A Laboratory Study on the Effects of Winter Surface Applications on the Hydraulic Conductivity of Porous Concrete Pavements

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ABSTRACT

A laboratory study evaluating the effects of winter surface applications on the hydraulic conductivity of porous concrete pavements is presented. The objectives of the study were to: (1) determine the effects of typical winter surface application (sand and salt, 2:1 ratio by weight) on the hydraulic conductivity of porous concrete specimens, (2) determine the effects of maximum fines infiltration on hydraulic conductivity; and (3) examine the effectiveness of vacuuming as a tool to reclaim hydraulic conductivity after some amount of clogging had occurred. Hydraulic conductivities of virgin specimens ranged from 0.18 cm/s (255 in/hr) to 1.22 cm/s (1,729 in/hr). Reduction in hydraulic conductivity after the winter surface application of 0.12 g/cm^2 was found to be 15%. After maximum clogging had been achieved, reductions in hydraulic conductivity were measured around 35%. Specimens that were vacuumed to reclaim hydraulic conductivity after clogging were on average restored to within 10% of the initial hydraulic conductivity.

Key Words: Porous concrete, Pervious concrete, Hydraulic conductivity, Winter surface applications, Fines infiltration, Pore space reclamation

INTRODUCTION

The main use of porous concrete pavements, primarily designed as parking lots, has been as a stormwater management technique. These types of systems have been identified as a best management practice (BMP) for stormwater pollution prevention (EPA, 2000). There are several advantages to choosing porous pavements over more traditional methods of stormwater prevention. Porous pavements are ideal for sites that have existing structural components, when systems such as retention ponds are not a viable solution due to area restrictions. A porous pavement system could easily be retrofitted to the site, as it could replace existing parking areas and serve a dual purpose as both a stormwater BMP and parking lot (Leming, et al., 2007).

Porous pavement systems are effective stormwater management tools for multiple reasons. One of the main benefits is that these systems are able to capture the "first flush" from a storm event, or approximately the first inch of rainfall that occurs (Tennis, et al., 2004). This "first flush" is generally the most polluted stormwater that is produced during a storm event, and being able to capture and treat this stormwater significantly reduces the amounts of pollutants that make their way into streams and other water bodies. Porous pavement systems are also able to create short-term detention of rainfall, resulting in a reduced amount of surface runoff, recharging of the groundwater table, and reducing the sediment load that makes its way into water bodies via stormwater (Leming, et. al, 2007). Porous pavements have been shown to be effective in pollutant removal, capable of eliminating up to 95% of the total suspended solids (TSS), 65% of the total phosphorous (TP), 85% of the total nitrogen (TN), and 99% of the metals from stormwater runoff (Schuler, 1987).

Porous concrete pavements are generally designed as retention structures, much like other more traditional stormwater BMP's such as retention ponds. There are two possible categories porous pavement systems fall into, either a passive system or an active system. A passive system is designed to only replace impervious surface with pervious surface, and is not intended to store or treat stormwater runoff from other areas within the selected site. Alternatively, and active system is designed to accommodate stormwater resulting from more than just its own "footprint" (Leming, et al., 2007). An active system is ideal for areas where remediation is a priority, as they can be designed to store and treat stormwater from nearby impervious surfaces.

However, the effectiveness of these systems can be compromised by clogging of the pores. Infiltration of fines, and packing due to vehicular traffic or plowing could potentially reduce the hydraulic conductivity of the system significantly. The objectives of this study are to examine the effects that winter surface applications have on the hydraulic conductivity of porous concrete pavements, by testing in the laboratory: (1) samples after one winter surface application; (2) samples with maximum fines infiltration; and (3) samples after reclaiming some amount of the pore space via vacuuming. Virgin samples were tested previously and the results published separately (McCain and Dewoolkar, 2010). Effects of freeze-thaw on engineering properties of porous concrete as well as field verification of the effects of winter surface application are currently being studied and the results will be published at a later date.

BACKGROUND

Research into the hydraulic conductivity characteristics of clogged porous concrete systems are reviewed in this section.

Clogging of Porous Concrete Systems

A porous concrete pavement system can be severely affected by infiltration of fines into its void spaces. Clogging of these voids can reduce the porosity of the system and reduce its hydraulic conductivity. This occurs primarily due to (Scholz & Grabowiecki, 2007):

- Fines being compacted into the pore spaces by vehicular traffic;
- In active systems, sediment being carried onto the system by stormwater runoff, and infiltrating the pore spaces, and;
- Stresses due to vehicular traffic that result in collapsed pores.

Haselbach et al. (2006) conducted research to develop a theoretical relationship between the effective permeability of a clogged porous concrete sample versus a clean sample. The study also performed physical experiments to confirm the accuracy of the theoretical relationship. Tests were performed to examine both passive and active runoff by simulating rain events in a flume. Specimens were then completely covered by extra-fine sand with known permeability before testing began. The results showed that there was a marked decrease in the permeability of the porous concrete sample, with values before clogging greater than 0.2 cm/s (280 in/hr) and values of the clogged system of approximately 0.004 cm/s (6 in/hr). Although this was a large reduction in permeability, the clogged permeability was still found to be sufficient for a 100-yr 30-minute storm event for the southeastern United States.

Joung and Grasley (2008) also investigated the hydraulic conductivity characteristics of clogged porous concrete samples. The study first determined the hydraulic conductivity of clean samples utilizing a falling head permeameter. In order to clog the sample with fines, a slurry of sand and water was created and then poured through the sample multiple times. When all water had drained from the sample, falling head permeability tests were repeated on the sample to measure the reduction in hydraulic conductivity. The results showed that samples with a void ratio greater than 33% were not affected by clogging sand, whereas samples with a void ratio of less than 33% were affected, reducing the hydraulic conductivity by approximately 40%. The results also showed that the largest incremental decrease in hydraulic conductivity occurred after the first clogging cycle.

Some studies have also evaluated the effects of fines infiltration and clogging in the field. Bean et al. (2007) examined several porous concrete installations across North Carolina, Maryland, Virginia, and Delaware to determine what factors went into creating and maintaining high surface infiltration in the field. Surface infiltration capacity was determined with the use of either a single-ring or double-ring infiltrometer, depending on which was more suitable for the specific site. The study found that porous concrete sites that had no visual evidence of fines infiltration had surface infiltration capacities ranging from approximately 0.2 cm/s (280 in/hr) to 2.0 cm/s (2,800 in/hr), with an average value of about 1.1 cm/s (1,600 in/hr). Alternatively, at those sites where there was significant visual evidence of fines infiltration, the surface infiltration capacity ranged from 0.003 cm/s (4 in/hr) to 0.008 cm/s (11 in/hr), with an average value of 0.004 cm/s (6 in/hr).

Chopra & Wanielista (2007) also surveyed the effects of fines infiltration on porous concrete installations as well as the effectiveness of rehabilitation techniques. The study obtained cores from multiple porous concrete pavement facilities in Florida and the surrounding States and determined surface infiltration capacity with the use of a single-ring infiltrometer. The results of rehabilitation maintenance showed that a typical increase in surface infiltration capacity after rehabilitation was at least 200%. Of the three rehabilitation methods that were studied (pressure washing, vacuuming, and a combination of both) the results showed that either pressure washing or vacuuming yielded similar increases in surface infiltration capacity, whereas a combination of both methods was found to be ideal and led to the largest increase in surface infiltration capacity for the sites examined.

Henderson et al. (2008) performed field investigation of surface infiltration capacity at three porous concrete facilities in Canada. At two of the sites, half of the porous concrete parking lots received winter surface applications at a rate similar to conventional parking areas. Surface infiltration capacity was then measured utilizing a Gibson asphalt permeameter. The study found that there was no significant difference in surface infiltration capacity between areas where winter surface applications had been applied and areas that had not seen these materials. The effectiveness of vacuuming as a rehabilitation technique was also examined by vacuuming three locations at one site and performing additional tests. The study found that all three sites saw increased infiltration capacity, with increases of 119%, 287%, and 1.3%.

RESEARCH METHODS

This section presents the methods that were used to determine the effects of winter surface applications, maximum infiltration of fines and reclamation of pore space on the hydraulic conductivity of porous concrete specimens. These methods were conducted in the laboratory and do not recreate all conditions that would be observed in the field such as thermal issues, vapor transport and snowmelt.

Mix Designs and Sample Preparation

The porous concrete mix designs that were utilized in this study were based on constituents locally available in the central Vermont region along with local experience in constructing porous concrete pavements. All mix designs included a 10 mm (3/8”) crushed stone as coarse aggregate, no fine aggregate, and Lafarge type I-II cement with no supplemental cementitious materials (SCM’s). Several admixtures were utilized as well: a viscosity modifying admixuture (VMA), and air entraining agent (AEA), a high range water reducer (HRWR) and a stabilizer. Several different water-cement ratios and combinations of admixtures were used to characterize their effects on clogging of porous concrete samples. Proportions for each mix design can be found in Table 1.

Table 1: Porous Concrete Mix Designs

Mix Number	Cement (kg/m^3)	Aggregate (kg/m^3)	Water (kg/m^3)	AEA (mL/m^3)	HRWR (mL/m^3)	VMA (mL/m^3)	Stabilizer (mL/m^3)
LAB-1	374	1,660	94	77.4	488	1,180	1,180
LAB-2	374	1,660	109	77.4	488	1,180	1,180
LAB-3	374	1,660	124	77.4	488	1,180	1,180
LAB-4	374	1,660	124	77.4	-	1,180	1,180
LAB-5	374	1,660	124	-	488	1,180	1,180
FIELD*	374	1,660	109	77.4	488	1,180	1,180

***as reported by project documents at Randolph Park-and-Ride, Randolph, VT

Mixes were prepared in general accordance with the procedure suggested by Schaefer et al. (2006). Specimens were prepared as cylinders, with a diameter of 10.2 cm (4") and length of 15.2 cm (6"). Previous research by McCain & Dewoolkar (2010) suggested that 10.2 cm (4") diameter specimens were ideal for hydraulic conductivity testing. The specimen length of 15.2 cm (6") was chosen as a representative value of porous concrete pavement thickness found in the field. Specimens were cast in general accordance with ASTM C192; *Practice for Making and Curing Concrete Test Specimens in the Laboratory*. To provide as uniform compaction as possible, each specimen was cast in two lifts, and each lift was rodded 25 times with a 10 mm (3/8") tamping rod. Specimens for all mixes were prepared in laboratory with the exception of the field mix, specimens for which were cast from material provided at the Randolph Park-and-Ride in Randolph, VT.

Test Procedures

Hydraulic Conductivity

A falling head permeameter was designed for use with 10.2 cm (4") diameter specimens, as shown in Figure 1. The specimens were enclosed in a mold after being lined by a thin rubber sheet. The mold was secured using hose clamps to prevent any flow along the sides of the specimen that would affect the measured results. The specimen was then secured in the apparatus, and water was added to the downstream pipe in order to expel any air voids that may have been present in the specimen. When the water level had risen above the surface of the porous concrete sample water was added to the upstream water pipe, and the water level was allowed to reach equilibrium (zero head level). The head was then increased to 30 cm (about 12") and the time it took for the water to fall to a head of 10 cm (about 4") was recorded. This head difference has been shown to maintain laminar flow in typical porous concrete specimens for the hydraulic conductivities expected (Montes & Haselbach, 2006). Tests were performed a minimum of three times per sample and average results are reported here.

Figure 1: A Photograph of the Falling Head Permeameter

Winter Surface Applications

The application of winter maintenance materials was done as an attempt to evaluate how the fines on the surface may affect the permeability of the concrete. In Vermont, typically a 2:1 sand to salt ratio is used for winter maintenance activities to protect against ice buildup and provide traction for vehicles. In order to model these activities, a similar mixture of sand and salt was created using materials that were representative of those found in central Vermont. Visual inspection of the porous concrete surface showed that a representative amount of sand-salt to use on the surface of the porous concrete specimens was about 0.12 g/cm^2 (0.24 lbs/ft^2). This amount of winter maintenance material was enough to coat the surface of the specimen and visually clog a significant amount of the pore space. This amount was set constant so that each size sample would have an equivalent amount of the winter maintenance materials applied. A representative sample after WSA is shown in Figure 2. At this point it is not clear if this amount of winter surface application is representative of that in the field. Local data on that are presently being collected, but the amount applied can be taken as a conservative estimate, as it represents a significant amount of the surface pores covered with winter maintenance materials. After the application of these materials, the samples were placed in the falling head permeameter, and generally the same procedure (explained above) was followed to determine their hydraulic conductivities. The gradation of the sand used in the winter surface application mix is presented in Figure 3.

(a) (b) (c)

Figure 2: Hydraulic Conductivity Sample at Three Stages: (a) Virgin Sample, (b) After One WSA, (c) Maximum Infiltration

Maximum Clogging of Porous Concrete Specimens

Specimens were also clogged with as much sandy fines as possible by shaking. The porous concrete samples were enclosed in a rubber mold, as seen in Figure 2, slightly taller than the samples. Once the samples were in the mold a layer of sand, approximately 25 mm (1”) thick, was placed on the surface. Samples were then shaken to introduce fines into the pore structure. The specimens were then placed on a shake table with a frequency of 2 Hz and shaken for 60 seconds, and then rotated 90 degrees. This process was repeated four times for a total shaking time of four minutes per sample. Once the sample was shaken, excess material was removed by scraping the surface of the sample with a flat blade, using hand pressure to mimic the removal efficiency of a plow blade. Sand and other fines that had entered into the pores were not removed during the scraping process. Samples were then tested for hydraulic conductivity in the apparatus discussed above. For clogged porous concrete samples the head was only increased to 15 cm (6”) and the time it took for the water to fall to a level of 5 cm (2”) was recorded. Based on the theoretical equations for a falling head permeameter the change in head values would produce identical results to the original head values. Each specimen was tested a minimum of eight times to allow hydraulic conductivity to reach equilibrium.

Reclamation of Hydraulic Conductivity

Specimens were then cleaned in an attempt to restore pore space and hydraulic conductivity. Once samples had been tested for maximum clogging, they were allowed to dry for a period no less than 24 hours. Air dried samples were vacuumed to remove sand from the surface and clogged pores. This was performed with a ShopVAC 2.0 peak horsepower vacuum with a 1” diameter circular hose attachment. The surface of each sample was vacuumed for five seconds in an up and down motion and then rotated 90° and vacuumed for an additional five seconds. This cleaning was intended to simulate field vacuuming, however effects present in the field, such as brushing, were not simulated in the laboratory. Samples were then tested for hydraulic conductivity in the apparatus shown in Figure 1. For these tests, the head value was again increased to 30 cm (12”) and the time it took for the water to fall to a head of 10 cm (4”) was recorded. A minimum of three tests per sample were performed.

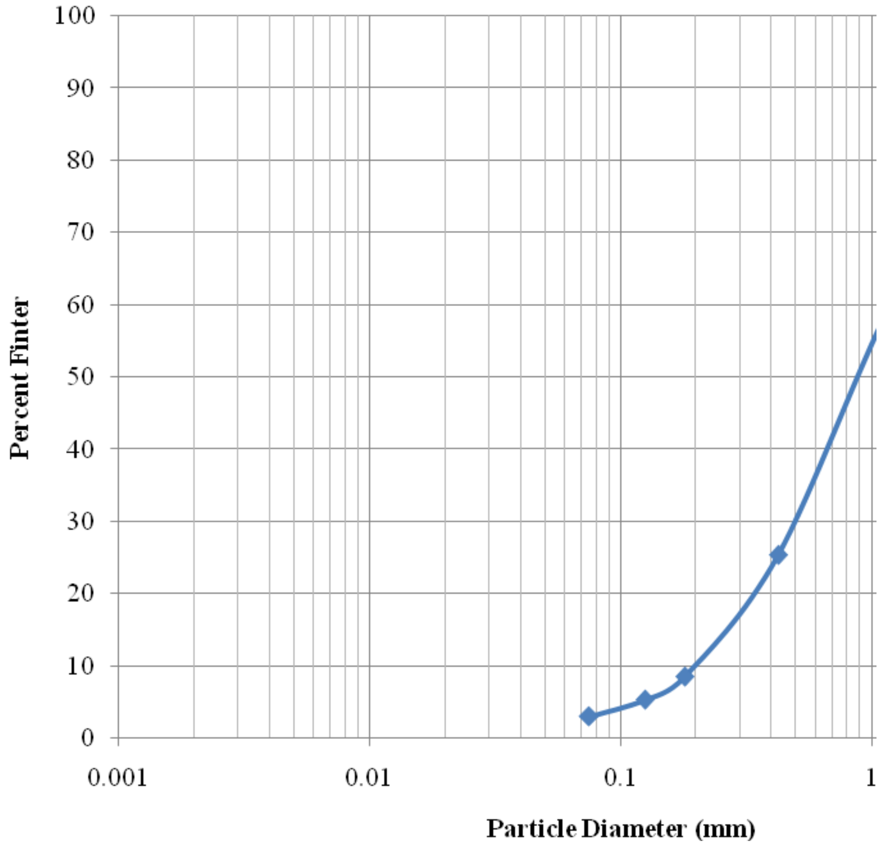


Figure 3: Sieve Analysis of the Sand used in Testing

RESULTS AND DISCUSSION

This section presents the results of experiments performed during the testing process. These results include the effects of one winter surface application on hydraulic conductivity, the effects of clogging the sample as much as possible, attempts at reclaiming lost pore space, and effects of winter maintenance activities.

Hydraulic Conductivity

Results for hydraulic conductivity of virgin porous concrete specimens are presented in another paper, *Porous Concrete Pavements: Mechanical and Hydraulic Properties* (McCain & Dewoolkar, 2010). These results include the effects of sample density, effects of water-cement ratio and effects of selected admixtures as well as field comparisons and comparisons with previous research. Relevant values to determine the effects of winter surface applications and fines infiltration are included in the following tables and figures.

Winter Surface Applications

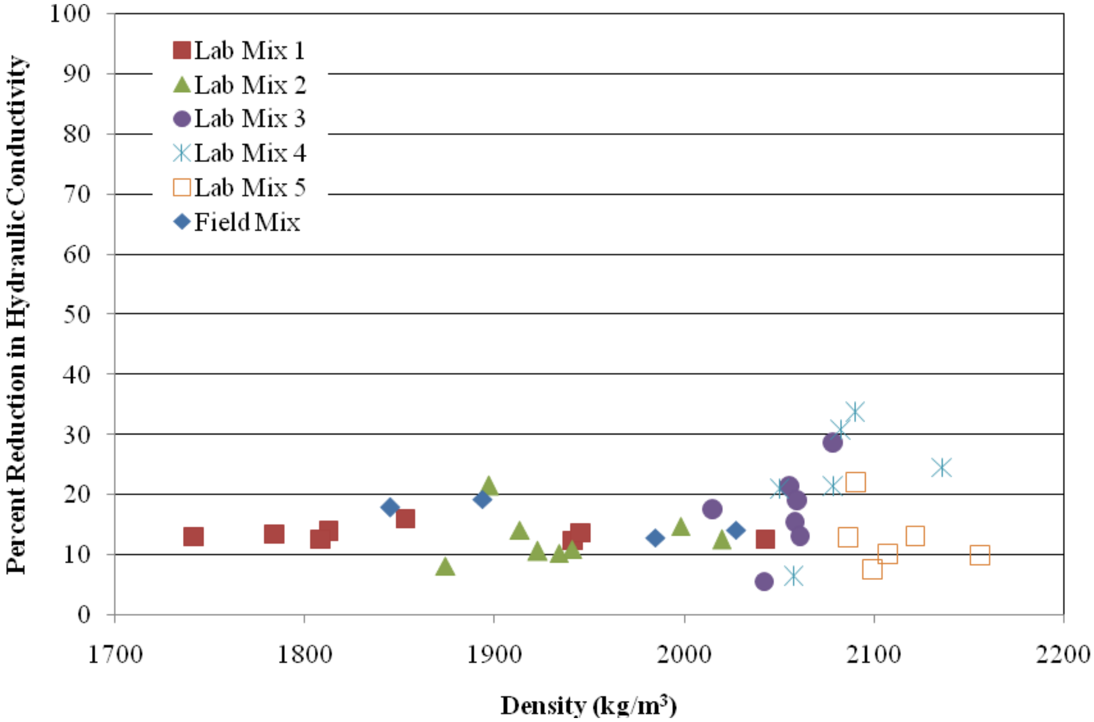
The effects of one winter surface application are summarized in Table 2. Average values for virgin hydraulic conductivity range from 0.18 cm/s (255 in/hr) to 1.22 cm/s (1,729 in/hr). After application of 0.12 g/cm^2 of winter maintenance material, hydraulic conductivity values ranged from 0.16 cm/s (227 in/hr) to 1.05 cm/s (1,488 in/hr). This corresponded to an average reduction of about 15% among the mix designs studied. Figure 4 shows the reduction in hydraulic conductivity for all samples tested. The reductions in hydraulic conductivity are plotted versus density in plot a and versus hydraulic conductivity of virgin specimens in plot b.

In examining Table 2 and Figure 4, it is clear that these materials have a marked impact on the hydraulic conductivity of porous concrete pavement specimens. The average reduction after one winter surface application of about 15% is a significant decrease from the virgin hydraulic conductivity. Even with this reduction, the lowest value was observed to be around 0.2 cm/s (about 280 in/hr), which can be considered adequate to allow water to pass through the system when looking at design storms for northern communities. It could be advantageous to perform similar testing on field cores after winter surface applications have been applied for a season for field verification. Figure 4 shows that density of the porous concrete sample does not have a significant effect on the reduction in hydraulic conductivity after one winter surface application, as all samples demonstrated similar reduction in hydraulic conductivity over varying density. Also the initial hydraulic conductivity does not appear to have any significant effect on the percent reduction in hydraulic conductivity, as shown in Figure 4. All samples had similar reductions even with initial conductivities that had differed by more than 1 cm/s (1400 in/hr). It should however be noted that the initial hydraulic conductivity of virgin porous concrete specimens decreased with increased density (McCain & Dewoolkar, 2010).

Table 2: Hydraulic Conductivity of Porous Concrete Specimens

Mix	Average Dry Density	Initial *k*		One Winter Surface Application			Maximum Clogging of Specimen			After Vacuuming		
				Average *k*		Average Reduction in *k*	Average *k*		Average Reduction in *k*	Average *k*		Average Reduction in *k*
	(kg/m^3)	(cm/s)	(in/hr)	(cm/s)	(in/hr)	(%)	(cm/s)	(in/hr)	(%)	(cm/s)	(in/hr)	(%)
Lab Mix 1	1,866	1.22	1,729	1.05	1,488	13.9	0.86	1,219	29.5	1.08	1,531	11.5
Lab Mix 2	1,938	1.03	1,460	0.90	1,276	12.6	0.64	907	37.9	0.98	1,389	4.9
Lab Mix 3	2,053	0.32	454	0.27	383	15.6	0.21	298	34.4	0.31	439	3.1
Lab Mix 4	2,082	0.36	510	0.28	397	22.2	0.22	312	38.9	0.33	468	8.3
Lab Mix 5	2,110	0.18	255	0.16	227	11.1	0.1	142	44.4	0.15	213	16.7
Field Mix	1,938	0.93	1,318	0.78	1,106	16.1	0.75	1,063	19.4	0.78	1,106	16.1

(a)



(b)

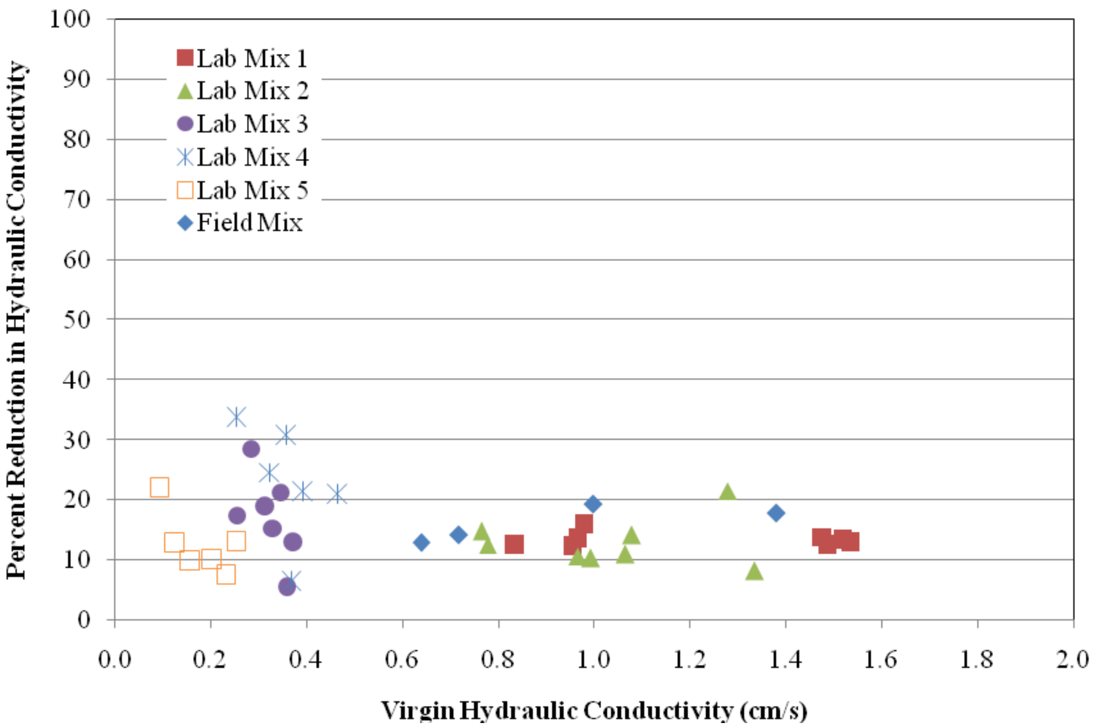


Figure 4: Reduction in Hydraulic Conductivity after One Winter Surface Application

Maximum Clogging

Table 2 also summarizes the average values for hydraulic conductivity after maximum clogging had been performed. Average values were determined from three individual tests with results ranging from 0.10 cm/s (142 in/hr) to 1.07 cm/s (1,516 in/hr) for the mix designs studied. This corresponded to an average reduction of about 35% between the virgin samples and fully clogged samples. Figures 5 (which is in a format similar to Figure 4) shows that sample density had little effect on the reduction of hydraulic conductivity after maximum clogging had taken place.

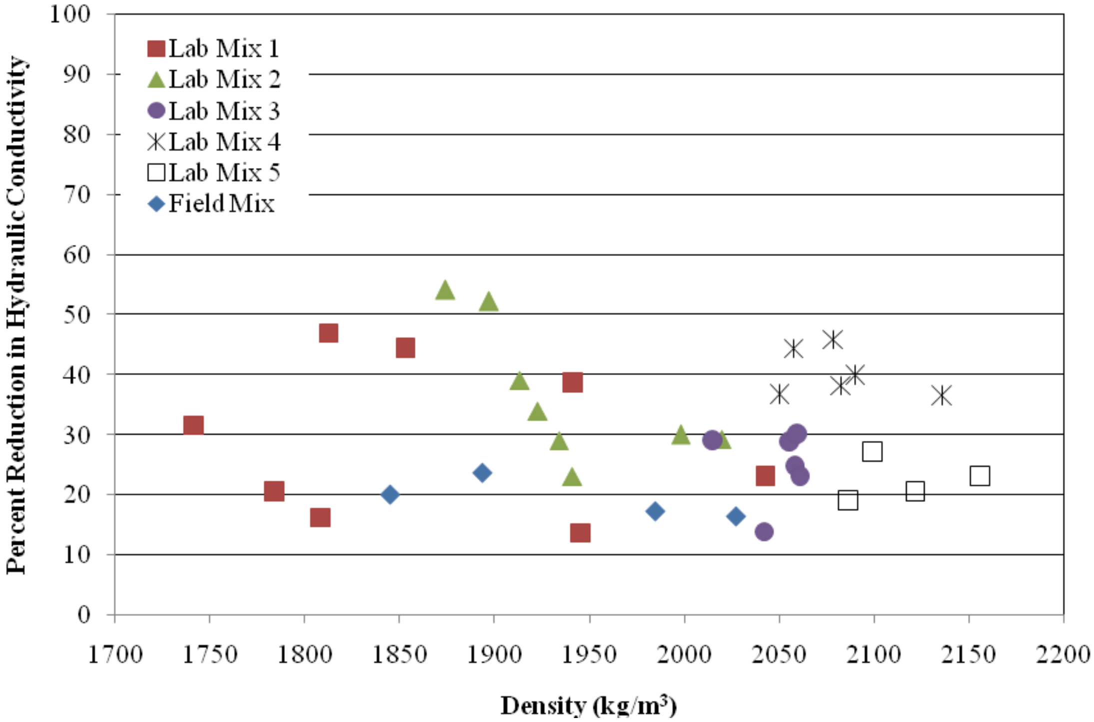
Results presented in Table 2 and Figure 5 are considered to represent a worst-case scenario, where as much sand or debris as possible is introduced into the pore structure of the porous concrete pavement system. The results show that even when the surface of the porous concrete system is significantly covered with a sand mixture, there is still enough hydraulic conductivity to effectively drain stormwater from the surface. It is assumed that most of the hydraulic conductivity that the system is capable of providing will not be needed during winter months, as rainstorms are uncommon and most water passing through will be due to snowmelt. Figure 5 presents results similar to one WSA, in that the initial hydraulic conductivity does not appear to have a significant effect on the percent reduction after maximum clogging has been achieved.

Reclamation of Pore Space

Table 2 also presents the results for hydraulic conductivity after attempts had been made to reclaim pore space that had been clogged by sand. These results for hydraulic conductivity ranged from 0.15 cm/s (213 in/hr) to 1.31 cm/s (1,857 in/hr). This represented an average reduction of about 9% between virgin samples and cleaned samples. Figure 6 (which is in a format similar to Figures 4 and 5) shows the reduction in hydraulic conductivity after pore space reclamation. Figure 7 summarizes the effects of one winter surface application, the effects of maximum clogging, and the attempted reclamation of pore space on hydraulic conductivity of the mix designs studied. These values represent the average value of all samples categorized by mix design. Differences in hydraulic conductivity were observed between laboratory mix 2 and the field mix, both of which were made with identical mix designs. The observed differences are attributed to different curing conditions for the field mix compared to the laboratory mix.

Table 2 and Figure 7 show that the method used to reclaim lost pore space and hydraulic conductivity of porous concrete specimens can be an effective tool. Recall that after maximum clogging had been achieved, reductions in hydraulic conductivity for all mix designs studied were around 35%. After the surface of the specimens had been vacuumed, the hydraulic conductivity was increased significantly, with less than a 10% reduction from the virgin samples that were tested previously. Figure 6 also shows that density is not an important factor in how much hydraulic conductivity can be reclaimed, as all mixes studied had similar values across a wide range of densities. Vacuuming is one of the suggested methods for increasing in-situ hydraulic conductivity of porous concrete pavement systems, and this research supports the effectiveness of this tool for yearly maintenance. Future work will investigate repeated cycles of clogging and cleaning to determine if vacuuming is an effective tool for long-term maintenance of porous concrete.

(a)



(b)

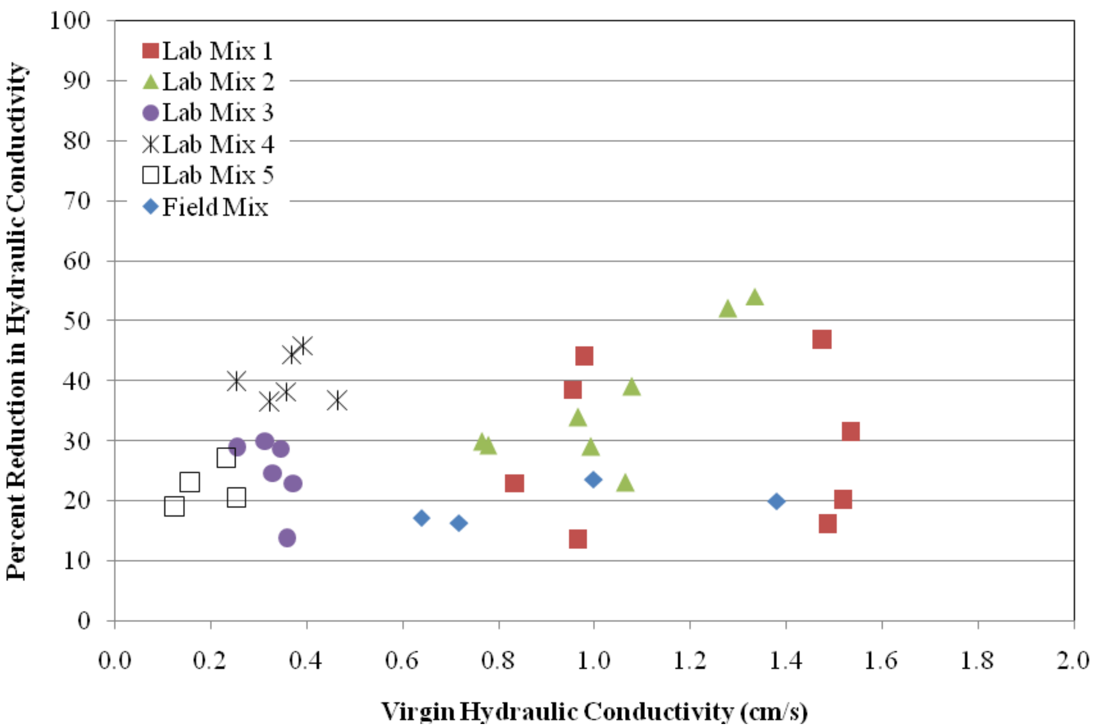
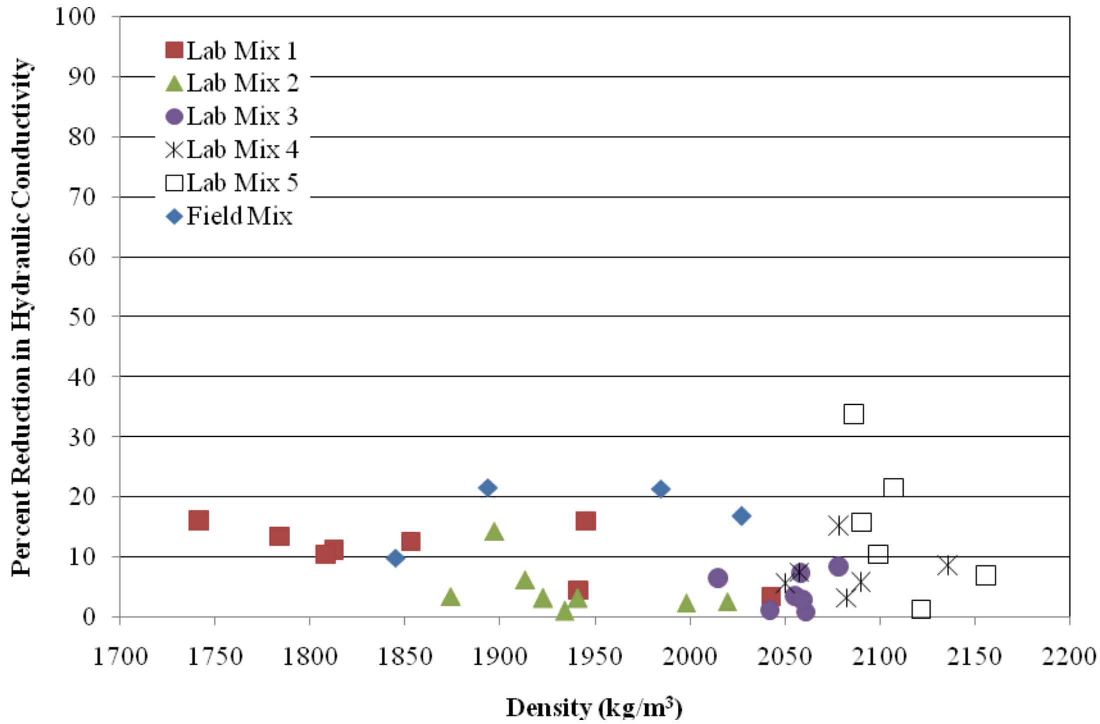


Figure 5: Reduction in Hydraulic Conductivity after Maximum Clogging

(a)



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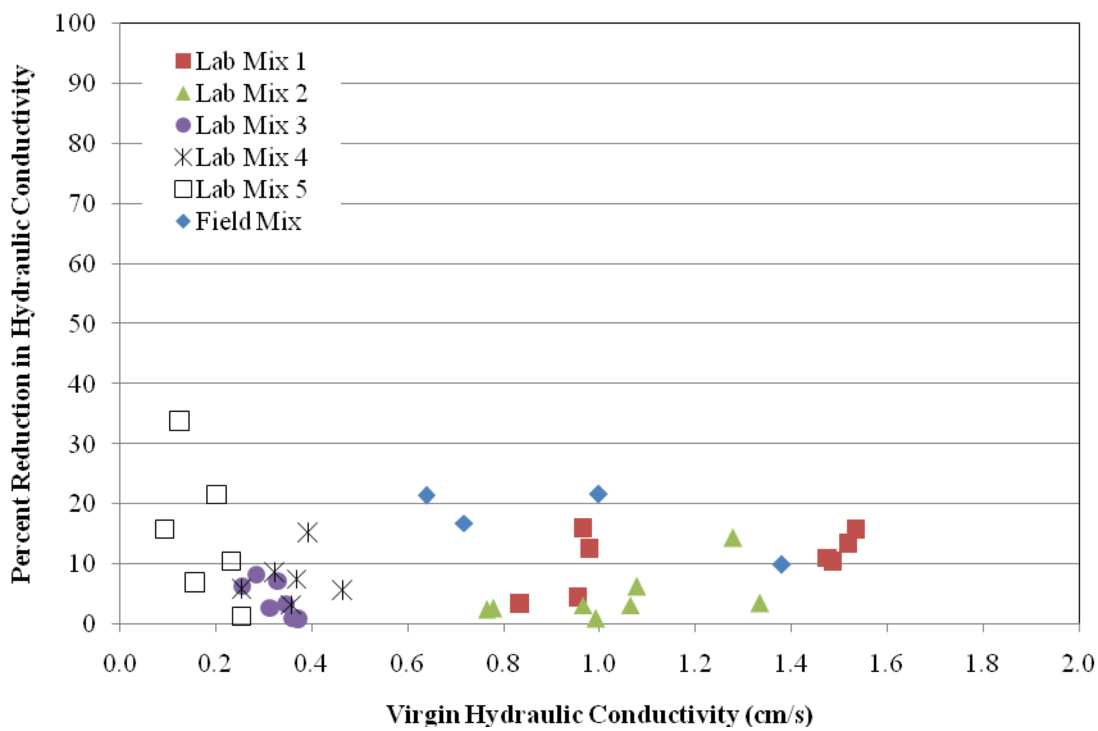

Figure 6: Changes in Hydraulic Conductivity after Vacuuming

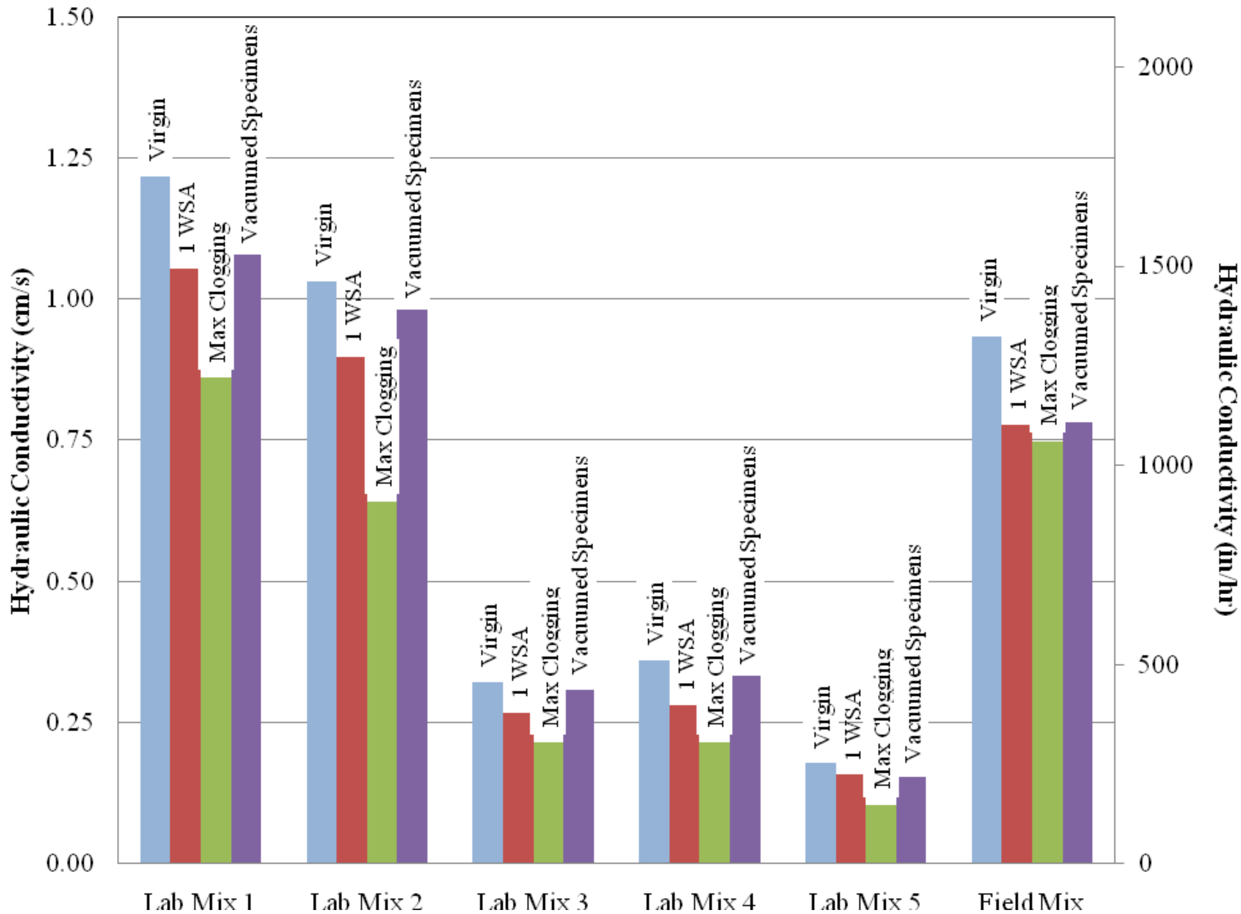

Figure 7: Effects of WSA, Max Clogging, and Reclamation of Pore Space

CONCLUSIONS

Summary

This laboratory study examined the effects of winter surface applications and fines infiltration on porous concrete specimens. The experiments included falling head permeability tests performed on specimens at four different stages: no winter surface application (virgin), after one winter surface application (0.12 g/cm^2 of sand and salt at 2:1 ratio by weight), after maximum clogging had been achieved, and after being vacuumed to reclaim pore space and hydraulic conductivity. The following conclusions were obtained for the mix designs studied. The following conclusions are drawn for the particular mixes studied:

1) The average reduction in hydraulic conductivity after one winter surface application (2:1 sand to salt mixture, surface application rate of 0.12 g/cm^2) was approximately 15%.

2) After maximum clogging of the porous concrete specimens had been achieved, the reduction in hydraulic conductivity was measured to be around 35%. Even though this

was considered a significant reduction, it still appears to be sufficient to provide adequate hydraulic conductivity for design storms in Vermont.

3) Vacuuming specimens in an attempt to reclaim pore space and hydraulic conductivity proved to be quite successful, resulting in hydraulic conductivities that were within 10% of the virgin samples that had been tested previously. Field verification will have to be conducted to confirm these results.

4) Sample density appears to have no effect on the reduction in hydraulic conductivity of porous concrete specimens for any amount of winter surface applications and clogging for the samples tested.

5) Sample density also appears to not have an effect on how much hydraulic conductivity can be reclaimed by vacuuming the specimens after maximum clogging has been achieved.

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