Performance of Pervious Concrete Pavement in Freeze-Thaw Conditions and With Winter Maintenance

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Abstract

In 2007 the Cement Association of Canada, industry members and the Centre for Pavement and Transportation Technology at the University of Waterloo partnered to carry out a study to evaluate the behavior of pervious concrete pavement in the Canadian climate. Field sites have been constructed and monitored and laboratory testing has also been carried out on pervious concrete pavement. This paper focuses on the behavior that has been demonstrated by pervious concrete in the laboratory when exposed to two factors: freeze-thaw cycling and moisture; and winter maintenance. The behavior was assessed in terms of permeability and surface distress development. Freeze-thaw cycling and moisture proved to on occasion alter the interior structure of the pervious concrete pavement. The extent to which this occurs is deemed to be related to the paste characteristics. Salt solution as a winter maintenance technique was found to be very damaging to the pervious concrete samples. Sand as a winter maintenance method led to minimal surface distress development. Permeability was decreased with the use of sand and salt solutions as winter maintenance techniques; however, remained adequate with both. This laboratory research presents results that should be applied to field sites for verification in full scale scenarios. In general the presence of freeze-thaw cycles, moisture and winter maintenance did not lead to poor performance of the pervious concrete pavement in the laboratory.

Introduction

Pervious concrete pavement offers several benefits for urban environments. It has been used in warm climates, such as the southern United States for more than two decades (Huffman D. , 2007). Interest to use pervious concrete pavement in freeze-thaw climates has grown as the potential benefits continue to increase (Cement Association of Canada, 2011). Pervious concrete pavement has two functions: a rigid pavement surface; and a stormwater management alternative. Conventional, impermeable pavements generate stormwater water runoff when they are used and pervious concrete provides an alternative: water drains through the pavement structure and infiltrates into the groundwater as would occur in nature. By allowing water to drain through the pavement and infiltrate into the existing subgrade, pervious concrete is a Low Impact Development (LID) (Huffman D. , 2009). Pervious concrete also has the same potential benefits as a concrete pavement that is impermeable. These benefits are a result of the light color of concrete. The light color can result in less lighting being required and less heat generation, therefore minimizing urban heat islands which are generated partially by dark pavements (Cement Association of Canada, 2011). Pervious concrete pavement is a stormwater alternative and can provide sustainable benefits to a community (Henderson & Tighe, 2011).

There has been caution in using pervious concrete pavement in freeze-thaw climates as it is unknown what the behavior and possible distress development would be in winter conditions. The effect of winter maintenance on pervious concrete pavement was also a concern. Research has been done in the northern United States to evaluate the behavior of pervious concrete pavement in freeze-thaw conditions. The results of this research have generally been promising towards further use of pervious concrete pavement in freeze-thaw climates (Kevern, Wang, Suleiman, & Schaefer, 2005; Delatte, Miller, & Mrkajic, 2007; Wang, Schaefer, Suleiman, & Kevern, 2006). Prior to the initiation of this project limited published research had been carried out in Canada regarding the use of pervious concrete pavement.

Objective

The objective of this paper is to evaluate factors that may affect the performance of pervious concrete pavement when it is used in freeze-thaw climates. The factors that have been considered include: exposure to freeze-thaw cycles; and winter maintenance activities. The effect that each factor has on the performance of pervious concrete pavement will be assessed by the changes in permeability and surface condition. Pervious concrete pavements will be evaluated in two scenarios. The two scenarios are: cores; and laboratory cast slabs. Table 1 outlines the factors that each scenario has been exposed to.

Table 1: Sample and Associated Factors

Sample	Freeze-Thaw Cycles	Winter Maintenance
Cores	X	
Slabs	X	X

Details of the cores and slabs and the frequency and extent of their exposure to the factors is described later in this paper. The intent of this work is to highlight the factors of freeze-thaw climates that adversely affect the performance of pervious concrete pavement, as well as those that do not.

Samples

Cores The six cores included in the results and analysis in this paper are from a field site constructed in Laval, Quebec in the summer of 2009, as a portion of a Canada wide study which is described in Henderson & Tighe 2011 (Henderson & Tighe, 2011). The pavement structure of the site included a cement stabilized reservoir base layer (200 mm) and a pervious concrete layer (200 mm). The cement stabilized reservoir base layer was constructed directly on the existing subgrade. The field site included three mixes: control mix (control); control mix including fibers (fiber); and control mix including a latex additive (latex). The control mix and fiber mix included 7.6 % fine aggregate and the latex mix included 8.2 % fine aggregate. A 14 mm granite aggregate was used as the coarse aggregate in each mix.

The pervious concrete was mixed in a volumetric mobile mixer and placed from the chute of the truck directly on to the base. The pervious concrete was then leveled and slightly compacted with an automated roller. A vibratory plate compactor was finally passed over the surface. The pervious concrete was covered with a sheet of plastic for curing.

The cores were extracted from across the field site, two from the fiber mix, two from the latex mix and two from the control mix. The cores were taken for material characterization. The void content of the cores was measured using a Corelok® vacuum system. The void contents ranged from 21 % to 28 %. The average void content for the control mix was 26 %, the fiber mix 25 % and the latex mix 28 %. The freeze-thaw durability results will be the focus of this paper.

Freeze-thaw durability of the cores was evaluated following a modified version of ASTM C666 (ASTM, 2008). Approximately every 20 freeze-thaw cycles the cores were weighed and then submerged in water for approximately 10 minutes. The cores were then lifted out of the water bath, at which point most water drained away, and they were then placed in trays. The cores were freeze-thaw cycled in trays such that the cores lay horizontal and were raised off the bottom of the tray to allow for water to drain out of the core without leaving the core partially submerged. When the cores were weighed they were not dried to a constant mass first, they were weighed in their current state which in many instances included having moisture on the surface due to being recently removed from the freezer.

Slabs Slabs were cast in the Centre for Pavement and Transportation Technology (CPATT) laboratory at the University of Waterloo in 2009 using the mix design and aggregate sources that had been used to construct one of the field sites in this project. The mix design included a 13.2 mm gravel and no fine aggregate. Fibers were included in the mix as well. There were 20 slabs cast in total, all with surface dimensions of 300 mm by 300 mm. Of the 20 slabs, six were 300 mm in height and the other 14 were 200 mm in height. The slabs were prepared in order to evaluate the effects of winter maintenance on pervious concrete pavement.

Two of the slabs were cast for material characterization and the remaining 18 were divided into six groups of three. Each group experienced a different winter maintenance scenario. The six winter maintenance scenarios are listed below:

1. Heavy sand loading, heavy precipitation (HSHP);
2. Average sand loading, average precipitation (ASAP);
3. Heavy sand loading, average precipitation (HSAP);
4. Average sand loading, heavy precipitation (ASHP);
5. Heavy salt loading, heavy precipitation (HSaltHP); and
6. No salt or sand loading, heavy precipitation (HP).

The slabs were freeze-thaw cycled for 255 cycles, the equivalent of five years of freeze-thaw exposure in Toronto, ON, on average (Ho & Gough, 2006). During each cycle precipitation was applied to the slabs as well as the winter maintenance treatment for the particular scenario: heavy sand; average sand; salt solution; or no treatment.

During casting of the slabs a sensor was included in the center of some of the slabs. The data collected by the sensors was used to determine how long each portion of the freeze-thaw cycle was in order to achieve a consistent temperature throughout the slabs. It was determined that 14 hours were required to take a slab through a complete freeze-thaw cycle, ranging from -12 °C to 12 °C (Henderson & Tighe, 2010).

The slabs were compacted in two lifts using a rod, typically used for casting 150 mm diameter concrete cylinders. Cores were extracted from the material characterization slabs for void content measurement. The void content of the extracted cores was 29 % on average.

Factors

Freeze-Thaw Cycles Pervious concrete pavement that is exposed to freeze-thaw cycling while moisture is present has the potential for the voids to be filled with frozen water. Water getting trapped and frozen in the voids could not only limit permeability but also possibly be destructive to the pervious concrete itself. Both types of samples being evaluated in this study were exposed to freeze-thaw cycling. The ranges in temperature for the freeze-thaw cycling were aggressive but not uncommon in many regions of Canada. The slabs were cycled from 12°C to -12°C. In the Canadian climate pervious concrete would be exposed to temperatures as low as -12°C and lower: however, not during each freeze-thaw cycle. Similarly the cores were cycled from 12°C to -10°C and the low end of the range is not uncommon in Canada does not occur in every cycle necessarily.

Winter Maintenance Winter maintenance generally involves the removal of snow from the pavement surface. Following the removal of snow from the surface, there is often sand applied to the surface. An alternative to sand is a salt solution which is applied to the surface of a pavement prior to a snow event. Both the sand and salt solution are used to create a pavement surface that is not slippery for vehicular and pedestrian users. The sand provides traction on top of icy conditions while the salt solution minimizes the potential of water freezing on the surface and slippery conditions developing. Salt is also sometimes applied to the surface after a winter storm to melt ice that is present. Sand could fill the voids in the pervious concrete and lead to a reduction in permeability. Application of solid salt could also fill voids. A salt solution is deemed to not likely reduce the permeability of the pervious concrete as it is a liquid.

In this project sand and salt solution were evaluated as winter maintenance techniques. Sand was applied to the laboratory slabs at two rates. The first rate was referenced as the average rate and is equivalent to that used by local contractors in the area of the University of Waterloo. This rate was also found to be a common rate in many areas throughout North America. The second rate of sand application, which some of the laboratory slabs received was heavy sanding, meaning that sand was applied at 1.5 times the average rate. Sand was applied at both the average and heavy rates to evaluate if this difference in debris on the surface was reflected in the permeability. Similarly, the salt solution was prepared and applied by the same rates as are used in the Region of Waterloo. The salt solution was prepared at 23 % by weight. The average application rate of both the sand and salt is 0.02 kg/m^2.

Winter maintenance includes the removal of snow from the surface as well. This was not represented in this paper but has been monitored at field sites in this research. Removal of snow using conventional equipment such as a front end loader or highway snow plow has not been found to lead to additional surface distresses developing. Henderson and Tighe 2011 discuss these results (Henderson & Tighe, 2011).

Testing

Both types of samples were monitored for changes in two characteristics: permeability and surface condition. Similar techniques were used to measure both of these characteristics on each sample type.

Permeability The permeability of the pervious concrete has been measured throughout the project using a Gilson Field Permeameter. The permeameter uses the falling head principle. This permeameter was used in the laboratory for measuring the permeability of the cores and slabs. An operating instructions manual was provided with the permeameter from Gilson Company Inc. (Gilson Company Inc., 2007). The process that has been used to measure permeability using the permeameter follows the guidelines in the operating instructions manual with a few modifications. This test method is described in (Henderson & Tighe, 2011).

Surface Condition Evaluation Distresses on the surface of a pervious concrete pavement generally do not limit the permeability of the pervious concrete pavement and therefore do not reduce the functionality of the pervious concrete however they do decrease the performance. Surface distresses take away from the appearance of a pervious concrete pavement and therefore demonstrate poorer performance for the owner than if they had not developed. If the surface distresses become extensive they may require repairs to be performed.

The condition of the surface of the cores and slabs was monitored visually by the same individual, throughout the project. A surface condition evaluation form was developed in the preliminary work of this project and has been used throughout (Henderson, Tighe, & Norris, 2009). Photos were taken during the surface evaluations of cores and slabs. The cores and slabs were both weighed during surface condition evaluations. Changes in weight could be the result of pieces falling off the samples due to raveling. The sand being applied to the slab samples continually increased the weight until maintenance was carried out. However, it is known how much sand was added to each sample and can be considered in evaluating changes in weight.

Results

Permeability of Cores The cores were tested for permeability before freeze-thaw cycling began. Permeability testing was also repeated throughout the completion of the 250 freeze-thaw cycles. At the field site that the cores were extracted from, one year includes approximately 25 freeze-thaw cycles on average. The average annual freeze-thaw cycles were determined from Environment Canada data and were only counted if considered to be such that the pervious concrete pavement temperature would change. The change in permeability over 10 years of freeze-thaw cycling is shown in Figures 1 and 2.

There were two cores for each mix (Control, Latex, Fiber) at the beginning of the freeze-thaw cycling and each core is represented by a separate line in Figures 1 and 2. The cores were tested in both directions. Figure 1 shows the first direction of testing, as they would be in place in the field, with water draining from the surface to the bottom. Figure 2 shows the permeability of the cores when they were tested such that water drained from the bottom to the surface, opposite of the orientation in the field. The cores were tested in both directions because some of the cores showed a visible difference in density between the portion of the core closer to the surface and the portion closer to the bottom. When a difference was visible, the surface always appeared denser, therefore appearing to have less voids, than the bottom.

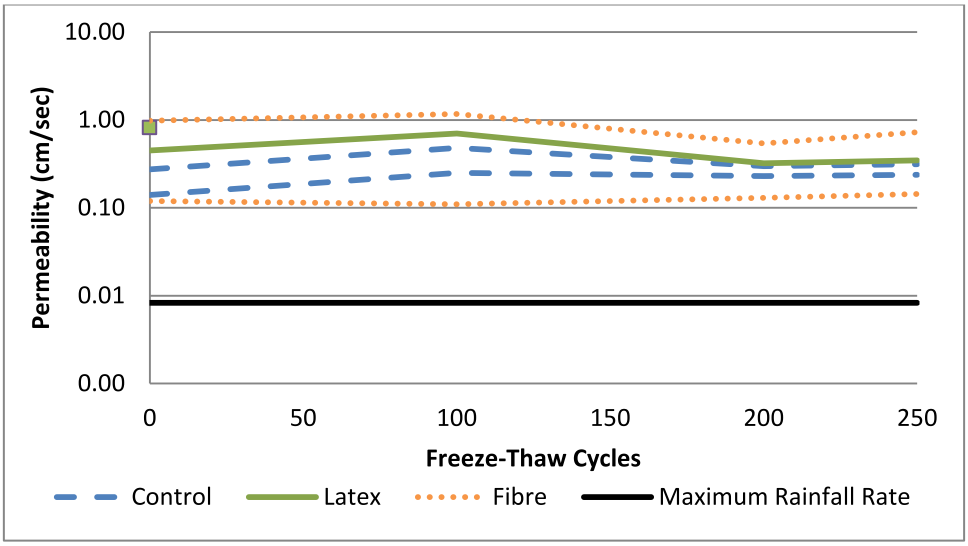

Figure 1: Core Permeability (Surface to Bottom)

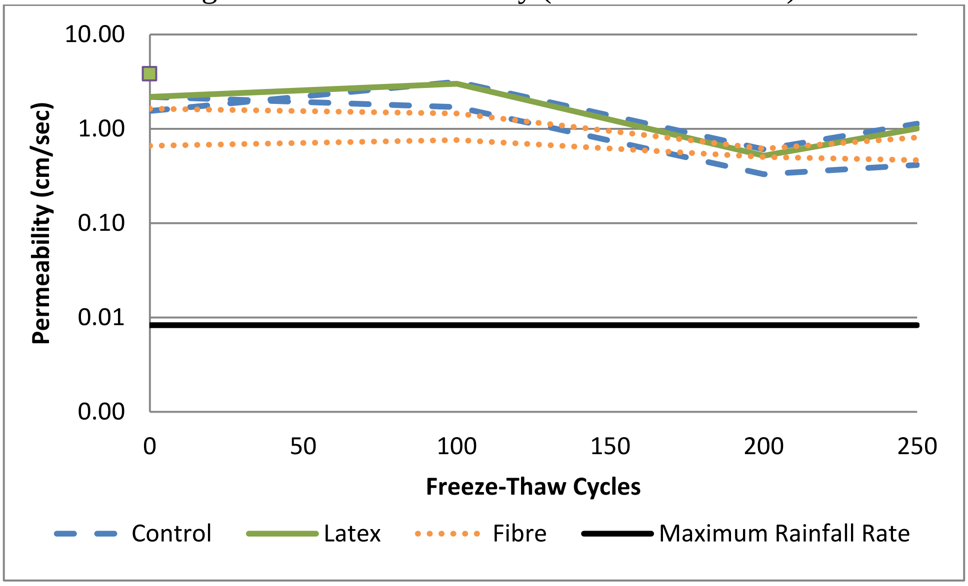

Figure 2: Core Permeability (Bottom to Surface)

Both Figures 1 and 2 show only the initial reading for one of the Latex Mix cores. This core failed prior to the next round of testing at 100 freeze-thaw cycles. The failure of this core will be described later in this paper.

Surface Condition of Cores Surface condition of the cores was monitored throughout the freeze-thaw cycling. The cores were weighed regularly during the freeze-thaw cycles and photos were taken. The weight of the cores throughout the equivalence of approximately 10 years of freeze-thaw cycling for Laval, Quebec is shown in Figure 3.

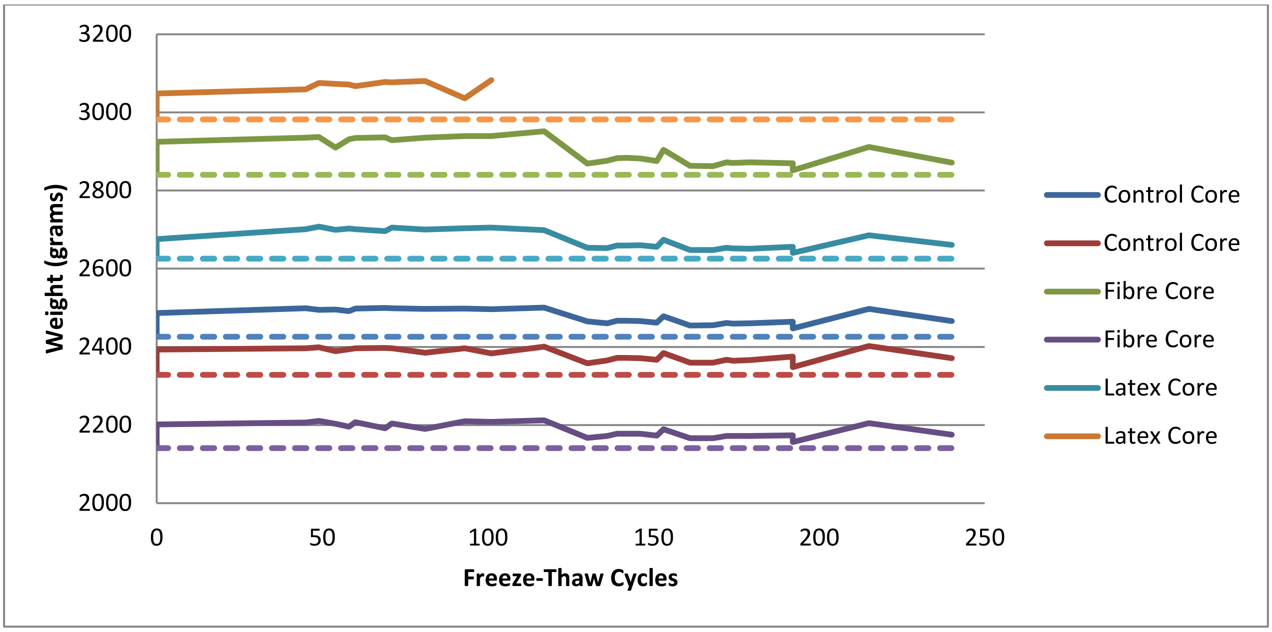

Figure 3: Weight of Cores During Freeze-Thaw Cycling

Figure 3 shows two lines for each core, a dashed line and a solid line. The dashed line shows the weight of the core prior to starting freeze-thaw cycling. The cores had been dried to a constant mass before freeze-thaw cycling was started. The cores then increased in mass when exposed to water during the routine submersion. The mass of the cores never dropped below the initial mass, indicating that material was not raveling off the cores. Decreases in weight are due to cores having been dried for testing recently or exposed to air with no saturation for multiple days, such as over multiple day holidays.

Figures 3 shows that measurements ended for one of the latex cores at 100 freeze-thaw cycles due to the core failing. Following being weighed at 100 cycles the core was submerged in water, as was done throughout the testing. As the core was removed from the water it broke in half, horizontally. Visual inspection showed that the paste throughout the inside of the core had crumbled or broken down. Figure 4 shows the latex core before and after failure.

The remaining five cores did not show evidence visually of failure occurring. However, the latex core did not have any indication of failure prior to completely breaking into two pieces. Each core has lost a couple small pieces off of the sides. Generally the pieces that have come off the cores have only been one piece of aggregate in size. These pieces have come off the vertical sides rather than the surface. Some deterioration may have occurred to the cores during coring: however, this is not anticipated.

A. 69 cycles, B. Failure at 100 cycles, C. Remaining intact portion of core

Figure 4: Failure of Latex Core (4)

Permeability of Slabs The permeability of the slabs has been evaluated several times throughout the equivalence of five years of freeze-thaw cycling (Toronto, 50 cycles). Maintenance was also performed to some of the slabs during the freeze-thaw cycling. Figure 5 shows the average permeability of each of the four groups of slabs that had sand loaded on the surface. Vertical lines in the results in Figure 5 indicate when maintenance was performed to the slabs. The maintenance included sweeping sand off the slabs and then vacuuming them with a wet/dry vacuum.

Figure 5 shows the permeability of the slabs starting at 12 freeze-thaw cycles. The slabs were tested prior to being loaded with any sand and the permeability rates were very high, ranging from approximately 2.5 cm/sec to more than 7.5 cm/sec. The data presented in Figure 5 is from 12 freeze-thaw cycles onward so that differences between the groups of slabs can be seen. All four slab groups had similar permeability rates throughout the five years of freeze-thaw cycling.

Figure 6 shows the average permeability of Groups HSaltHP and HP.

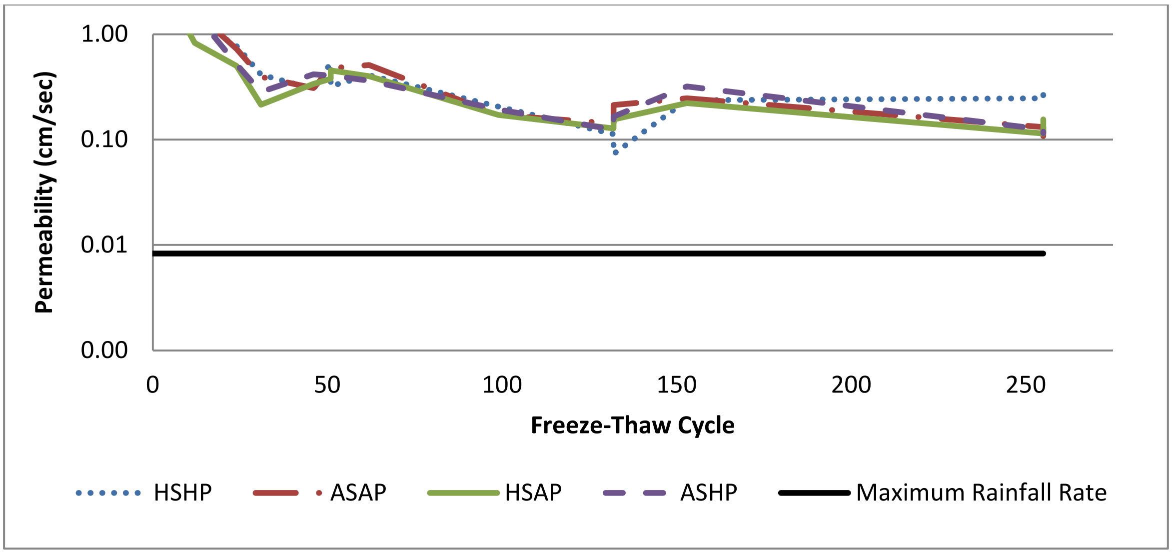

Figure 5: Permeability of Slabs Loaded with Sand

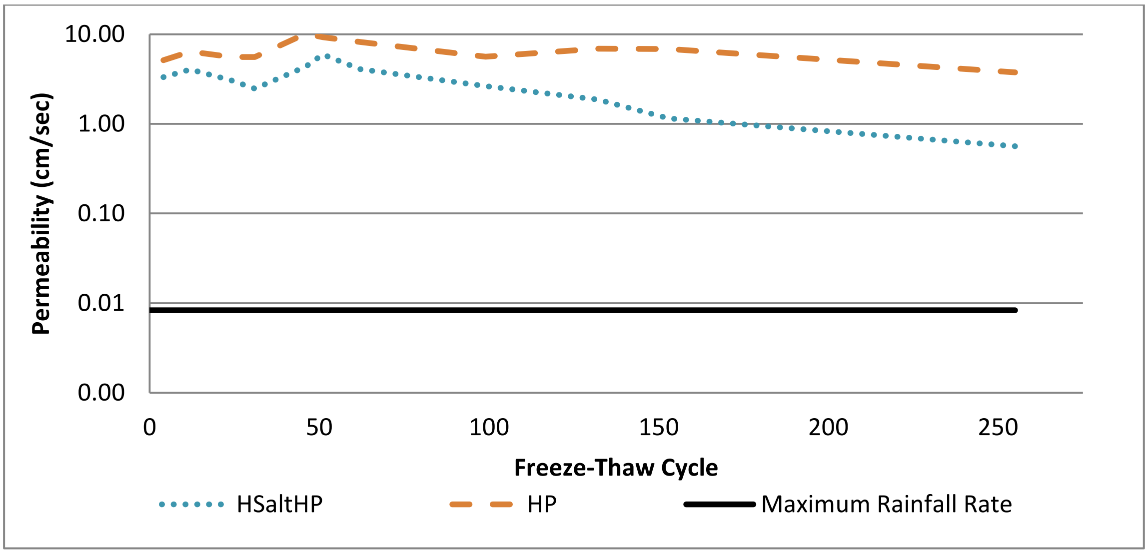

Figure 6: Permeability of Slab Groups HSaltHP and HP.

Surface Condition of Slabs The surface distresses that developed on the slab samples were generally limited and included a small amount of raveling, some paste loss and fracturing of very few aggregates. Table 2 shows the surface distress present on each slab throughout the simulation of five years of freeze-thaw cycling in the laboratory. One group of slabs showed more surface condition deterioration than the others. Slab Group HSaltHP, which experiences winter maintenance including application of a salt solution, had cracks develop throughout the slabs. Substantial portions of the slabs fell off and at the end of five years, two of the three slabs fell apart entirely.

Table 2: Slab Surface Condition

Slab	**Age (Years)**		
	1.25 Years	2.5 Years	5 Years
HSHP - A	Very Slight Paste Loss	Slight Paste Loss, Slight Raveling	Slight raveling
HSHP – B	Fractured Aggregate, Slight Paste Loss	Slight Paste Loss, Slight Raveling	Slight Raveling
HSHP – C	Fractured Aggregate, Very Slight Paste Loss	Fractured Aggregate, Slight Raveling	Slight Raveling, Very Slight Paste Loss, Fractured Aggregate
ASAP – A	Moderate Paste Loss	Slight Raveling, Slight Paste Loss	Slight ravel, Slight Paste Loss
ASAP – B	Moderate Paste loss	Slight Raveling, Slight Paste Loss	Slight Raveling, Slight Paste Loss
ASAP – C	Moderate Paste Loss	Fractured Aggregate, Slight Raveling	Slight Ravel, Slight Paste Loss
HSAP – A	Very Slight Paste Loss	Slight Raveling	Slight Raveling
HSAP – B	Fractured Aggregate, Slight Paste Loss	Fractured Aggregate, Slight Raveling	Fractured Aggregate, Slight Raveling, Slight Paste Loss
HSAP – C	Very Slight Paste Loss	Fractured Aggregate, Slight Raveling	Slight Raveling, Slight Paste Loss
ASHP – A	Very Slight Paste Loss	Fractured Aggregate, Very Slight Paste Loss, Slight Raveling	Slight Raveling
ASHP – B	Very Slight Paste Loss	Very Slight Paste Loss, Fractured Aggregate, Slight Raveling	Slight Raveling
ASHP – C	Slight Paste Loss, Fractured Aggregate	Fractured Aggregate, Slight Paste Loss, Very Slight Raveling	Very Slight Raveling
HSaltHP - A	Fractured Aggregate, Moderate Paste Loss	Extensive Paste Loss, Fractured Aggregate	Failed
HSaltHP – B	Fractured Aggregate, Moderate Paste Loss	Moderate Paste Loss, Fractured Aggregate, Salt Visible on Surface	Failed
HSaltHP – C	Fractured Aggregate, Moderate Paste loss	Extensive Paste Loss, Fractured Aggregate, Salt Visible on Surface	Surface Colour has Darkened, Extensive Material Loss on Bottom of Slab, Fractured Aggregate, Extensive Paste Loss
HP – A	Fractured Aggregate, Slight Paste Loss	Very Slight Raveling	Very Slight Raveling
HP – B	Fractured Aggregate, Slight Paste Loss	Fractured Aggregate, Slight Raveling, Very Slight Paste Loss	Slight Raveling
HP – C	Fractured Aggregate, Slight Paste Loss	Very Slight Paste Loss, Very Slight Raveling	Very Slight Raveling

The surface distress of the slabs showed a common trend in many of the slab groups. This trend was the initial presence of paste loss and at a later point the presence of raveling. This tendency suggests that raveling maybe a result of the paste characteristics in comparison to only resulting from forces caused by use. The integrity of the paste to withstand exposure to freeze-thaw cycling could have a large effect on the amount of raveling experienced by a pervious concrete pavement. Similar to the cores, the weights never fell below the initial weight, therefore suggesting that extensive material loss is not occurring.

Figure 7 shows the weight of the slabs in Group HSaltHP during the five years of freeze-thaw cycling. In all three slabs, material loss became visible at approximately 150 cycles (after three years of exposure). After five years (250 freeze-thaw cycles) two of three slabs loaded with the salt solution failed completely and substantial portions were lost off the third slab.

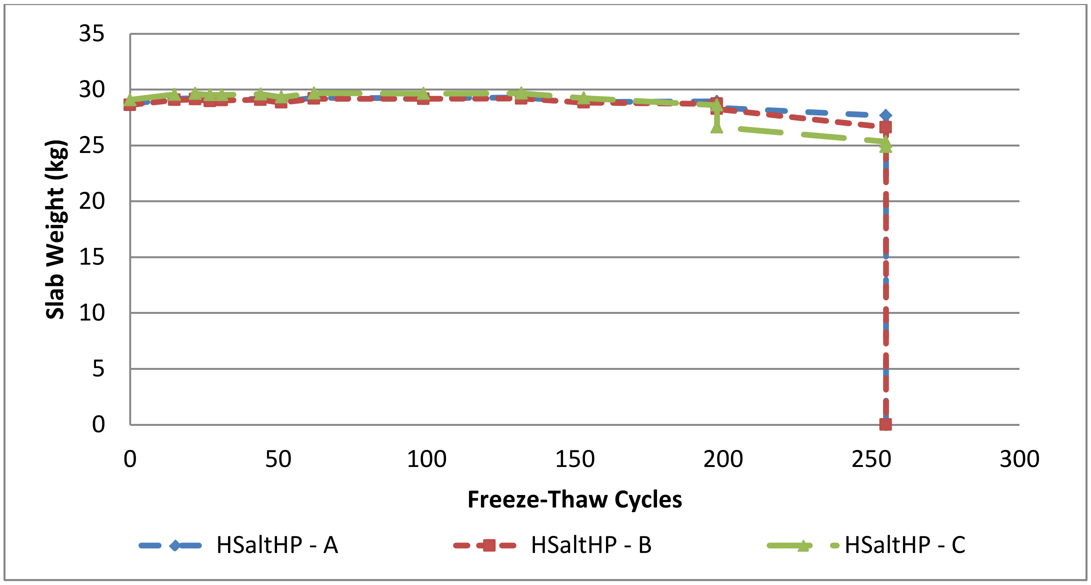

Figure 7: Weight of Slab Group HSaltHP throughout Freeze-Thaw Cycling

The three slabs in the HP group were only loaded with precipitation and no winter maintenance materials. They remained within approximately 500 g of their initial weight throughout the five years of freeze-thaw cycling.

Analysis

Permeability The cores and slab group HP were each exposed to similar conditions. All of the slabs included in this project looked consistent in pavement structure throughout. As is noted earlier in the paper the cores tended to appear denser at the top (surface) of the core and to have more voids at the bottom of the core. Both the cores and slab group HP showed fluctuations in permeability but did not show a continual, constant trend in terms of change in permeability. The changes in permeability of these samples is deemed to be the result of two reasons; changing internal structure of the pervious concrete sample; and variability in the test procedure.

Changes in the internal structure of the pervious concrete samples are believed to occur based on two occurrences: The first occurrence is the failure of the latex core. As noted in the paper, when the latex core failed the visible interior of the core appeared as though the paste had completely broken apart or fractured. This fracturing of the paste is likely occurring in the other cores as well and as the fine particles from the fractured paste move within the core, the permeability is changed. The fine particles moving within the core would close or partially close existing voids but also create new voids. The cores have not all failed likely due to the variability in the void structure in each core. It is unknown as to whether the paste was thinner in the core that did fail. This seems possible as the permeability of both the latex cores were some of the highest in comparison to the other cores.

It is anticipated that some of the fluctuation in permeability in slab group HP is also due to changes in the internal structure of the slab. The characteristics of the paste in a pervious concrete pavement would likely be reflected in the amount of change that is seen in the internal structure of the pervious concrete pavement.

The method used to test permeability of the pervious concrete in this project inevitably allows for variation. Variation can result due to the falling head principle. Additionally, the intent is to measure permeability at the same location on samples. However, if permeability is measured at a slightly different location on the surface this could also lead to differences between measurements.

Slab group HSaltHP was initially anticipated to behavior similarly to the cores and HP slabs given that it was receiving winter maintenance in the form of a liquid. Initially the HSaltHP slabs did exhibit the same permeability trend as the HP slabs. This being fluctuations from the initial permeability of the slabs but no apparent continual decrease in permeability. After approximately 100 freeze-thaw cycles and therefore 100 loadings with the salt solution, the permeability of the HSaltHP slabs began to change from that of the HP slabs. A constant decrease in permeability was identified. It is anticipated that although the salt was being loaded onto the slabs in a solution state the following two activities were occurring:

1. Salt solution was being trapped in the pervious concrete. The solution had drained into a void that was not connected to other voids in the pervious concrete. The water in the solution evaporates over time and the salt remains in the void. The salt may build up in the void over time and block voids that did previously allow for drainage through the pervious concrete.
2. The complete solution is not flowing through the pervious concrete structure. It is anticipated that this is occurring to some degree. The surface of the HSaltHP slabs all changed in color from that of the other slabs. The slabs became darker and eventually salt accumulations were visible and were white. The salt solution was applied at the same rate it would be on a parking lot and without continual additional water not all of the solution moved into and through the pervious concrete. Salt solution that did move deeper than the surface of the pervious concrete may not have drained all the way through the pervious concrete simply due to the limited amount of solution that was applied to each winter maintenance loading. Similarly to the activity described in point 1, water would evaporate and salt would remain in or on the pervious concrete pavement.

The slabs loaded with sand as a winter maintenance technique showed more change in permeability than the control slab group, HP, group HSaltHP and the cores. The decrease in permeability of the slabs loaded with sand was not so extensive as to bring the pervious concrete close to being dysfunctional. The pervious concrete is deemed to not be functional when the permeability is below the maximum rain fall rate. The application of sand to the surface alone did not prove to make the pervious concrete incapable of draining water at an adequate rate.

This finding is not unexpected as all infrastructure deteriorates after construction. The rate of deterioration or decline in performance can be regulated with routine maintenance, which in the case of pervious concrete pavement would include permeability renewal maintenance.

Surface Condition As noted earlier in the paper, the development of some surface distresses in pervious concrete pavement does not necessarily affect the ability of the pervious concrete to function adequately. Functioning adequately includes sufficient drainage capabilities. Development of surface distresses leads to poor performance from the owner and user perspective as the appearance of the pavement can deteriorate. If surface distresses develop to such an extent in both severity and density then they may result in the pavement being less serviceable by users.

The cores, in general, and the control slab, HP, showed very little surface distress development with exposure to moisture and freeze-thaw cycling. Both the cores and control slabs have shown a small amount of raveling. In the slabs there was initially paste loss visible and then raveling. At five years of freeze thaw cycling the slabs do not continue to have paste loss presence which would be anticipated to lead to raveling. Therefore the slabs suggest that under no winter maintenance and no traffic minimum raveling can occur but is not anticipated to continue. It is anticipated that where raveling did occur, the paste did not cure sufficiently during casting and was weaker in these areas and more susceptible to deterioration.

Paste loss has not been visible in the cores but raveling of individual aggregates off the edges of the cores has been noticed. Raveling off the surface of the cores has not been identified and this is what would be visible in the field site. Raveling from the edges of the cores could be a result of the paste being weakened or damaged slightly during coring. The latex core did fail entirely. The failure of the latex core appeared to be throughout and is not likely due to damage during coring. As this occurred in only one sample of seven, from four different mixes, it is attributed to the materials in this sample and possibly the void distribution throughout the material.

The slabs loaded with salt solution, HSaltHP, showed the most severe surface distress of any of the samples in this project. All three slabs deteriorated to the extent that they were no longer holding their initial shape. The deterioration was in the form of cracks developing throughout the thickness of the slabs and aggregate raveling off the bottom on the slabs in large handfuls. This raveling is different than what was identified in the cores and other slabs. In the cores and other slabs raveling appeared to occur at a rate of individual aggregates. In the HSaltHP slabs large pieces of multiple aggregates were separating from the slab. Given that the aggregate was separating in large pieces it is likely that salt had been building up along the area where the piece fractured away from the slab. The believed reasons for salt building up is described in the permeability portion of the analysis. The development of the cracks through the thickness of the slabs also suggests that salt was accumulating in the pervious concrete pavement. The easiest path initially for water drainage through the pervious concrete is likely to have been along the path where the cracks developed. The salt was therefore deposited in this area, causing cracking in the pervious concrete when the salt accumulation exceeded the capacity of the structure.

The slabs that were loaded with sand showed more surface distress development than the HP slab group (control) but much less than those loaded with salt. The raveling is generally a bit more severe on the slabs loaded with sand than the HP slabs. The other difference is that paste loss is visible on the slabs that were loaded with sand, at five years of age, and the HP slabs did not show any paste loss at that age. This suggests that more raveling may occur in the future on the slabs loaded with sand. It is anticipated that this additional raveling is not entirely a result of the loading from sand but more so the frequency on the cleaning of the surface. During much of the freeze-thaw cycling and slab loadings, there was a thick layer of sand on the surface of the slabs, enough that the pervious concrete was not visible. This thick layer, although permeable is less permeable than the pervious concrete pavement. Water loaded onto the slabs during the precipitation loading may move slowly through the sand and in some cases still be in the sand when the slab is moved back into the freezer to initiate the freezing portion of the cycle. This water would have expanded and put pressure on the pervious concrete and paste, leading to the paste breaking down and fracturing off the aggregate. As the paste around an aggregate breaks down and fractures away from the aggregate, the bond keeping the aggregate secured to the remainder of the pervious concrete is lost and therefore it ravels.

Conclusions

Pervious concrete pavement behavior was evaluated under the presence of two factors: freeze-thaw cycles and moisture; and winter maintenance. Two types of samples were included in the evaluation: cores taken from field sites; and slabs cast in the laboratory. The behavior of the pervious concrete was assessed in terms of permeability and surface condition.

Freeze-thaw cycling and moisture were found to have the means to alter the internal structure of pervious concrete. The internal structure was deemed to be altered by the paste in the pervious concrete deteriorating due to the freeze-thaw cycling and possibly trapped moisture. This deterioration creates small particles which can move throughout the pervious concrete and close previously available drainage paths. The extent to which this occurs is anticipated to be highly dependent on the characteristics of the paste in the pervious concrete and the dispersion of the voids in the pervious concrete.

The type of winter maintenance that was used on the pervious concrete affected the permeability and surface condition. The application of sand as the winter maintenance method decreased the permeability but not to an unacceptable level. When a salt solution was used the permeability also decreased. However, not as much as when sand was applied. The surface conditions of the slabs loaded with salt were worse than any other samples in the project. All three slabs deteriorated to a point of failure as the original size and shape of the slabs was not apparent.

The results of this laboratory investigation provided unique findings that should now be verified with work at field sites. The use of sand as a winter maintenance method did not lead to the pervious concrete becoming clogged. The next step would be to evaluate this at field sites where additional factors exist. Only one of the 24 samples failed due to the presence of freeze-thaw cycles and moisture and this was one of the cores from the latex mix. This result highlights the importance of evaluating the characteristics of the paste in pervious concrete pavement as well as the void distribution that will be achieved in the field. Finally, the use of a salt solution lead to failure of all three slabs exposed to this winter maintenance. The salt solution was loaded during each freeze-thaw cycle which is likely more frequent than would occur in applications in the field. However, from this research it is recommended that the use of a salt solution or salt on pervious concrete pavement be avoided. If interest remains regarding using salt then an environmentally friendly alternative could be research or other options such as a blend of salt and vegetable products.

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