous pavement and the impemeable pavement sections were frozen down to 1.4 m and 1.6 m below the asphalt surfaces respectively. However, there were no significant differences between the ground temperatures in the two pavement sections during a mild winter (1994/1995).

The thickness of the frozen layer in the underlying soil increased by 50-100 % when the sub-base thickness was 0.6 m instead of 1.0 m. The maximum frost penetration depth in the porous pavement with blast furnace slag sub-base was similar to the frost penetration in the porous pavement with macadam sub-base.

The soil below the sub-grade thawed faster in the porous pavement than in the impermeable pavement (**Paper II**). The in-situ measurements in spring 1995, 1996 and 1997 showed that the porous pavement thawed during the first two weeks of April, i.e. shortly after the commencement of the snowmelt period.

5.3 Frost heave

The frost heave of the porous pavement was less or equal to the frost heave of the comparable impermeable pavement (**Paper I**). During the cold winter of 1995/1996, the porous pavement with 1.0 m sub-base of macadam heaved 1-2 cm and the impermeable pavement with similar sub-base heaved 7-8 cm (figure 7). The porous pavements with 0.6 m sub-base heaved 4 cm (blast furnace slag base) and 8 cm (macadam base) during the same period. During the mild winter of 1994/1995, the frost heave of the porous pavement and the impermeable pavement was comparable (1-2 cm). A larger heave (4 cm) was observed in the porous pavements with thinner sub-base.
The frost heave that occurred was evenly distributed over the road surface and no damage on the road construction due to irregular frost heave has been observed.

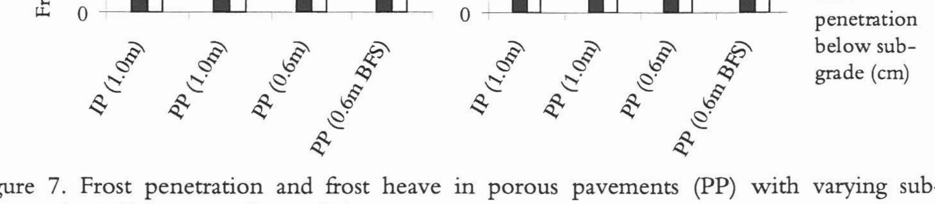


Figure 7. Frost penetration and frost heave in porous pavements (PP) with varying sub-base constructions (1.0m macadam sub-base, 0.6 m macadam sub-base and 0.6m blast furnace slag (BFS) sub-base) and impermeable pavement (IP) with 1.0 m macadam sub-base. Freezing index for winters 1994/1995 and 1995/1996 was 700 °Cd and 1500 °Cd respectively. Frost heave was measured 5th May 1995 and 14th April 1996.

6. CONCLUSIONS

It was found by in-situ investigations that porous pavements have the potential to reduce meltwater runoff, avoid excessive water on the road surface during the snowmelt period and accomplish groundwater recharge by local disposal of stormwater.

The draining function of the porous asphalt was maintained during the snowmelt period even though the infiltration capacity of the porous asphalt at extreme temperature conditions was impaired due to ice clogging of the pores in the surfacing material.

The porous pavement was more resistant to freezing than the impermeable pavement, probably due to higher water content in the soil below the sub-grade of a porous pavement and due to the insulating effect of the air in the porous pavement. Thawing of porous pavement was a rapid process, which was explained by meltwater infiltration during the beginning of the snowmelt period.

The full-scale porous pavement construction was not damaged by frost heave and the frost heave of the porous pavement was less or equal to the frost heave of the comparable impermeable pavement. This behaviour can be explained by the decreased frost penetration and by the fact that the porous pavement was a homogenous road construction due to the elimination of conventional stormwater pipes and manholes.

A significant increase of frost heave and frost penetration was observed when the sub-base thickness was 0.6 m instead of 1.0 m. As a consequence, a sub-base depth of 1.0 m is recommended in regions with similar climate conditions to Luleå. No clear differences in frost penetration and frost heave between porous pavement with macadam sub-base and porous pavement with blast furnace slag sub-base were observed.

7. DISCUSSION

7.1 Advantages and disadvantages of porous pavements in cold climates

The results presented in this thesis have shown that a porous pavement construction works well under cold climate conditions. In fact, several advantages may be obtained by using porous pavements instead of conventional road constructions and stormwater pipe systems in cold climate regions. The advantages are:

- Construction costs may be decreased since there is no need for a stormwater pipe system.
- Surface flooding is avoided during snowmelt and heavy rains.
- Inflow to wastewater treatment plant may be reduced during wet weather and snowmelt.
- Improved conditions for vegetation growth are achieved due to increasing groundwater levels in the area.
- The efforts needed for repair of frost damages on roads may decrease because porous pavements are more resistant to frost penetration and frost heave.
- Lower costs for maintenance because irregular frost heave around stormwater pipes and manholes is avoided.
- Improved road safety during temporary freezing conditions since there is no water on the road surface able to freeze.

There are also possible disadvantages of porous pavements. The draining function of porous surfacing materials decreases gradually due to clogging. The cleaning (unclogging) operations needed to avoid this problem are more costly than regular sweeping of conventional road surfaces. Several researchers have shown that stormwater pollutants are accumulated in the porous pavement structure (see Chapter 3.2). However, on a long-term basis, there is a risk that these pollutants are transported further down into the underlying soil and groundwater. Local disposal of stormwater by infiltration is not applicable in areas with high groundwater levels.

The full-scale porous pavement construction presented in this thesis was more expensive to build than a comparable conventional road construction. The reason for this was that the porous pavement took longer time to build than a conventional pavement. However, Larson (1982) reported potential savings of 25-30% by using porous pavement instead of conventional pavement.

7.2 Further investigations

The pollution reduction potential of the full-scale porous pavement was not investigated since there were no major pollutant sources in the residential area. There is a need for more investigations on the pollutant reduction capacity of porous pavements during the snowmelt period. It is also important to investigate the long-term effects of pollutant accumulation in the pavement structure, such as the risk for ground water pollution.

This study has indicated that ground temperatures and frost heave were different for the porous pavement compared with the impermeable pavement. The factors controlling this behaviour have to be more deeply investigated. For example, the effects of varying soil water content and the insulating effect of the porous pavement need to be analysed. In order to answer these questions, model simulations may be compared with the data on ground temperatures presented in this thesis.

Long-term studies of structural damage and clogging of porous asphalt in cold climate regions have to be carried out. Even though the studies carried out so far have not revealed any major structural problems with porous asphalt in cold regions it is of utmost importance to know if low temperatures or ice formation in the asphalt pores may cause deterioration of porous asphalt surfaces. More research is needed to describe how the use of friction material for slippery control during winter affects the clogging process of the porous pavement.

An important factor for the total economy of the porous pavement is the maintenance costs. There is a need for more long-term investigations in this subject. Furthermore, application of porous pavements in cold climates may reduce frost heave damage on roads. Most likely, this can decrease the maintenance costs considerably.

Finally, the future stormwater system must sustain natural resources for coming generations. It is therefore important to analyse the resource utilisation during construction and operation of different stormwater systems.

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Paper I

VATTEN 54: 115–121. Lund 1998

AN ALTERNATIVE ROAD CONSTRUCTION FOR STORMWATER INFILTRATION IN A COLD CLIMATE

Alternativ gatukonstruktion för dagvatteninfiltration i kallt klimat

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Abstract

By using an alternative road construction with permeable asphalt over an open-graded aggregate base, the stormwater is infiltrated into the ground. No regular stormwater pipes and manholes are needed. A full scale study of an alternative road construction in a cold climate is presented in this article. Two roads in a housing area in Luleå, Sweden were rebuilt in 1993. The construction costs for an alternative road construction and a conventional road construction were comparable.

Stormwater runoff, groundwater levels, frost heave and frost penetration have been studied. The runoff reduction during the snowmelt period was 50–60 %. Frost heave was uniformly distributed over the road surface. No damage caused by frost heave was observed. The type of asphalt, permeable or impervious, did not influence the frost penetration.

Key words – stormwater, runoff, permeable asphalt, cold climate, snowmelt, alternative road construction.

Sammanfattning

En alternativ gatukonstruktion med dränerande asfalt och enhetsöverbyggnad av makadam är en metod för infiltration av dagvatten. Med den alternativa gatukonstruktionen behövs inga dagvattenledningar och brunnar. Ett full-skale försök i kallt klimat presenteras i denna artikel. Två vägar i ett bostadsområde i Luleå byggdes om 1993. Kostnaden för byggande av den alternativa gatukonstruktionen var jämförbar med anläggningskostnaden för en konventionell gatukonstruktion.

Dagvattenavrinning, grundvattennivåer, tjällyft och tjälnedträngning har studerats. Avrinningen under snösmältningen reducerades med 50–60 %. Tjällyft var jämnt fördelade över vägytan och inga tjälskador har uppstått. Resultaten antyder att tjälnedträngningen inte påverkas av asfalttyp.

Introduction

Stormwater management of today is mainly based on drainage systems with large pipes and manholes, often placed in conjunction with roads and other impervious surfaces. The aim of these systems has been to accomplish rapid conveyance of rain and melt water to the nearest recipient. Although the transport of stormwater is functioning well enough in many cases, there are problems with the conventional systems. Overflows are common, stormwater causes pollution in receiving waters and the costs for maintenance of the large scale systems with pipes and manholes are rising. Furthermore, frost heave damage and ice blockage of pipes and gutters often occur within or nearby the stormwater systems in cold climate regions. As a consequence of these problems researchers have been investigating alternative solutions for stormwater management, such as methods for detention and local disposal.

The main advantages of stormwater infiltration are runoff control, source control, groundwater cultivation, conservation of water resources and improvement of the water environment (Fujita, 1994). However, stormwater infiltration systems have not been applied at a larger scale in urban areas. One of the reasons for this is the risk for soil and groundwater pollution (Mikkelsen et al., 1993).

One of the stormwater infiltration methods is an alternative road construction with permeable asphalt over an open-graded aggregate base. No regular stormwater pipes and manholes are needed as the stormwater percolates into the subgrade and down to the groundwater. Previous studies have shown that the alternative road construction with permeable asphalt reduces peak flows, runoff volumes and stormwater pollution load to receiving waters (Hogland & Wahlman, 1990; Pratt et al., 1988).

Stenmark (1992) reported that the alternative road construction works well under cold climate conditions with respect to minimizing frost heave. Some preliminary results showed that the construction had a capacity to reduce the snowmelt runoff (Stenmark, 1995), which

Table 1. *Temperature and precipitation in Luleå, average 1961–1990 (SMHI)*

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly basis
Temperature (°C)	−11.5	−10.7	−6.0	0.1	6.4	13.0	15.5	13.6	8.3	3.0	−4.0	−9.0	1.5
Precipitation (mm)	40	28	32	29	33	33	50	60	58	50	52	41	506

is the critical factor for stormwater systems in cold climate regions.

This paper presents the results of a full-scale study of an alternative road construction in a housing area in Luleå, Sweden. The investigations were performed during 1995 and 1996. This paper will mainly focus on the stormwater runoff reduction in the facility. Groundwater, frost heave, frost penetration and costs will also be discussed briefly.

Study area

The site for the field study, previously described by Stenmark (1995), was a housing area at the outskirts of Luleå (N: 65°36′, E: 22°13′) in northern Sweden. The climate in Luleå could be characterised as warm summers and cold winters (table 1). About half of the precipitation falls as snow and the snowmelt period generally occurs in late March or April. Proximity to the sea makes the climate somewhat milder than inland.

The area of the streets and swales in the housing area is 0.49 ha and the total drainage area is 3.3 ha (figure 1). There are 29 detached houses in the drainage area. Before the roads were rebuilt the asphalt was in a bad condition due to frost heave and there were problems with water on driveways and streets during snow melt periods. The stormwater system consisted of ditches by the roadside and ducts under the roads. The sewage and water pipe trench was located approximately one metre from the asphalt edge, under the asphalt. Silty moraine is the dominating soil in the area and infiltration tests showed that the infiltration capacity was between 0.06 mm/min and 2.3 mm/min (Stenmark, 1995).

In autumn 1993 the former sub-base of the road was replaced with a one meter thick layer of macadam (16–80 mm) (figure 2) except for 45 m of 0.6 m macadam and 30 m of 0.6 m blast furnace slag. A geotextile was used to separate the fine soil from the macadam layer and a drainage pipe was placed in the sub-base to allow drainage of excess water. The following summer permeable asphalt was laid on top. Vegetated road-side ditches were also constructed which were connected to the drainage pipe by gutters at the lowest parts. The outlet was situated at the beginning of a ditch in a forest. Figure 2 shows a cross section of the alternative road construction.

Methodology

Climate

Precipitation and air temperature were measured continuously in the study area (sampling locations G and H, figure 1). The data were stored in loggers at site and then copied to PC for analysis. Weather data (temperature, snowpack thickness and precipitation) from the local government weather station at Kallax airport (30 km from the study area) were also collected.

Stormwater runoff

A V-shaped weir which was placed in the outflow manhole (sampling location F) was used to measure the

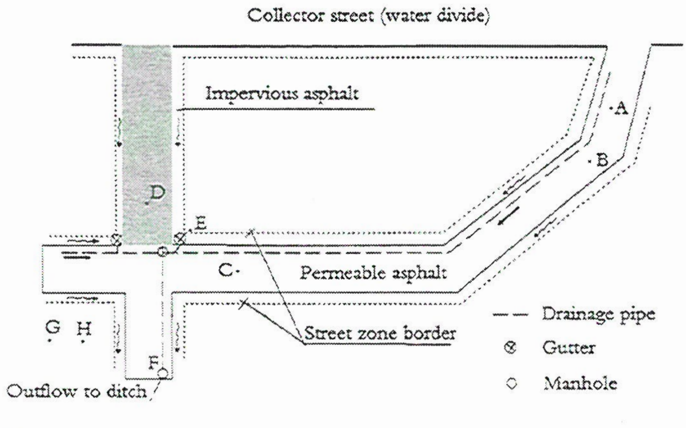


Figure 1. *An outline of the study area with sampling locations (A to H) marked out.*

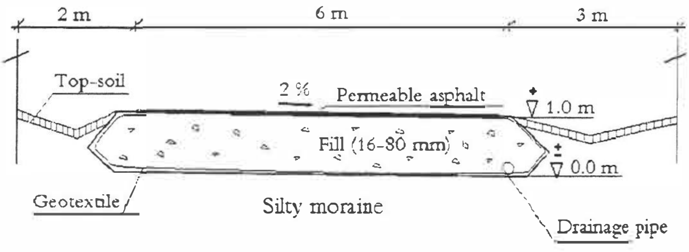


Figure 2. *Cross section of the alternative road construction.*

stormwater runoff from the study area. A pressure probe connected to a logger measured the water level of the weir in the manhole and the data were used to calculate the flow. Samples were taken every fifth minute and stored in the logger.

The peaks in runoff were compared with weather data in order to spot the critical situations and to understand the flowpaths of water within the area. Runoff is defined as the flow of water to the outflow manhole (location F), i.e. excess water from road base and ditches.

Groundwater

Groundwater levels have been measured approximately twice a month at locations A–E.

Frost heave and frost penetration

Road levels were measured in spring and summer/autumn to be able to compare frost heave for different road surfaces and road bases.

Temperature probes were installed in the sub-base and the underlying soil at locations A–D. Temperatures were measured approximately twice a month. The temperature data were put together in frost penetration profile charts.

Cost analysis

The costs for building and maintaining the alternative road construction were investigated by personal contacts with the local authorities in Luleå.

Results

Climate

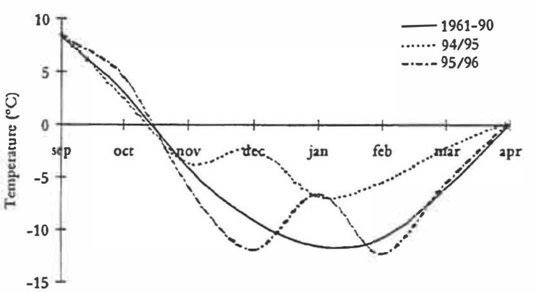
The winter of 1994/1995 was warm and had more precipitation than average (1961–1990). The period between September 1995 and April 1996 was on the other hand colder and had less rain and snow than normal (Figure 3).

Stormwater runoff

The critical runoff volumes arose when the snow melted during a few weeks in late March and April. The runoff from heavy rains was very small compared with the snowmelt runoff. Between 1994 and 1996 only two rainfall runoff situations were observed. In both cases the rainfall intensity was high (4–5 mm/h). On the other hand, long periods of rain with quite low intensity did not cause any runoff.

There were some backwater problems in the outflow manhole during the snowmelt periods. Therefore, the evaluation of the snowmelt runoff was done both quantitatively and qualitatively. Flow measurements in the outflow manhole were interpreted together with the information from ocular observations.

The measurements in spring 1995 showed that 30–40 % of the snowmelt in the road area ended up as runoff during the snowmelt period (Stenmark, 1995). Thus, the main part of the water took other ways than the drainage pipe, most likely it was stored in the road base and/or infiltrated into the ground.



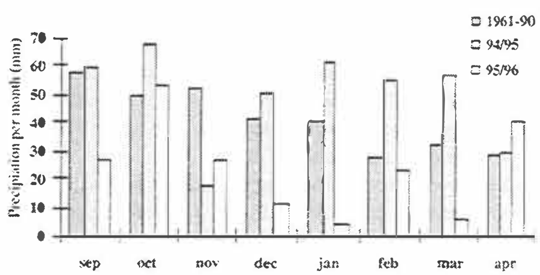


Figure 3. *Winter climate 94/95 and 95/96 compared with long-term average (1961–1990).*

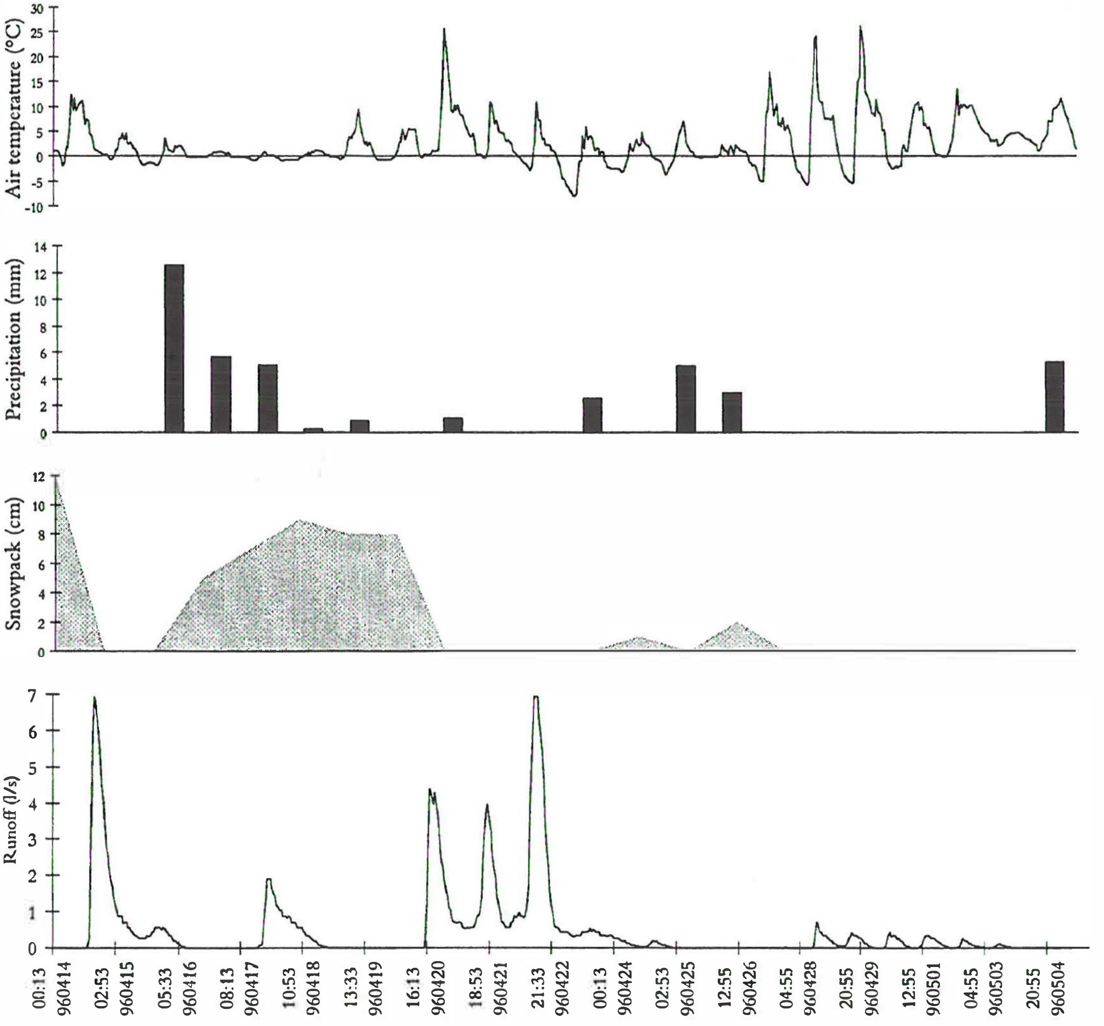


Figure 4. *Runoff, air temperature, precipitation and snowpack thickness during the period 960414–960505.*

The snowmelt runoff in the spring of 1996 together with climate conditions is presented in figure 4. The maximal snowpack thickness during the winter of 1995/1996 was 35 cm, which is less than normal.

The snow and ice on the permeable asphalt surface melted in the first days of April and gave the first runoff event but due to some problems with the measuring equipment at that time no flow rate could be calculated. Between April 14th and May 5th (1997) there were approximately 14 days with runoff and the runoff started generally in the afternoon.

It is possible to see a strong correlation between high air temperature and high runoff. The highest runoff peaks occurred when both day and night temperatures were high. Between April 20th and April 24th there were runoff events in series (figure 4). This indicates that the snowmelt runoff was started as a consequence of a hot day and then continued several days. During this period there was also a small rain event which contributed to the runoff and accelerated the snowmelt.

The high peaks in figure 4 might be misleading because the outflow structure did not have enough capacity. Nevertheless, figure 4 gives a good indication when the runoff events appeared.

The typical runoff hydrograph shows that the highest flow rate is reached at the beginning of the runoff event and that the flow decreases slowly (figure 5).

The total precipitation between November 1995 and April 1996 was 118.1 mm. This precipitation were stored in the snowpack. Assuming that it was only the road area (road surface and swales) that contributed to the runoff, the total meltwater volume could be calcula-

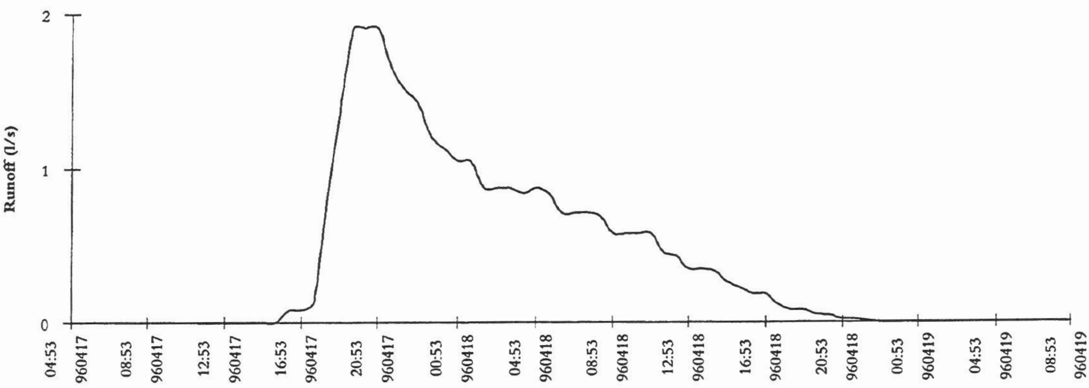


Figure 5. *Runoff hydrograph for a day in spring 1996 (960417–960418).*

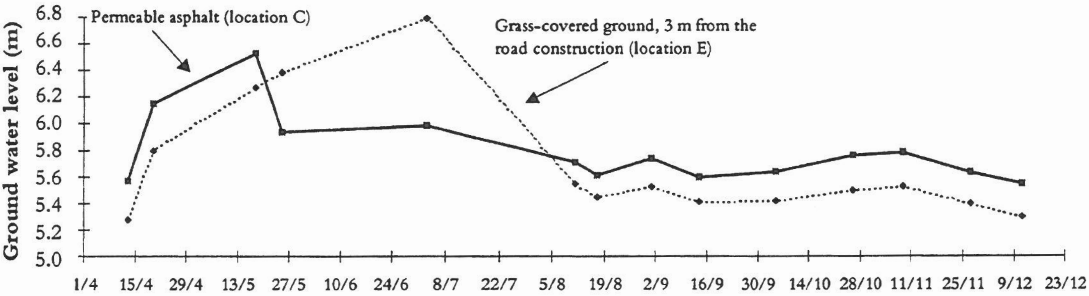


Figure 6. *Groundwater levels under permeable asphalt compared with grass-covered ground (April 4th–December 12th (1995)).*

ted. The road area is 0.49 ha, so the total meltwater volume was 580 m³. The total runoff volume during the snowmelt period 1996 was 280 m³. Thus, the meltwater runoff reduction was approximately 50 % in 1996.

Ground water

No major changes in groundwater level as a consequence of infiltration through the road construction have been detected, but the rise of the groundwater level occurred earlier under permeable asphalt compared with grass-covered ground (figure 6).

Frost heave and frost penetration

Frost heave was uniformly distributed over the surface. No irregular frost heave causing frost damage on the road surface was observed. The pavement structure with permeable asphalt and 1.0 m macadam sub-base decreases the maximal frost heave, compared with other road structures (figure 7).

The frost heave during spring 1996 was larger than the previous year. The explanation of this is that the winter of 1996 had lower temperatures and much less snow which resulted in poorer insulation of the ground and the frost could penetrate deeper (figure 8 and 9).

For two road sections identical except for the type of asphalt the frost penetration profiles are shown in figures 8 and 9. For the mild winter 94/95, the maximum frost penetration depth was 1.2–1.3 m for both permeable asphalt and impervious asphalt (sub-base 1.0 m). The only difference was that the road section with permeable

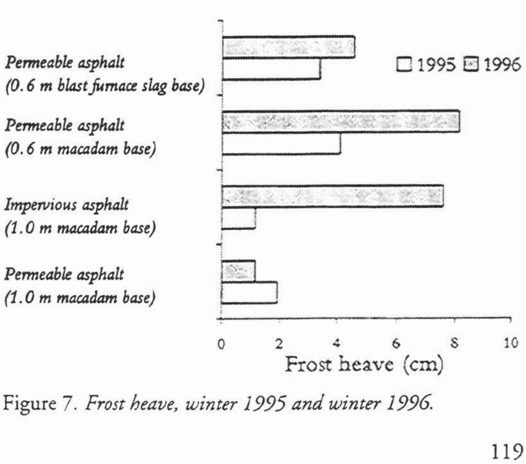
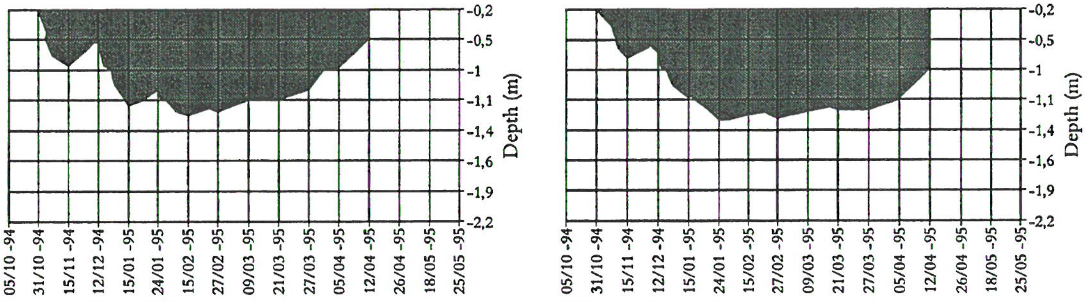


Figure 7. *Frost heave, winter 1995 and winter 1996.*



[a] permeable asphalt

[b] impervious asphalt

Figure 8. *Frost penetration profiles during winter 94/95 for [a] permeable asphalt (1.0 m sub-base of macadam) and [b] impervious asphalt (1.0 m sub-base of macadam).*

asphalt thawed faster (figure 8). The frost penetration profiles for the cold winter 95/96 showed larger differences between the two types of road sections with the same sub-base but different asphalt. Permeable asphalt seemed to decrease the maximum frost penetration depth by approximately 0.2 m (figure 9). Furthermore, the thawing processes for the two sections were different. With permeable asphalt the heating of the ground was fast and the ground temperature in the whole road section was above 0°C in early April. With impervious asphalt the thawing process was slower and there were temperatures below zero in the ground almost two weeks longer.

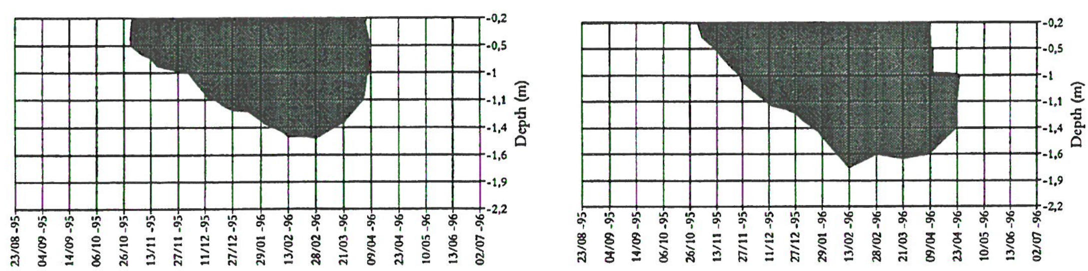
Costs

The total cost for rebuilding the two roads was SEK 2.03 million (1993). To rebuild the roads with an ordinary construction the local authority estimated that the cost would have been about SEK 1.63 million.

The major reason why the alternative road construction was more expensive was that it took longer time to build. The movable coarse material caused difficulties for the housing traffic and the asphalt machines during the construction phase. There is little experience of building these kind of road constructions which delayed the construction work. On the other hand, no conventional stormwater system with pipes and manholes was needed which decreased the investment costs. A conventional stormwater system would have cost approximately SEK 0.5 million. Bearing this in mind, the two road constructions become comparable in cost. The local authorities have not yet calculated how much they have saved through less road maintenance.

Discussion

The largest runoff volumes and the largest peak flows arise in the beginning of the snowmelt period (figure 4). The reason for this could be that the frost is still in the ground which decreases the infiltration capacity. Niemczynowicz et al. (1985) reported a peak flow reduction of about 80 % and a reduction in volume between 77 and 81 % from permeable asphalt and macadam areas compared to impermeable asphalt areas. These results were based on simulations of the runoff from a housing area in the southern part of Sweden. This is not fully applicable in cold climate regions where melt water is a greater problem. In this study, the snowmelt runoff volumes were reduced by 50–60 %.



[a] permeable asphalt

[b] impervious asphalt

Figure 9. *Frost penetration profiles during winter 95/96 for [a] permeable asphalt (1.0 m sub-base of macadam) and [b] impervious asphalt (1.0 m sub-base of macadam).*

The alternative road construction seems to be resistant to frost heave, even if the underlying soil consists of frost susceptible soil and the groundwater is quite high. However, the roads in this study are not yet so old, so it is not possible to draw any final conclusions concerning the long term frost damage.

More investigations are needed to be able to statistically confirm that the frost penetration is less under a permeable asphalt surface compared with an impervious asphalt surface. If these indications are correct, permeable asphalt must be considered suitable as road surface material in cold climate regions.

If frost heave damage is reduced as the preliminary results indicate, then the alternative road construction will have low costs for maintenance in the future. One cost that probably will be important for the total economy of the construction is the price of cleaning the asphalt (for example by vacuum-cleaning) and how often it needs to be done. There is equipment available for this today, but there is as yet not so much experience of operating it.

The road base of the alternative road construction consists of coarse material, either macadam or blast furnace slag. At Luleå University of Technology, laboratory experiments on leakage from roads with blast furnace slag as ballast have been done without finding any large metal or sulphur leaching (Lindgren, 1992). Macadam is not a limited resource but great amounts of energy are needed in its production. Natural gravel is a limited resource and important for the formation of groundwater. A system for local disposal of stormwater uses less material and resources than a conventional system with pipes and manholes. Furthermore, the natural water balance is maintained.

Stormwater pollutants originate from traffic, industry, corrosion etc. Experiments done in Lund show that the concentrations of suspended solids, metals and phosphorous are reduced when the stormwater flows through the alternative road construction (Hogland et al., 1987).

Nevertheless, as long as there are pollutants in the stormwater they will end up in the construction or in the underlying soil. There is inevitably a risk for groundwater contamination on a long term basis.

Conclusions

The alternative road construction with permeable asphalt and open-graded aggregate base was functioning satisfactory in cold climate regions. The runoff reduction during the snowmelt period was 50–60 %.

Frost heave was uniformly distributed over the road surface. No damage caused by frost heave was observed.

The construction costs for an alternative road construction and a conventional road construction were comparable. The alternative road construction reduced the frost damage which probably will give lower costs for maintenance.

Acknowledgements

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Paper II

GROUND TEMPERATURE IN POROUS PAVEMENT DURING FREEZING AND THAWING CONDITIONS

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ABSTRACT

Porous pavements are widely used for local disposal of stormwater. This paper presents the results of a full-scale study of ground temperatures in porous pavement during periods with prolonged freezing conditions and during snowmelt. The pavement construction was situated in a housing area in Luleå in northern Sweden and it consisted of porous asphalt over an aggregate base of macadam.
It was found that the cooling of the porous pavement was governed by variations in ambient air temperature and that freezing of the soil below the sub-grade was related to the freezing index. The porous pavement was more resistant to freezing than a conventional impermeable pavement due to higher water content in the underlying soil, which increased the latent heat in the ground. Thawing of the porous pavement was a rapid process, which depended on meltwater infiltration. The thawing process in a comparable impermeable pavement was slower.

KEYWORDS

Cold climate, freezing, frost penetration, porous pavement, stormwater, thawing

INTRODUCTION

The porous pavement construction may provide many benefits in an urban environment, such as stormwater flow attenuation, aquifer recharge and stormwater pollution control (Pratt, 1997). The porous pavement construction consists of a porous surface, normally porous asphalt, over an aggregate base for stormwater detention and infiltration (reservoir structure).
In cold climates, the temperature may be below the freezing point for several months and a large portion of the precipitation falls as snow. As a consequence, the ground is frozen, frost heave occurs and large amounts of meltwater are produced during spring thaw. It is important to investigate how these conditions affect the porous pavement function before applying the technique on a broad scale in cold climate regions.

Studies on porous pavements in Sundsvall in mid-Sweden have shown that the freezing of the soil below the sub-grade of a porous pavement was delayed compared with conventional road constructions (Hogland and Wahlman, 1988a). As a consequence, the risk for frost damage was decreased. The delay was explained by the insulating effect of air in the pavement. Studies in the UK showed that during short spells of cold weather, the air in the pavement released heat to the surface to thaw frost (Pratt, 1997). Thus, the air within the porous pavement construction acted as 'night storage heater'. It has been shown that porous asphalt responded much quicker to variations in the surrounding temperature than impermeable asphalt (Shao *et al*, 1994).

Studies in the USA have shown that the ice and snow conditions during mid-winter are similar on both a porous asphalt surface and an impermeable asphalt surface (Ferguson, 1994). However, there are indications that roads with porous asphalt become free from snow and ice earlier than conventional roads. This has been observed in several ocular inspections in different parts of Sweden (Hogland and Wahlman, 1988b). Meltwater infiltrated immediately through the porous asphalt, which gave fewer problems with slipperiness, as there was no water on the road surface that could refreeze during cold nights.

Sellgren and Stenmark (1992) measured temperatures in a street section with porous pavement in Haparanda in northern Sweden. The measured data were compared with the results from a simulation of non-linear heat conduction in soil. The freezing process was simulated with reasonable accuracy. Stenmark (1995) reported that porous pavements, compared with conventional stormwater pipe systems, reduce the risk for frost damage on roads because of the homogenous road construction. A porous pavement in a residential area in Luleå reduced the runoff volumes during the snowmelt period by 50-60% (Bäckström and Forsberg, 1998).

OBJECTIVES

The major objective of this study was to examine the variations in ground temperature in a porous pavement during periods with prolonged freezing conditions and snowmelt. This was done in order to evaluate if porous pavements are suitable for stormwater management in cold regions. Another aim of the study was to compare the winter performance of porous pavements with impermeable pavements.

FIELD SITE

The site for the field study was a housing area with 29 detached houses on the outskirts of Luleå in northern Sweden (N: 65°36′, E: 22°13′). The total drainage area was 3.3 ha. The old road construction in the housing area was in poor condition due to frost damage and there were problems with excessive surface water (puddles), especially in spring time when the snow melted. The underlying soil consisted of highly frost susceptible silty moraine. In 1993/1994, the road was rebuilt by replacing the old sub-base with a base of macadam (16-80 mm) (figure 1).

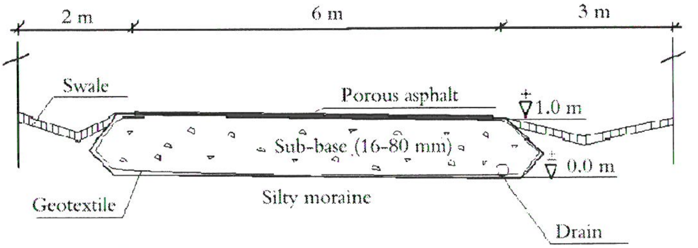

Figure 1. Cross-section of porous pavement construction (not in scale).

A geotextile was used to prevent intrusion of the underlying soil. Porous asphalt (thickness 45 mm) was placed on top of one of the roads and impermeable (conventional) asphalt on the other. The width of the grassed roadside swales was increased to create a larger area for stormwater infiltration. The area of streets and swales was 0.49 ha. No conventional stormwater pipes or manholes were installed, the only pipes remaining under the road surface

were perforated drainage pipes at the sub-grade and the drinking water and sewage pipes which were placed approximately 1.0 m below the sub-grade. The stormwater quality was assumed to be good since no major sources of pollutants existed.
Stenmark (1995) and Bäckström and Forsberg (1998) have previously described the field site.

MEASUREMENTS

Temperatures were measured in two different road sections; [a] a porous pavement with porous asphalt over a 1.0 m macadam base and [b] a pavement with impermeable asphalt and 1.0 m macadam base. The distance between the two road sections was 32 meters. Temperature probes (thermocouples) were installed at 12 different levels between 0.2 m and 4.0 m below the asphalt surface. Temperature readings were performed every two weeks between 1994 and 1996, and February 1997 to April 1997. The accuracy of the instrument was ± 0.1° C. Groundwater levels below the road surface were measured every two weeks.
Air temperature readings were done automatically every 50 minutes at the field site and stored in a logger. Data on the climatic conditions were also gathered from the nearest weather station, at Kallax airport in Luleå, 30 km from the field site. Furthermore, ocular inspections were done frequently to study the performance of the pavement constructions.

RESULTS

Climatic conditions

In table 1, temperature and precipitation during winters 1994/1995 and 1995/1996 are compared with the average values (1961-1990). The winter of 1994/1995 was milder and richer in snow than average. The winter of 1995/1996 was slightly colder than average and the amounts of snow were much less.

Table 1. Winter climate 1994-1996 compared with average of 1961-1990 (SMHI, 1996).

	Temperature (°C)			Precipitation (mm)		
	1961-90	94/95	95/96	1961-90	94/95	95/96
September	8.3	8.6	8.5	58	59.4	26.6
October	3.0	2.5	4.4	50	67.6	53.0
November	-4.0	-3.6	-5.9	52	18.2	27.0
December	-9.0	-2.2	-11.8	41	50.4	11.6
January	-11.5	-6.7	-6.5	40	61.2	4.2
February	-10.7	-5.4	-12.2	28	55.3	23.4
March	-6.0	-2.1	-5.5	32	56.6	6.3
April	0.1	0.4	0.3	29	29.6	40.5

The air temperatures (daily average) between October and May 1994/1995 and 1995/1996 are shown in figure 2. The winter of 1995/1996 had long periods with temperatures below -15 °C while the winter of 1994/1995 just had a few days with temperatures below –10 °C.

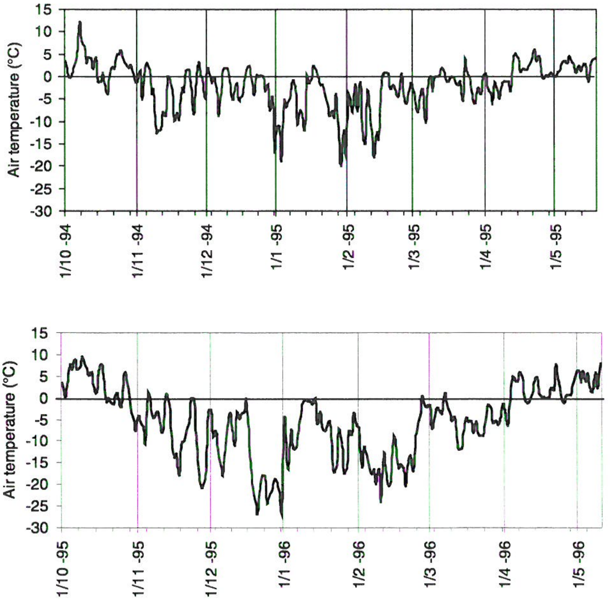

Figure 2. Air temperature (daily average), October 1994 –May 1995 (Kallax airport, Luleå) and October 1995 –May 1996 (Field site, Luleå).

The amount of precipitation in October 1994 was higher and more concentrated to the last week of the month than in October 1995. The snow cover started to increase late in the winter of 1994/1995 due to the mild weather conditions in the early winter (figure 3). The maximum snow depth was 0.79 m and the snowmelt occurred between April 12th and May 6th. During the winter of 1995/1996, a small snow cover was established quite early in November and it increased slowly all through the winter until April 4th when the snow depth was 0.35 m. The snowmelt period in 1996 lasted for approximately 3 weeks, ending on April 24th. The road surfaces were clear from snow and ice in the first week of April, i.e. before the snowmelt period started.

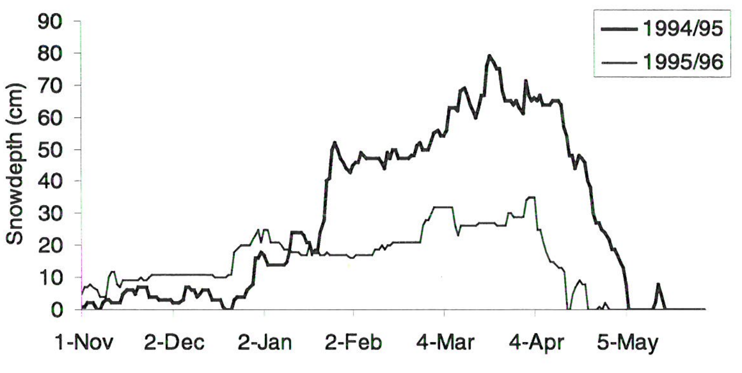

Figure 3. Snow depth during winters 1994/95 and 1995/96. Undisturbed snow cover at Kallax airport, Luleå (SMHI, 1996).

Groundwater level

The groundwater level varied between 1.3 and 2.9 m below the porous asphalt surface (figure 4). The groundwater level in the impermeable road section was normally 0.5 m lower than in the porous pavement. The major differences between the two sections appeared during snowmelt and autumn. The groundwater level rose one month earlier in the porous pavement compared with the impermeable pavement structure. Furthermore, the porous pavement seemed to maintain a relatively high groundwater level during late autumn/early winter (November 1994 and 1995, figure 4). The lowest groundwater levels were reached in January – March each year.

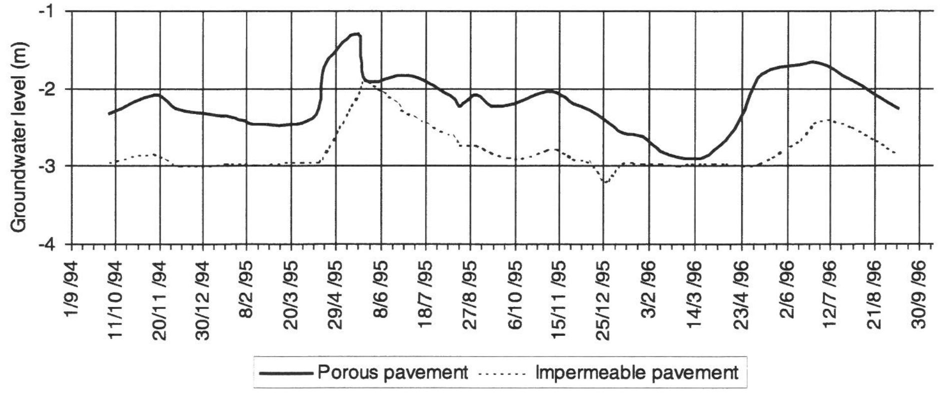

Figure 4. Groundwater levels in the porous and impermeable pavement sections respectively, October 1994 to September 1996. (Road surface level was ±0.0 m)

Ground temperature

The ground temperature at 4.0 m below the asphalt surface varied between 3°C in April and 8°C in October. Thus, the maximum temperature at this depth occurred at the end of the autumn. This represents the variations of the groundwater temperature, since the temperature probe at 4.0 m was in the saturated zone during the studied time period (figure 4).

The variation in ground temperatures during freezing in 1994/1995 and 1995/1996 in a 2.0 m deep section of the porous pavement is shown in figure 5. The temperatures in the entire section decreased gradually from early October to mid-February. The temperature decrease in the soil below the sub-grade was approximately linear with time.

The temperatures in the aggregate base (0.0 - 1.0 m depth) were generally lower than in the underlying soil and the temperature variations were also larger between different measurements.

The temperature profiles of 11th–12th December for the two winters were different. The freezing process was more rapid in the winter of 1995/1996 and the sub-grade was already frozen in December.

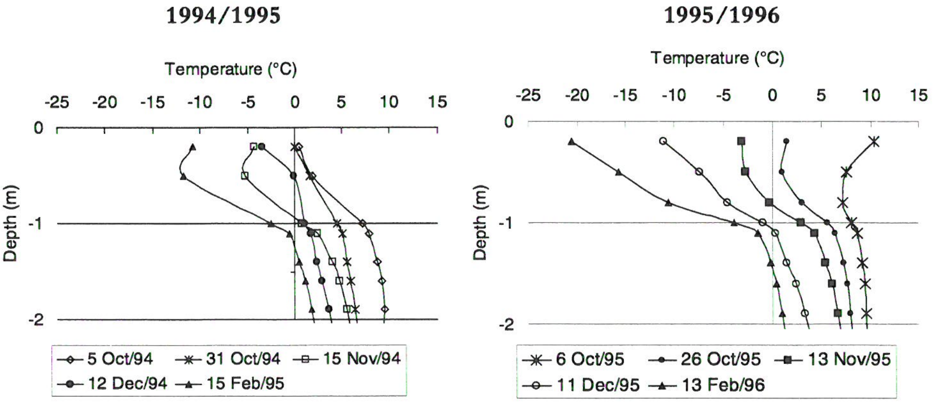

Figure 5. Temperature profiles in the porous pavement during 1994/1995 and 1995/1996.

Thawing of the sub-grade and the underlying soil occurred during the first two weeks of April, both in 1995 and 1996 (figure 6). The major difference between the two studied years was that the heating of the soil below the sub-grade was faster during April and May in 1995 than in 1996.

The porous pavement had a temperature close to 0 °C from the surface down to 1.5 m during the early stage of the snowmelt period (April 12th 1995 and April 9th 1996). In late April and May, the temperatures in the aggregate base (0.0 - 1.0 m) were much higher than in the underlying soil. This behaviour was most pronounced in 1996.

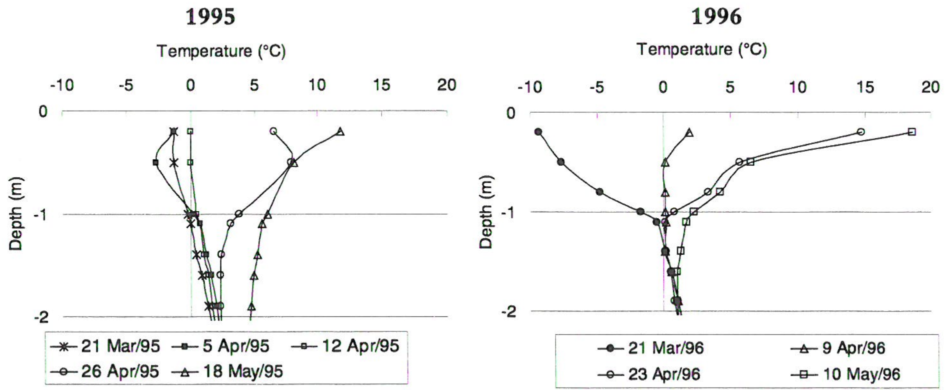

Figure 6. Temperature profiles in the porous pavement during thaw in 1995 and 1996.

Temperature response

In figure 7, a comparison is made of the average daily air temperature and the temperature at a point 0.2 m below the porous and impermeable asphalt surfaces respectively. In general, limited differences in temperature between the porous and impermeable pavements at a depth of 0.2 m were obtained. However, there were differences between the two pavement structures during a period of cold weather in late March 1997 as well as during late April. The porous pavement temperature was lower and more closely correlated to the ambient air temperature than the impermeable pavement temperature during cold weather. In late April (April 24th), the porous pavement temperature was similar to the air temperature, while the impermeable pavement had a lower temperature.

The measurements made on 9th, 14th and 17th April showed that the ground temperatures at 0.2 m below the asphalt surfaces were higher than the daily average air temperatures. At this time, the asphalt surfaces were clear from ice and snow and the pavement temperatures were similar to the air temperatures during daytime.

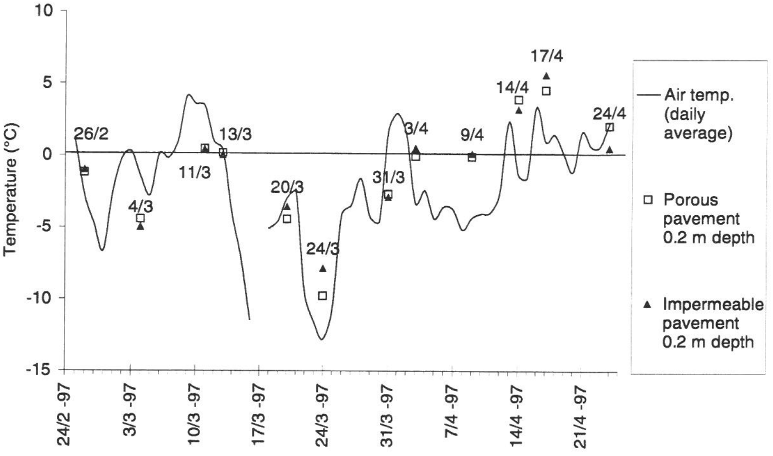

Figure 7. Comparison of air temperatures (daily average) and temperatures at 0.2-m below the asphalt surface (February 1997 – April 1997).

The temperature at the sub-grade of the porous pavement was influenced by air temperature according to figure 8. During 1995 and 1996, the sub-grade had temperatures below 0°C from February until the beginning of April. When the snowmelt was intensified during April, the ground temperature at a depth of 1.0 m increased.

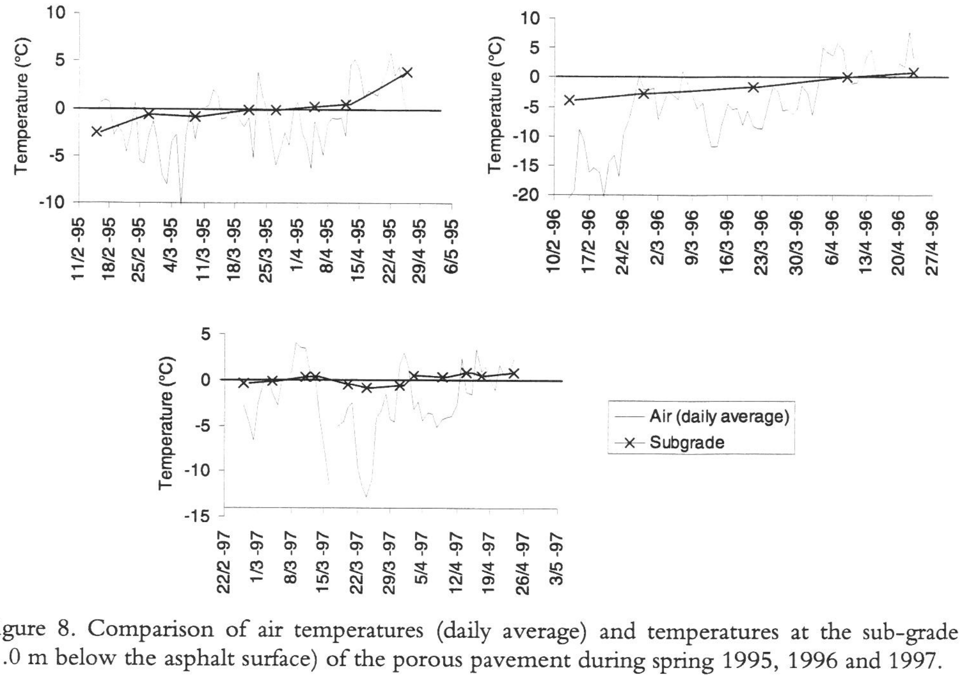

Figure 8. Comparison of air temperatures (daily average) and temperatures at the sub-grade (1.0 m below the asphalt surface) of the porous pavement during spring 1995, 1996 and 1997.

The temperature behaviour of the sub-grade during springtime was different in 1997 compared with 1995 and 1996. It can be seen in figure 8 that the sub-grade temperature was significantly lower in February 1995 and 1996 than in February 1997. In 1997, the sub-grade thawed during a warm period between March 9th and March 12th. Comparable warm weather during March 1995 and 1996 did not manage to thaw the sub-grade.

Frost penetration

The maximum frost penetration depth during winter 1994/1995 was 1.1 m below the asphalt surfaces, i.e. 0.1 m below the sub-grade (figure 9). The sub-grade was frozen for approximately three months between January and March.

A greater frost penetration depth was obtained during the cold winter of 1995/1996 (figure 9). The impermeable pavement was frozen down to 1.6 m below the asphalt surface (0.6 m below the sub-grade) in February and March. The ground was frozen below the sub-grade from early December to April.

The porous pavement was more resistant to freezing. The maximal frost penetration depth was 1.4 m below the asphalt surface and thawing of the underlying soil occurred one month earlier than in the impermeable pavement.

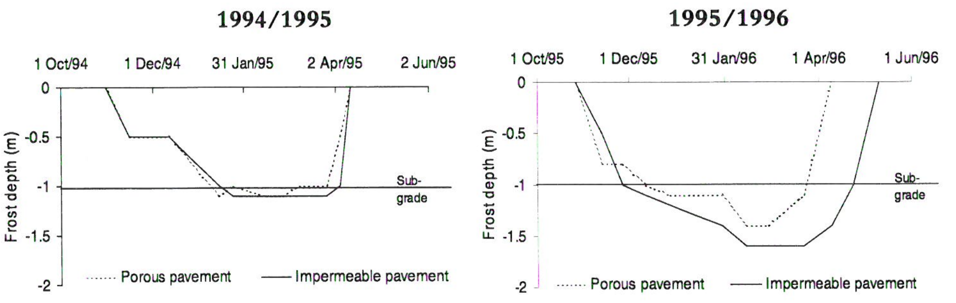

Figure 9. Frost penetration in porous pavement and impermeable pavement during 1994/1996 and 1995/1996.

A comparison of accumulated negative degree-days (freezing index) and frost penetration in the porous pavement was made for the winters 1994/1995 and 1995/1996. The frost penetrated the sub-grade of the porous pavement on January 15th 1995 during the winter 1994/1995 and on December 11th 1995 during the winter 1995/1996 (figure 9). The corresponding values of the freezing index were 316 °Cd and 355 °Cd respectively. The total sum of negative degree-days was 700 °Cd in 1994/1995 and 1500 °Cd in 1995/1996.

The accumulated positive degree-days during spring (March-May) were compared with the thawing of the porous pavement in 1995 and 1996. The porous pavement thawed on April 12th 1995 and on April 9th 1996, as shown in figure 9. The accumulated positive degree-days at the time for thaw were 10 °Cd in 1995 and 25 °Cd in 1996.

DISCUSSION

The difference in frost penetration between the impermeable pavement and the porous pavement during the cold winter of 1995/1996 is explained by differences in water content in the soil below the sub-grade. The groundwater level was approximately 0.5 m lower in the impermeable section, as shown in figure 4. Infiltration of stormwater most likely increased the soil water content in the porous pavement, which increased the amount of latent heat available. Studies of porous pavements and impermeable pavements in Lund in southern Sweden also showed that the water content increased in the soil below the sub-grade of a porous pavement (Hogland and Wahlman, 1989). The underlying soil was a moraine with a high content of clay.
Another explanation of the differences in frost penetration in the two pavements may be that the heat insulating effect of air is more pronounced in the porous pavement.

The two major factors influencing the freezing of the porous pavement were the variations in air temperature (I) and the ground heat flux from the underlying soil (II) (figure 10-A). The frost penetration in the soil below the sub-grade was related to the accumulated negative degree-days, also referred to as the freezing index. The freezing index needed to freeze the sub-grade was comparable for 1994/1995 and 1995/1996.

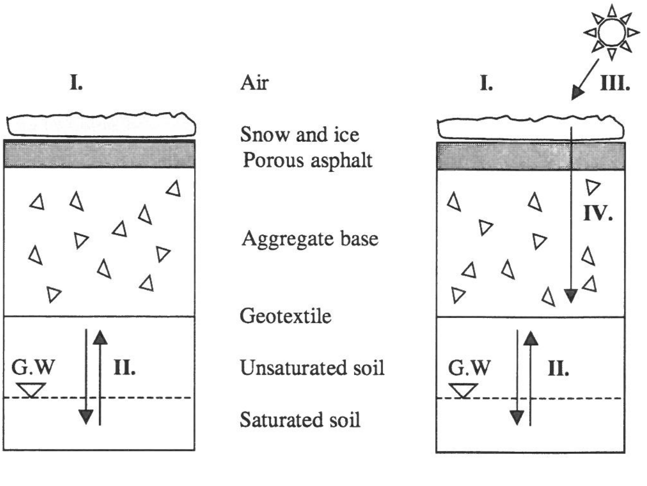

Figure 10. Major factors controlling the ground temperature in porous pavement during freezing and thawing conditions.

The thawing of porous pavement was to some extent governed by the variations in air temperature (I). Other important factors controlling the thawing process were, as shown in figure 10-B, ground heat flux from the underlying soil (II), increased net radiation (III) and energy content in infiltrated meltwater (IV). The increasing air temperature is normally the key to producing meltwater, which infiltrates through the asphalt surface and down to the underlying soil. Eventually, the asphalt surface becomes free from ice and snow and the effect of solar radiation increases as the black asphalt adsorbs more energy than the snow cover does.

The unique feature of the porous pavement is the draining function of the surface. The infiltrated meltwater most likely had an important role in the thawing of the pavement. The results from thaw 1995, 1996 and 1997 showed the same pattern, namely that the sub-grade thaw was associated with the first snowmelt. The accumulation of positive degree-days during early spring was not suitable as an indicator of the temperature increase of the porous pavement.

Approximately 90% of the frozen soil are thawed due to heat fluxes from the ground surface under normal conditions (RNCSIR, 1976). The results indicate that the thawing of the soil below the sub-grade of the porous pavement was entirely governed by heat fluxes from the surface.

The sub-base of the porous pavement seemed to respond quickly to changes in air temperature. The temperature response was more pronounced when there were no snow or ice on the asphalt surface. This behaviour could be explained by convection of air through the pores of asphalt.

A reduced capacity of a porous pavement could be caused by blockage of the pores in the asphalt or by a decrease in the hydraulic conductivity of the underlying soil. The draining function of porous asphalt was tested in a climate room (Bäckström and Bergström, 1999). Alternation of freezing and thawing cycles showed that the porous asphalt retained a sufficient infiltration capacity during snowmelt.
The infiltration capacity of frozen soil is much lower than that of unfrozen soil (Engelmark, 1986). When the pavement is frozen at the sub-grade and snowmelt starts, stormwater infiltration into the underlying soil may be hindered and most of the meltwater will be transported in the drainage pipes. The worst case would be intensive snowmelt or rain between periods with cold weather. This type of climate condition is common during early spring when there could be rapid changes in air temperature. Furthermore, the large runoff volumes during snowmelt could cause a temporary elevation of the groundwater level below the porous pavement and the underlying soil may be saturated.
Bäckström and Forsberg (1998) previously presented measurements of stormwater runoff at this site during the snowmelt period in 1996. Runoff was defined as excess water from the pavement construction (including the roadside swales). The largest runoff volumes occurred in late March and April.

Late autumn seemed to be a less critical period than the snowmelt period as the energy stored in the underlying soil delayed the frost penetration. The sub-grade had temperatures above 0°C at least a month after the freezing period started.

Slippery control on roads is necessary during wintertime. The conventional method used in Luleå is spreading of friction material, such as sand or crushed stone. Normally, friction material was not used in the area with porous pavement in order to minimise the risk for clogging of the asphalt pores. However, a few times coarse-grained friction material had to be applied due to icy conditions.

Frost heave was measured in 1995 and 1996 (Bäckström and Forsberg, 1998). Road levels in early spring were compared with road levels in late summer and autumn. The frost heave during winter 1994/1995 was 1-2 cm for both the impermeable and the porous pavement. The impermeable pavement heaved 7-8 cm and the porous pavement heaved 1-2 cm during the cold winter 1995/1996. The frost heave of the impermeable pavement fitted the simple correlation between frost penetration depth in the underlying soil and frost heave presented by

Jumikis (1977). The reported coefficient of relative frost heave for silt was 0.10 cm heave per cm frost penetration (Jumikis, 1977).
The relation between frost heave and frost penetration depth was different for the porous pavement during a cold winter (1995/1996). A frost penetration of approximately 0.4 m below the sub-grade caused the road surface of the porous pavement to heave 1-2 cm. The reason for this anomaly could be that the porous pavement had started to thaw at the time of measurement. Consequently, it was not the maximum frost heave that was measured.
There is a need for further studies to be able to clarify the mechanisms of frost heave in a porous pavement. Another important question is if there is a risk for long-term frost damage on the road construction, for example deterioration of the porous asphalt due to ice formation.

Further investigations of porous pavement performance during thaw are needed. For example, studies of bearing capacity and transport of pollutants in meltwater. There are several computer-based models available for calculations of freeze-thaw processes in pavements. These models have to be validated for porous pavement constructions.

In order to avoid temporary flooding problems, it is recommended to design roadside grassed swales along porous pavement roads. Frost heave damage is reduced if the pavement construction is as homogenous as possible. Pipes, manholes or other constructions should not be placed in the pavement structure.

CONCLUSIONS

The study of the ground temperature in porous pavement during freezing and thawing did not reveal any major operational setbacks. The most important findings were:

- The results indicate that a porous pavement is more resistant to freezing than an impermeable pavement due to higher water content in the underlying soil, which increased the latent heat in the ground.
- Cooling of the porous pavement is governed by variations in ambient air temperature and freezing of the soil below the sub-grade is related to the freezing index.
- Thawing of the porous pavement is a quick process, which was explained by meltwater infiltration. The thawing process in a comparable impermeable pavement is slower.
- The frost penetration depth is decreased and the frost period is shorter in a porous pavement compared with an impermeable pavement. Consequently, there is a lower risk for frost damage on porous pavement roads than on conventional roads.

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Paper III

POROUS ASPHALT PAVEMENT IN COLD CLIMATES

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ABSTRACT

Urban runoff creates problems with flooding and pollution of receiving waters. Furthermore, cold climate conditions have a degenerating effect on stormwater systems and road constructions. Porous asphalt has been used as a wearing course on highways and in porous pavement constructions all around the world. The main focus of this paper was to evaluate the function of porous asphalt in cold climates. Measurements of the draining function of porous asphalt were carried out in a climate room with adjustable temperature in the range -10 °C to +20°C. At freezing point was the infiltration capacity of porous asphalt approximately 50 % of the infiltration capacity at +20 °C.
When the porous asphalt was exposed to alternating melting and freezing during two days, conditions similar to the snowmelt period, the infiltration capacity was reduced by approximately 90 %. Based on the results of this study and previous studies, the infiltration capacity of porous asphalt was estimated to be 1-5 mm/min during snowmelt conditions.

KEYWORDS

Cold climate, infiltration, porous asphalt, porous pavement, stormwater.

INTRODUCTION

The area of paved surfaces has greatly increased through urban development. This has led to an increased amount of surface discharge. The urban runoff creates problems such as flooding, streambank erosion and pollutant discharge to rivers and other aquatic systems. One way to prevent these problems is to take care of the urban runoff by infiltration. Stormwater infiltration is the artificial forcing of urban runoff away from surface discharge and into the underlying soil. By returning runoff to the earth, it decreases pollutant discharge and replenishes ground water supplies (Fujita, 1994).

A way to decrease the amount of urban runoff is to use porous pavements in municipal regions. One type of porous pavement consists of an open-graded asphalt concrete (porous asphalt) over an open-graded aggregate base. This construction can be used at parking lots, lightly trafficked streets and pedestrian paths etc. The installation and maintenance costs for this construction may be greater compared with other types of pavements. On the other hand, porous paving is less expensive considering the need of a simplified storm drainage system (Göransson and Jonsson, 1990). Porous asphalt has also been used as a wearing course on highways and airfields. By laying the porous asphalt on top of an impervious asphalt, rainwater is drained off efficiently to the shoulder of the road.

In northern territories cold climate has a degenerating effect on road constructions. Freezing and thawing processes as well as soil frost, break down the construction. Frost heave around storm drainage system components, is a common cause of road damage (Hanaeus and Stenmark, 1989). The yearly costs to repair this damage are very high. A major part of the surface discharge in northern regions occurs during snowmelt. It is therefore very important that the drainage function of the porous asphalt is sufficient during the snowmelt period. It may, for example, be affected by the formation of ice at the road surface.
This paper presents the results from studies in laboratory on porous asphalt performance in cold climates.

RESEARCH OBJECTIVE AND SCOPE

The aim of the study was to investigate how cold climate and low temperature conditions influence the draining function of a porous asphalt. For practical applications, the snowmelt period with high runoff flows and temporary freezing was of special interest.
The investigations were done in lab-scale in a climate room. This procedure was chosen in order to minimise the influence of other parameters than temperature and precipitation/snowmelt. The lab-scale procedure also made it possible to perform multiple experiments in similar conditions, which increased the certainty of the results.

POROUS ASPHALT PAVEMENT FOR STORMWATER INFILTRATION

Porous pavements have been used around the world since the 60's. Studies on runoff reduction and water quality improvement have previously been described by Pratt et al. (1989).
In Sweden, the porous pavement structure with porous asphalt was first used at the beginning of the 80's. Studies performed in Lund and Luleå showed that the porous pavement reduces peak flows, runoff volumes and stormwater pollution load to receiving waters (Hogland and Wahlman, 1990; Bäckström and Forsberg, 1997).

The porous asphalt has a low amount of filler (grain size <0.075 mm) compared with conventional, dense asphalt (figure 1). Stormwater infiltrates through pores in the asphalt (15-25 % pore space). Hogland and Wahlman (1990) reported an initial infiltration capacity of 500-700 mm/min but after a few years in operation the infiltration capacity decreased to approximately 10% of the initial value. It is possible to clean porous asphalt by vacuum cleaning or by using high-pressure water equipment.
In the porous pavement construction used in Sweden the porous asphalt is laid on top of an open-graded aggregate base, also called a unit superstructure. The open-graded aggregate base functions both as a bearing structure and waterstoring layer. The base consists of macadam or blast furnace slag, fraction 8-80 mm or 32-120 mm. Void space is 20-40 %. Normally, a geotextile separates the base material from the underlying soil and improves the stability of the road construction.

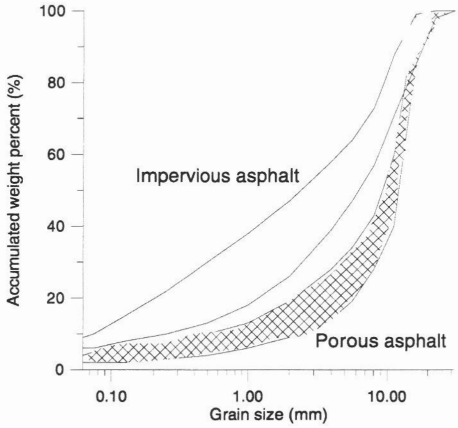


Figure 1. Grain size distribution (by weight) for filler material in porous asphalt and conventional impervious asphalt. Data from the Swedish Road Authorities (1994).

PREVIOUS STUDIES ON POROUS ASPHALT UNDER COLD CLIMATE CONDITIONS

Shao et al. (1994) reported that porous asphalt responded much more quickly to the variation of its surrounding temperature than impervious (dense) asphalt. Stenmark (1995) measured the infiltration capacity of porous asphalt pieces in a climate room with a temperature between -1.1 and -1.9 °C. The initial infiltration capacity of 290 mm/min at room air temperature (+20°C) decreased to 130 mm/min. The asphalt pieces were kept at the colder temperature and the tests were repeated for two days without drying the asphalt. After one day the infiltration capacity had decreased to 5 mm/min and at the end of the experiment the asphalt was completely clogged by ice.

There are indications that roads with porous asphalt become free from snow and ice earlier than conventional roads. This has been observed in several ocular inspections in different parts of Sweden (Hogland and Wahlman, 1988). Melted water infiltrated immediately through the porous asphalt, which gave fewer problems with slipperiness, as there were no water on the road surface that could freeze, for example during cold nights.

Noort (1996) has described temperature behaviour of porous asphalt pavements in the Netherlands. About 40 percent of the highways in the Netherlands are paved with porous asphalt. The porous asphalt is used as a surface layer in which stormwater can flow horizontally to the shoulder of the road. Data from 1986-1987 showed that porous asphalt dropped below freezing sooner, and as the air temperature increased, the temperature of porous asphalt stayed below freezing longer than that of a comparable road section of dense asphalt. The studies indicated that the minimum temperatures of porous asphalt were often a little higher than those of dense asphalt. When the air temperature remained at or a little above freezing and cold weather was prolonged, porous asphalt sections remained below freezing longer than comparable dense asphalt sections.

Noort (1996) concluded that there were no problems with ice formation and slipperiness on porous asphalt during normal winter conditions. Only in the case of freezing rain have there been problems. Supercooled raindrops congealed immediately when they reached the asphalt surface and the function of the porous asphalt was deteriorated.

LABORATORY STUDIES

The purpose of the laboratory studies was to simulate what happens during a snowmelt period. Two asphalt pieces (0.4x0.4 m^2) were cut out in late 1996 from a porous asphalt pavement with a mobile asphalt-cutting tool. The pavement was situated in the outskirts of Luleå town in Sweden (figure 2) and has been in operation since 1994. The porous asphalt thickness was 45 mm.

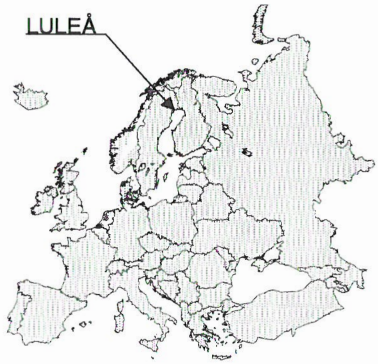
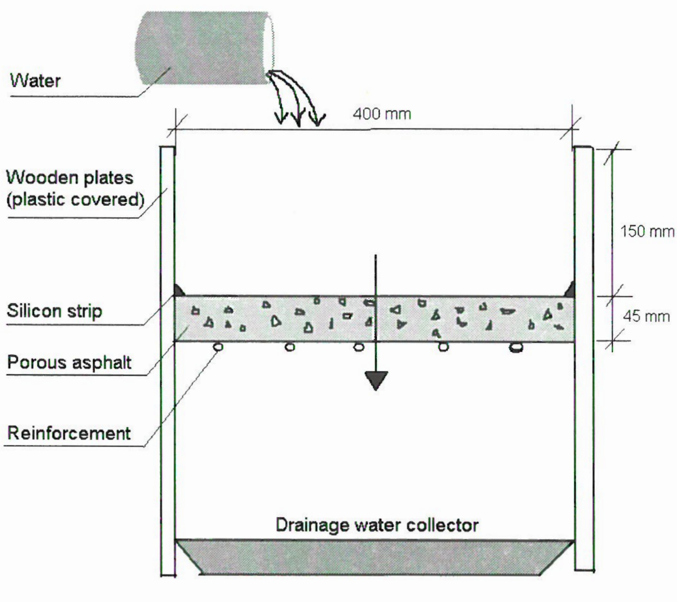


Figure 2. Map of Europe and the situation of Luleå.

One of the pieces was mounted in a wooden box and equipped with a temperature probe (accuracy ±0.2°C) within the asphalt layer (Figure 3). The second asphalt piece was mounted in a similar wooden box with a sloping plate below the asphalt. The plate directed the infiltrated water to a rectangular opening on one side of the box. The wooden boxes were then placed in a climate room in which the air temperature could be adjusted in the range -10 °C to +20°C.



Three experiments were performed:

1. Effect of ambient air temperature on the infiltration

Measurements of infiltration were done at +20°C, +5°C, ±0°C, -5°C and -10°C. The time for 6.25 mm of water to infiltrate was measured. The water used was drinking water from Luleå, Sweden. The temperature of the infiltrated water was in the range +0.2 to +3.0 °C. The experiment was repeated to improve the accuracy.

2. Simulation of the infiltration during the snowmelt period

A "worst case" was assumed where the air temperature was ±0°C and where water came in contact with the asphalt. The temperature of the water was in the range ±0.0°C to +4.2 °C. To simulate the melting periods, 0.625 mm of precipitation was applied to the asphalt every 30 minutes during three hours (figure 4). Between the water application periods there were periods with freezing conditions (-4°C) for 21 hours. The simulation continued for 48 hours. The infiltration rate was measured in the same way as in experiment 1 at 0 h, 24 h and 48 h. This simulation sequence was done twice.

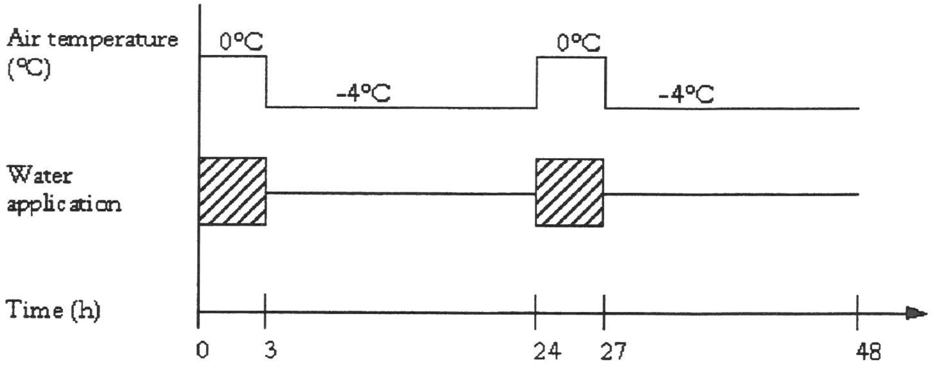


Figure 4. Schematic presentation of the "worst case" experiment.

3. Effect of temperature on the drainage process

In this experiment 12.5 mm of water at +2 to +4 °C were applied to the asphalt surface and after defined time intervals the infiltrated amount of water was collected in a plastic container and weighed. The time intervals were 30 seconds, 1, 2, 3, 4, 5, 10, 15, 20 and 30 minutes. By this procedure the remaining amount of water in the asphalt after a certain time could be calculated. The experiments were done at air temperature +10°C, +5°C and ±0°C. At each temperature five similar experiments were performed, at 2 hour intervals.

FINDINGS

The results from the infiltration capacity measurements at different ambient air temperatures (Experiment 1) are summarised in table 1.

Table 1. Infiltration capacity (mm/min) for porous asphalt which has been in use in a residential area for two years without cleaning. The initial water temperature was in the range +0.2 to +3.0 °C.

	Ambient Air Temperature		
Measurement number	+20°C	+5°C	±0°C
1	18.8	12.6	5.6
2	18.8	11.9	6.9
3	18.8	12.7	8.9
4	18.8	10.9	10.1
5	18.8	7.8	5.6
Average	19 mm/min	11 mm/min	7.4 mm/min

The infiltration rate at freezing point was about 40% of the infiltration rate at +20°C (figure 5). When the temperature was -5°C and –10°C, the infiltration rate was radically decreased due to ice formation in the asphalt. This made it difficult to measure the infiltration capacity accurately. Even if the infiltration rate decreased significantly, the asphalt was not completely clogged at a few degrees below freezing. This indicated that the porous asphalt still had a draining function in cold temperatures. However, the infiltration capacity was practically zero at temperatures below –5 °C.

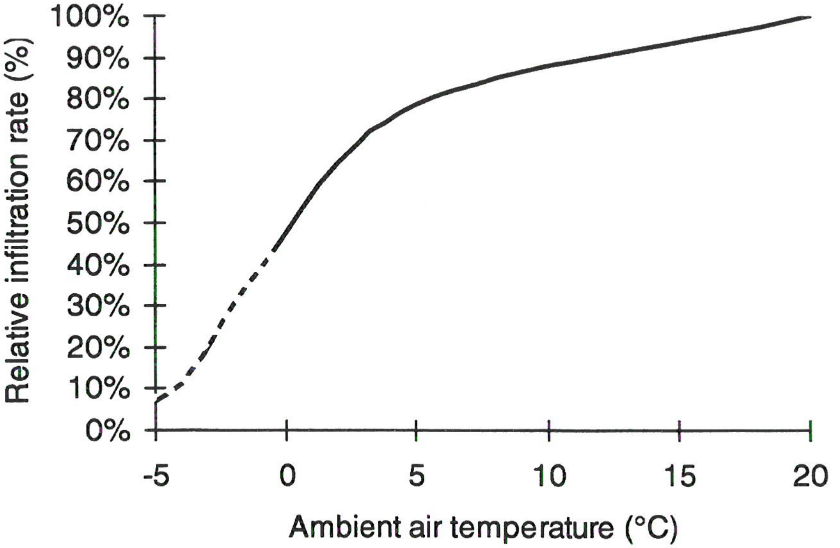


Figure 5. Relative infiltration rate of porous asphalt at different ambient air temperatures. Infiltration rate at +20°C was set to 100%. Dotted line represents the region where ice formation occurs.

The laboratory measurements of draining behaviour (Experiment 3) showed that the drainage through the asphalt was a rapid process (figure 6) and there was no large difference between the test runs at +20°C and ±0°C.

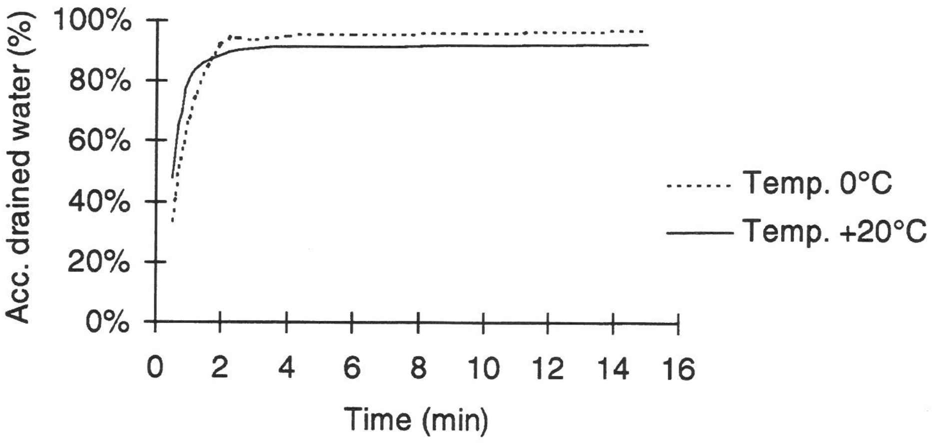


Figure 6. Accumulated amount of drained water at ±0°C and +20°C ambient air temperature.

The amount of water remaining in the porous asphalt during the first two minutes after water application is shown in figure 7. The asphalt retained slightly more water in the pores at the colder temperature during the first two minutes after water application. More than 90 % of the water applied to the asphalt drained off within 2 minutes in all the measurements that were performed.

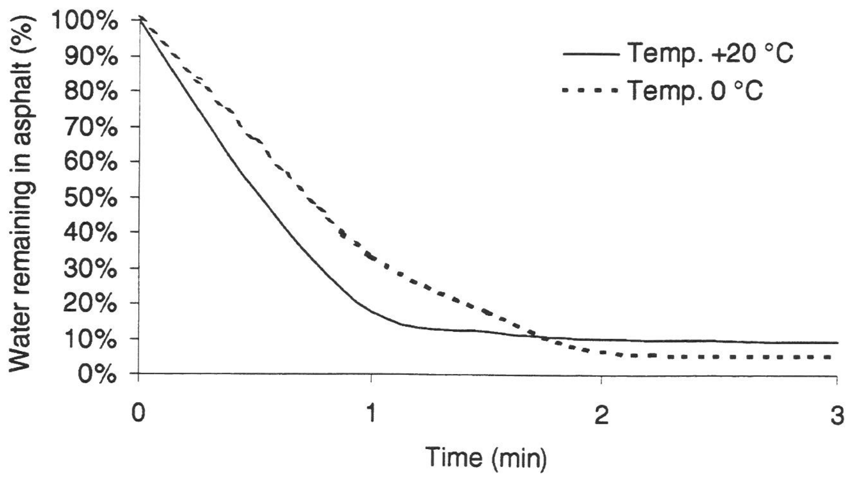


Figure 7. Draining function of porous asphalt at +20 °C and at ±0 °C (ambient air temperature). The variation of ambient air temperature during the experiment was ± 1°C. (n=5)

The porosity of the porous asphalt was approximately 20 % and the pore volume of the asphalt piece used in the laboratory testing was 1.44 * 10^{-3} m^3. A calculation of the retained amount of water able to freeze was performed. As mentioned before, the drainage of water through the porous asphalt was delayed during the first minutes at ±0°C compared to +20°C (table 2). This was in line with the results from Experiment 1. However, after 5 minutes of drainage the colder temperature gave smaller amounts of water in the pores. After 30 minutes of drainage in ±0°C it seemed like the asphalt contained 3 times less water than at +20°C.

Table 2. Percent pores filled with water compared with time passed after initially 100% filled pores. (Average of 5 measurements at each ambient air temperature)

	Pores filled with water	
Time (min)	+ 20°C	±0°C
0	100 %	100 %
1	28 %	45 %
5	12 %	7 %
15	11 %	4 %
30	9 %	3 %

The worst case simulations (Experiment 2) showed that the draining function of porous asphalt could decrease significantly during a melt-freeze-melt-freeze period (figure 8). The two experiments that were performed gave similar results. After one day the infiltration capacity was decreased to 30 % of the initial value and after two days only 7 % of the initial infiltration capacity remained.

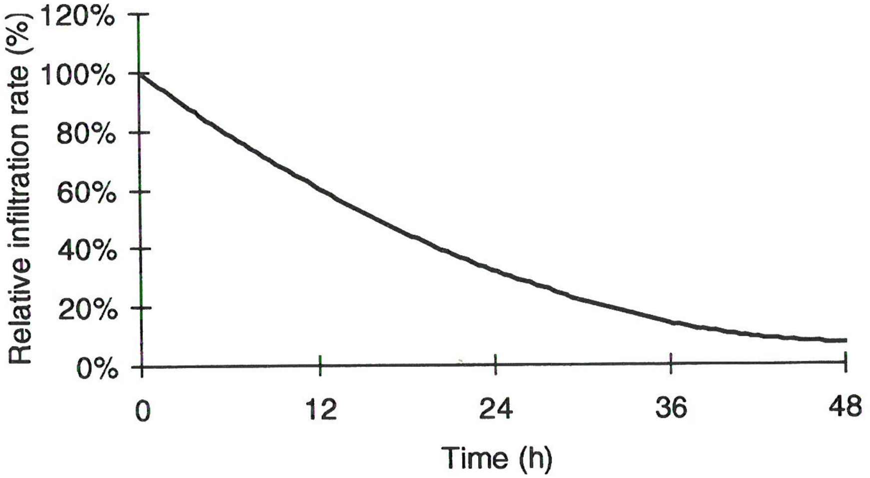


Figure 8. Relative infiltration rate during the worst case simulation. Infiltration rate at time=0 h and temperature=±0°C was set to 100%.

DISCUSSION

The infiltration capacity of the porous asphalt measured in the laboratory studies was approximately 19 mm/min at +20 °C, which was lower than expected. The initial infiltration capacity of porous asphalt is at least 10 times greater than this value (Hogland and Wahlman, 1990). This can be explained by the fact that the asphalt pieces used in the laboratory studies were taken from the field site road, which had been in operation for two years. No asphalt cleaning operations (high pressure washing or vacuum-cleaning) were done during this period. Therefore, the asphalt was clogged to some extent.

Since the laboratory studies were aimed at investigating critical situations in cold climates, namely the snowmelt period, the normal infiltration test was slightly modified. To be able to simulate snowmelt conditions, the volume of water applied on the porous asphalt during each infiltration capacity measurement was limited. The applied water volumes were equivalent to 6-12 mm of rain or meltwater.

The equipment normally used to measure infiltration capacity is the double ring infiltrometer (Ferguson, 1994). The most common way of operating the double ring infiltrometer is to maintain a constant water depth in the inner ring. The water in the outer ring creates a peripheral pressure so that the infiltrated water from the inner ring only flows vertically. A consequence of the use of a specialised measuring method in this study is that the infiltration capacity results are not fully comparable with results in other studies.

However, the main focus of this work was to investigate the draining function of porous asphalt in cold climate in a general sense. The major finding of this laboratory study was that the infiltration capacity of the porous asphalt was decreased by 90 % when the ambient air temperature was decreased to a few degrees below freezing. Based on the results presented in this paper and the previous work by Stenmark (1995) one can assume that the porous asphalt have an infiltration capacity of at least 1-5 mm/min during the snowmelt period.

Westerström (1984) measured snowmelt runoff in a residential area in Luleå, Sweden. The observed maximum hourly, 12 hour and daily snowmelt runoff rates during spring 1983 are presented in table 3.

Table 3. Maximum snowmelt runoff from snowcovered ground. (Westerström, 1984)

	Time		
	1 h	12 h	24 h
Runoff (mm)	1.5	12	15
Runoff per minute (mm/min)	0.025	0.017	0.010

The porous asphalt used in the laboratory tests was taken from a residential site outside Luleå. The total drainage area was 33 000 m^2 and the area of the streets and roadside swales was 4 900 m^2. Assume a worst case where all melt water from the drainage area is directed to the road area. The amount of snowmelt runoff that must be infiltrated in the road area will then be (33/4.9)*0.025 mm/min = 0.17 mm/min. In this example, the porous asphalt has an infiltration capacity that is enough (about 1 mm/min with a 10% function) during the snowmelt period.

Another important finding was that the water applied on the porous asphalt flowed through the asphalt quickly. 90 % of the water was drained within 2 minutes and the residual water remaining in the asphalt pores after 30 minutes was less than 1 %. The draining function appeared to be almost the same at an ambient air temperature of +20 °C as at freezing point. This indicates that the formation of ice within the pores of the asphalt is a slow process, probably due to the high level of latent heat in the infiltrating water.
The evaporation of water from the asphalt surface during the experiment was not measured. The evaporation could be a source of error in the drainage tests performed at +20°C but probably not at ±0°C.

Porous asphalt gets clogged due to passage of vehicles, construction works and winter maintenance (Hogland and Wahlman, 1990). Some kind of regular cleaning operations are therefore inevitable. The use of high-pressure water cleaning is widely used and the infiltration capacity can be regained to a large extent. It is recommended to clean the porous asphalt approximately every two to four years (depending on traffic load etc.) and the friction material applied during winter should be of a coarse fraction (2-4 mm).

As mentioned before, there is always a risk for clogging of the porous asphalt, either by sediment or by ice. This could cause flooding and problems with excessive water on the road surface. A construction that will avoid these problems is shown in figure 8. This road construction includes both porous pavement and roadside grassed swales. The swales will convey excessive runoff and provide space for local snow deposits. Furthermore, the grassed swales could give a reduction of pollutants and particulate matter in stormwater (Bäckström, 1998; Yousef et al., 1987).

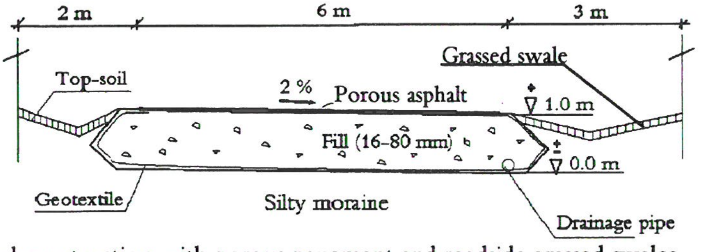


Figure 8. Road construction with porous pavement and roadside grassed swales.

CONCLUSIONS

The results show that porous asphalt retains some of its infiltrating function during wintry conditions. The infiltration capacity at freezing point was approximately 40 % of the infiltration capacity at +20 °C.
When the porous asphalt was exposed to alternating melting and freezing cycles for two days, conditions similar to the snowmelt period, the infiltration capacity was reduced by approximately 90 %.

It is difficult to give an exact value of the infiltration capacity of porous asphalt during the snowmelt period. However, based on the results of this study and previous studies, the infiltration capacity of porous asphalt could be estimated to be 1-5 mm/min during snowmelt conditions. This represents the maximum hourly snowmelt runoff from 40-200 m^2 snowcovered ground in northern Sweden.

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Porous pavement in cold climates

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Bäckström, Magnus

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Engelska

Sammanfattning
Local disposal of stormwater can be achieved by using porous pavements instead of impermeable pavements with conventional stormwater pipes and manholes. The objective of this thesis was to analyse the performance of porous pavements during freezing, thawing, and snowmelting conditions in order to evaluate if the porous pavement is suitable for stormwater management and road construction in cold climate regions. A full-scale porous pavement construction was built in 1993/1994 in a residential area on the outskirts of Luleå, Northem Sweden (N:65°36´, E:22°13´). In-situ measurements of ground temperature, frost heave, groundwater levels, and runoff were performed. The draining function of the porous asphalt at different ambient air temperatures in the range -10 °C to +20°C was investigated in laboratory.
It was found that porous pavements have a potential to reduce meltwater runoff, avoid excessive water on the road surface during the snowmelt period, and accomplish groundwater recharge by local disposal of stormwater. The porous pavement was more resistant to freezing and frost heave than a comparable impermeable pavement. The full-scale porous pavement construction was not damaged by irregular frost heave. Thawing of porous pavement was a rapid process, which was explained by meltwater infiltration and increasing air temperature during the beginning of the snowmelt period.

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Nyckelord
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