Pervious Concrete Pavement Performance in Field Applications and Laboratory Testing

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Abstract

Pervious concrete pavement is an environmentally friendly paving material that allows water to drain directly through the pavement structure and infiltrate into the subgrade. By reducing runoff, pervious concrete pavement decreases the demand on the stormwater management system. The Cement Association of Canada, the Centre for Pavement and Transportation Technology (CPATT) and industry members across Canada have partnered to carry out an integrated laboratory and field project to evaluate the performance of pervious concrete pavement in the Canadian freeze-thaw climate. The intended result of the project will be to develop a design, construction and maintenance guide for the use of pervious concrete pavement in the Canadian climate. Test areas, including staff parking lots and driveways, have been constructed in various regions of Canada to demonstrate the behaviour of pervious concrete pavement in low volume applications. The test areas are monitored regularly for changes in permeability and development of surface distresses. Monitoring of the sites has been ongoing for the life time of the sites, which in some cases is over three years.

The laboratory portion of the project involves accelerated freeze-thaw cycling of multiple pervious concrete slabs. The slabs have experienced the equivalency of three years of Canadian weather including precipitation and winter maintenance. Various winter maintenance techniques are performed and changes in permeability are monitored. Where applicable, slabs receive rehabilitative maintenance to renew and increase permeability. The performance and behaviour of the slabs will be included in this paper. The results collected to date from the test areas will also be included. The performance of the slabs in the laboratory and field sites will be compared and presented in this paper.

Introduction

Pervious concrete pavement is a sustainable paving material that is beneficial to not only pavement and transportation industries but also stormwater management and planning groups. The concrete contains 15% to 30% air voids by limiting the fine aggregate content. Schaefer et al note that when comparing pervious concrete mixes in laboratory freeze-thaw testing mixes containing small amounts of fine aggregate performed better than those without. The inclusion of some fine aggregate in the mix also increased the strength of the samples. In addition, mixes containing admixtures such as latex and air entrainment had the best performance in freeze-thaw testing [Schaefer, 2006].

The use of pervious concrete pavement in any portion of the streetscape can significantly reduce and in some cases eliminate runoff. It is intended for use in low speed, low volume applications. The high drainage capacity of this paving material allows for drainage of multiple impervious surfaces such as roadways and roofs.

As stormwater legislation becomes more stringent in the United States, methods have been developed to deal with the new regulations. The US Environmental Protection Agency has created the National Pollutant Discharge Elimination System (NPDES) to issue permits to alleviate flooding in densely populated areas and to improve surface water quality. Private owners and public agencies are required to reduce the amount of stormwater runoff and reduce the contaminants in the runoff water to near pre-development levels [EPA, 2008, Barnes et al., 2001, Novotney, 2008, Van Seters et al., 2006, Van Seters, 2007]. These reductions can be achieved by detention ponds and vegetative buffers, however, pervious concrete is an effective tool for achieving reductions in stormwater runoff and initially treating stormwater [WERF, 2005].

In addition to the stormwater management benefits of pervious concrete pavement it also exhibits common benefits of concrete pavement such as high reflectivity and light colouring. The high reflectivity is a benefit to society by providing brighter areas during night time use, such as parking lots and paths. The high reflectivity also offers economical benefits as less lighting is required than in a comparable area paved with a dark pavement. The light colouring of the pavements leads to minimal to no contribution to the heat island effect. Dark surfaces increase the air temperature which places local residents and citizens at a higher risk of suffering from heat related illnesses. Children and elderly individuals are more at risk of such illnesses [EPA, 2009, Gajda, 1997].

Implementation of pervious concrete throughout Canada requires that all parties involved have an understanding of the material as it is unique from conventional concrete. Mixes tend to be very stiff with low slump values, often 0mm. Construction practices for pervious concrete are not challenging but are different than those for conventional concrete streets and parking lots. Finally, the required maintenance for pervious concrete to perform in the Canadian climate needs to be understood [Tighe, 2007, Henderson, 2009].

Background

The Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, Waterloo, Ontario, the Cement Association of Canada (CAC) and industry leaders have partnered to carry out a Canada wide project to evaluate the behaviour of pervious concrete pavement in the Canadian climate. The intent of this project is to evaluate the performance of pervious concrete pavement in the Canadian freeze-thaw climate. The objectives of this research include several key areas including pavement structure design, construction practices, effect of winter maintenance activities and permeability rehabilitation maintenance methods. These topics are being evaluated in both laboratory and field applications.

Field Sites

Pervious concrete pavement is anticipated for use in low volume, low speed applications. In order to understand the behaviour of pervious concrete pavement in these applications and the Canadian climatic environment test sections have been constructed in partnership with industry members across Canada. In total, five test areas have been constructed to date and the details including use, winter maintenance and location are outlined in Table 1. Figure 1 shows a map of the test site locations.

Figure 1 and Table 1 outline the various locations, construction practices, applications, winter maintenance and instrumentation that is included at each site. At all sites where snow is removed, it is done so with front end loaders or highway grade equipment. Table 2 describes the pavement structure as well as mixes that are in place at each site.

Table 2 shows the pavement structure of each specific site. The subbases at Sites 1 and 2 were included to facilitate water collection for testing. All of the sections at Site 5 include a drainage pipe in the subgrade layer to handle drainage, should the pervious concrete become clogged. Site 5 is within city limits and in order to accommodate city regulations it was necessary that a drainage system be included in the design in a case that the pervious concrete pavement became clogged and permeability cannot be renewed. The entire area, pervious concrete as well as other pavement surfaces, slopes slightly towards a central drain. Site 3 includes two sections, one in the entrance driveway, 3A and the other in the exit driveway, 3B. The pervious concrete mixes used in sections 3A and 3B are identical however mix 3B has a higher water cement ratio. At Site 4 three mixes were placed to compare the effect of using various aggregate sizes and types. All three mixes are identical other than the aggregate. The mixes at Site 4 include no additives such as fibres or admixtures.

Site 5 includes three mixes and four sections. The three mixtures at Site 5 build on the control mixture that is in section 5C. Mix 5A is the control mix plus fibres and mixes 5B and 5D are the control mix with the addition of a latex admixture. Sections 5A, 5B and 5C were all placed in the same manner. The pervious concrete was placed from the back of a mobile mixer truck by hand, then rolled with a large steel roller and finally a vibratory compactor was used on the surface. The fourth area, 5D was placed by hand from the back of the mobile mixer and then a vibratory compactor was used on the surface. A roller was not used in this area due to space restrictions.

Performance

All five test sites are monitored regularly for changes in performance. Performance monitoring includes permeability testing as well as surface distress evaluations.

Surface Condition

Table 3 outlines the surface condition of each site since construction. A surface distress evaluation form was developed earlier in this research and is presented in Henderson et al., 2009. The form was developed from a literature review of distresses that had developed in pervious concrete pavements in place throughout the United States. The surface distress evaluations are subjective and consider the density and severity of each distress that is present. The distresses that are considered include; raveling and aggregate loss, surface abrasion, polishing, scaling, joint raveling, joint separation, distortion, faulting, cracking, ponding. Following the evaluations of the field sites in this project aggregate failure has been added to the distresses that are considered.

As Table 3 outlines many of the field sites have experienced some degree of surface distress development. Raveling is common throughout the sites however the density and severity is site dependent. At Site 4 the raveling has remained fairly localized to the construction joints. Site 4 was placed in three strips, one per mix with no specific method carried out to handle the construction joints between each strip and mix. One strip was placed beside the next immediately following the completion of the initial strip and each required a couple hours or less to construct.

Site 4 shows two unique distress patterns that have not been as apparent or abundant at the other sites. Within eight months of construction aggregate failure was occurring at Site 4, specifically in Mixes 4A and 4B. This distress is not a feature of poor construction but rather the selection of aggregate for the mix. The second distress builds on the first and was noticed at 18 months of age. The test site is a smaller area and the wheels of all vehicles site in line on the northern half of Mix 4A. This half of the section is experiencing more aggregate fracturing that the other half that is mainly used by foot traffic.

Minimal cracks have occurred at Sites 3, 4 and 5. At Site 3 there are joints that were constructed using a “pizza cutter” roller however the joints are a significant distance apart in comparison to the width of each slab (1m) therefore exceeding the suggested joint spacing of 1 to 1 or 1 to 1.5 for concrete pavements in general. Cracks at this site are generally located in the centre of the slabs. A single crack has developed in Section 4A.

Permeability

Permeability testing is carried out at all sites multiple times each year. Testing is done using a permeameter which allows the user to record the amount of time required to drain a specific quantity of water from the surface. The permeameter is sealed to the surface using putty to ensure that water moves into the pavement structure and does not seep horizontally on the surface. Testing is carried out three times on at least 25 points that are distributed across the site during each testing session. Figure 2 shows the permeability of each site section since construction. The maximum rainfall rate that is experienced at any of the sites is noted on Figure 2 and is 0.0083cm/sec.

As Figure 2 shows most of the sites are well above the maximum rainfall rate and continue to perform adequately with no maintenance. Site 3 started with a lower permeability rate than some of the other sites and efforts have been made to renew the permeability. As is shown in Figure 3, the permeability has been increased slightly and this was done with sweeping and vacuuming of the surface. The use of a power washer was evaluated however proved to decrease the permeability of the surface rather than increase it [Henderson, 2010]. Other rehabilitation maintenance has been trialed at various sites for research purposes. The other four sites have not required rehabilitation maintenance to date. The results of this research can be found in Henderson et al, 2010. Further rehabilitation maintenance is planned for 2010 as portions of Sites 1 and 2 are now performing below the required rate.

The three mixes at Site 4 are all showing similar decreases in permeability however at different rates. Mix 4A continues to maintain the highest permeability and contains the smallest aggregate. Mix 4B has the next highest permeability and only one type of aggregate, 20mm gravel. The third mix is more than adequate but has the lowest permeability of the three and has two types of 20mm aggregate, gravel and crushed limestone. While these trends may be solely related to the mix type it is also important to note two other features. The mixes were placed in the following order, 4A, 4B, 4C. As construction progressed it became more efficient, perhaps producing a denser material with less voids. In addition, Mix 4C is adjacent to the yard at the concrete plant and therefore has the most sand materials being tracked on to it from vehicles and snow removal equipment.

A common trend has developed at Sites 1 and 2 and that is more significant decreases in permeability in areas that are used primarily for driving. The areas that are used generally as parking spots have remained more permeable over time. Figure 3 shows the permeability of the driving and parking areas of Sites 1 and 2 since construction.

Figure 3 shows the driving areas of both Sites 1 and 2 decreasing at similar rates since construction. The parking areas at both sites are not exhibiting the same deterioration rates but both continue to remain well above the level of the driving areas. The fluctuations in permeability, where it increases at both sites is due to natural causes as maintenance has not been performed. The increases at both sites occurred during the summer and fall seasons and may be attributed to intense rain events.

Laboratory Testing

An accelerated laboratory testing project is ongoing as part of this research. Figure 4 shows the overall research methodology of the laboratory portion.

As shown in Figure 4, slab samples were prepared for full scale freeze-thaw cycling and material characterization. The design of the laboratory testing includes replicates which will be useful in determining trends in performance.

In total 20 slabs were prepared. Two were cast for material characterization which included coring and testing for void content, permeability and compressive strength. The remaining 18 slabs were cast for six loading programs. Each loading program includes three slabs that receive identical precipitation and winter maintenance loadings. Within these three slabs one includes a sensor to monitor freeze-thaw cycling. Maturity sensors were used for freeze-thaw monitoring as they are designed for concrete applications and record temperature and time.

The slabs are all 300mm in length and 300mm in width and six are 200mm in height and the remaining 12 are 150mm in height. All slabs were prepared in the same method; two layers, each layer being rodded 90 times and then the surface being leveled. The slabs were prepared following the method used in CSA A23.2-3C to prepare flexural beams. Fresh concrete testing was carried out during the slab construction. The two slabs that were prepared for material characterization were tested after curing. The results of the fresh and hardened concrete testing are shown in Table 4.

Table 4 shows the fresh and hardened concrete test results. As would be expected the slump was 0mm for all mixes. Cylinders were cast for compressive strength testing. In a continuation of the work done by Rizvi et al., 2009 cylinder preparation methods were evaluated. Two methods were compared the convention rodding method described in CSA A23.2 – 3C which consolidates the sample in three layers, 20 rods per layer. The other method related to the pervious concrete standard for unit weight measurements, ASTM C 1688 and includes two layers, 10 Proctor Hammer drops per layer. The results indicate lower strengths at 7 and 28 days for the samples prepared with the Proctor Hammer but more consistency based on the standard deviation values. The slabs were prepared using rodding and the compressive strength of the cores is similar to that of the rod prepared cylinders. The void content of the cores was high at 29.1% and this is perhaps higher than is needed for permeability and may negatively affect durability.

The difference between the slab permeability and the core permeability values is due to the fact that permeability of the slab allows for horizontal movement of water within the slab while this is mitigated in the core due to the small diameter (100mm). The permeability of the eight cores was very consistent with a low standard deviation. The difference in these values could be used to conclude that a significant portion of the permeability in the slabs and field trials is due to the ability of the water to move horizontally within the pervious concrete however more research is needed to confirm this. Although the exact path of water throughout the pervious concrete cores, slabs and field sites has not been covered in this work to date, it is anticipated that the water would tend to follow the easiest path. Therefore, in some cases water might move in a more horizontal direction than vertical until it found an easy path downward. While moving horizontally, water would also be traveling downward unless there was a driving force. A relation between the amount of vertical movement and horizontal movement maybe developed in future work related to this study as it would allow for direct comparison of core and field results. If horizontal movement was allowed in the cores, thus not sealing the sides of the cores, then the permeability results would inevitably be very high as water would not travel through the entire core but rather drain out the side at the first possible location if it was the easier path.

Table 5 shows the loading program for the slabs. The loading of the slabs, slab loading, is in reference to which scenario each group of slabs is experiencing in terms of quantity of winter maintenance, sand or salt solution and precipitation. Each slab is loaded once per freeze-thaw cycle. Freeze-thaw cycles are performed by moving slabs from a large walk in freezer in the CPATT laboratory to a room temperature environment. Ho and Gough indicate 51 freeze-thaw cycles occur annually in Toronto, Ontario [Ho and Gough, 2006]. The mix design that was used to construct the slabs is the same one that was placed at Site 1 in Georgetown, ON and therefore the local climatic conditions were used. The slabs are loaded for winter maintenance and precipitation. The quantity of precipitation varies depending on the month that is currently being replicated and was determined based on the monthly precipitation and the quantity of freeze-thaw events that generally occur in each month.

Both the precipitation and maintenance loading level “high” is 1.5 times the average loading rate. The average precipitation loading rate was determined from climatic data while the maintenance loading rate is representative of common practice in southwestern Ontario [SAS, 2009, Henderson, 2007].

Using the maturity sensors that were placed in the centre of the slabs during construction it was determined that freeze-thaw cycles require a minimum of 14 hours to cycle from 8°C to -13°C. Freeze-thaw cycles have various definitions but in general are described as occurring when the maximum daily temperature is 0°C or higher and the minimum daily temperature is below 0°C. Another definition is that the maximum daily temperature must be 0°C or higher and the minimum daily temperature must be -1°C or less, with the consideration that freezing will definitely occur in the surface [Ho and Gough, 2006]. To imitate real world scenarios the slabs are cycled to a larger range. Figure 5 shows data from the maturity sensors indicating the temperature changes.

Figure 6 shows the various conditions of the slab surfaces during the replication of one year of freeze-thaw cycling and loading. The slab group 5 is the only one that is loaded with a salt solution. Figure 6 shows slabs 2B, 5B and 6B and group 5 slabs are darker in colour than the rest of the slabs during all points of the freeze-thaw cycle.

Performance

Similar to the field sites the slab samples are monitored regularly for changes in performance with the benefit that loading is controlled in the laboratory environment.

Surface Condition

At the end of three years worth of equivalent cycling slabs had exhibited some surface distress development. Table 6 shows the surface condition of the slabs at the end of each year of cycling.

As Table 6 describes, slab groups 1 through 4, which are all loaded with various quantities of sand experienced raveling. During portions of the cycling the slabs are heavily loaded with sand as the amount of sand continues to build after each loading. It appears that the sand traps some of the water. When the slabs are frozen with water trapped in the sand it expands and this repetition wears down the paste and leads to raveling on the surface. This behaviour may indicate that it is key to consider maintaining pervious concrete surfaces prior to the winter season to avoid this condition.

The slab 5 group is the only one loaded with a salt solution and is showing different distresses than the other mixes. The salt solution seems to be wearing away the paste in the pervious concrete to the point where many of the aggregates on the surface of the slab are no longer covered in paste. The loss of paste has not yet lead to raveling however this could be the future condition.

Permeability

Permeability testing is carried out on the slabs using the same permeameter as is used at the field sites. The slabs have been maintained twice to date. At the end of year 1 only slab groups that are heavily loaded were maintained, being 1 and 3, and this was done by sweeping the surface of the slabs. In the middle of year three all four groups of slabs that receive sand loading were maintained and this was done by vacuuming the surface. Table 7 shows the permeability of the slabs at various points throughout the three years of freeze-thaw cycling, noting each year includes 51 cycles.

All four groups that receive winter maintenance in the form of sand have shown a continual decrease in permeability since the start of the loading. Group 5 which receives the salt solution loading has also shown a decrease in permeability. It is anticipated that salt is gathering in some of the voids in the group 5 slabs, at least those close to the surface. Salt can now be seen building up on the surface of these three slabs.

The permeability results at 153 cycles for groups 1, 2, 3 and 4 are close to those at 99 cycles or greater. The values at 153 cycles are greater than the values at 132[2] cycles which was immediately following rehabilitation. This may be related to the fact that following rehabilitation, 132[2] cycles, the slabs were tested and had been tested multiple times in a short period of time, 24 – 36 hours. The testing uses a significant amount of water, more than rain events. Some of this water was likely still accumulated in the slabs, therefore decreasing the permeability of these slabs. Following 21 cycles with regular loading this excess water would have left the slabs and a better permeability would have been recorded. Group 1 showed a similar trend between cycles 51[1] and 62. Cycling will continue on the slabs for at leats the equivalent of two more years and this trend will be monitored.

Conclusions

In conclusion many findings can be drawn from this project to date. The key point to highlight is that with proper mix designs and construction practices pervious concrete pavement can perform in the Canadian climate. The selection of appropriate applications for pervious concrete is critical. The permeability data from the field sites indicates that performance can remain at a high level in areas that are used for static traffic rather than areas with excessive traffic movement. The surface distress data also indicates that application is critical and material selection is of importance. The common occurrence of aggregate fracturing indicates that strong aggregates should be used or a different paving material should be placed in areas of repeated, high loading. The continual high permeability rates reinforces that pervious concrete pavement can handle runoff from impermeable surfaces in addition to the rainfall on the pervious area. The use of joints can eliminate the development of cracks if properly spaced.

The laboratory research is providing valuable details about the strength of pervious concrete. The raveling of loaded slabs indicates that maintenance should be considered before cold seasons to avoid water being trapped in debris on the surface and causing raveling. The results to date indicate that the use of salt solutions on pervious concrete pavement can decrease the permeability and lead to paste loss on surface aggregate. Loading of pervious concrete with sand material generally decreases the permeability and the quantity of sand has not been noted to strongly effect the changes in permeability.

The performance of the field and laboratory pervious concrete indicates that it is possible to achieve a high quality pervious concrete that will allow for the sustainable benefits to be gained by society and industry members.

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References

ACI, (1996) “Technician Workbook”, ACI Certification Program for Concrete Field Testing Technician – Grade 1, Canadian Edition

ASTM, American Standard Test Methods, (2008), “Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete”, ASTM C 1688.

Barnes, K.B., Morgan, J.M. III, Roberge, M.C., (2001) “Impervious Surfaces and Quality of Natural and Built Environments”, Department of Geography and Environmental Planning, Towson University, Baltimore, Maryland.

CSA, CSA A23.2-3C, (1994) “Making and Curing Concrete Test Compression and Flexural Specimens”, Canadian Standards Association, 1994.

Environment Canada, (2008), “Intensity Duration Frequency Statistics”, ftp://arcdm20.tor.ec.gc.ca/pub/dist/IDF/.

Environment Canada, (2009), “National Climate Data and Information Archive”, http://www.climate.weatheroffice.gc.ca/climateData/canada_e.html, accessed 2009.

EPA, (2008), “Effluent Limitations Guidelines and New Source Performance Standards for the Construction and Development Category”, U.S. Environmental Protection Agency.

EPA, (2009), “Heat Island Impacts”, Heat Island Effect, U.S. Environmental Protection Agency, www.epa.gov/hiri/impacts/index.htm .

Gajda, J.W.,Van Geem, M.G.,“A Comparison of Six Environmental Impacts of Portland Cement Concrete and Asphalt Cement Concrete Pavement”, PCA R&D Serial No. 2068, Portland Cement Association, 1997

Henderson, V., Tighe, S., Norris, J., (2009), “Pervious Concrete Pavement: Integrated Laboratory and Field Study”, Transportation Research Record 2113, Concrete Materials 2009.

Henderson, V., Tighe, S., (2010), “Developing Sustainable Design, Construction and Maintenance Techniques for Cold Climate Pervious Concrete Pavements”, First International Conference on Pavement Preservation, Newport Beach, CA, April 2010.

Henderson, V., Banfield, N., Bergsma, J., Malleck, B., (2007), “Pervious Pavement: The Green Solution”, CivE 400, University of Waterloo, Waterloo, ON.

Ho, E., Gough, W.A., “Freeze thaw cycles in Toronto”, Canada in a changing climate, Earth and Environmental Science, Vol 83, Numbers 1-4, January 2006.

Novotney M., (2008), “Comprehensive Stormwater Management Approach for the Coast”, Center for Watershed Protection, Ellicott City, MD.

Rizvi, R., Henderson, V., Tighe, S., Norris, J., “Laboratory Sample Preparation Techniques for Pervious Concrete”, Transportation Research Board 88th Annual Meeting, January 2009, Washington, DC.

SAS, Smart About Salt, (2009), “Smart About Salt”, http://smartaboutsaltcouncil.roundtablelive.org/, accessed 2009.

Schaefer, V. R., Wang, K., Suleiman, M., Kevern, J., (2006), “Mix Design Development for Pervious Concrete in Cold Weather Climates”, National Concrete Pavement Technology Center, Final Report.

Tighe, S., “Pervious Pavements: The Road to Sustainability in Northern Climates?”, Portland Cement Association Research and Development Program, February 2007.

Tighe, S., (2010), “Pavement Design 1”, CivE 642, University of Waterloo, Waterloo, ON.

Van Seters, T., Smith, D., MacMillan, G., (2006), “Performance Evaluation of Permeable Pavement and a Bioretention Swale”, 8th International Conference on Concrete Block Paving. San Francisco, CA.

Van Seters, T., (2007), “Performance Evaluation of Permeable Pavement and a Bioretention Swale”, Interim Report, Toronto and Region Conservation Authority, Sustainable Technologies Evaluation Program.

WERF, (2005), “International Stormwater Best Management Practices Database”, Water Environment Research Foundation, Alexandria, Virginia.

Tables

Table 1: Field Site Description

Site	Location	Construction Date	Construction Method	Application	Winter Maintenance	Instrumentation
Site 1	Georgetown, ON	Summer 2007	Hand Placement and Roller, Joints with "Pizza Cutter" roller	Staff Parking Lot	Entire Site Plowed, Sand Applied to Half	Water Sampling
Site 2	Campbellville, ON	Fall 2007	Bidwell Bridgedeck Paver and Razorback Paver, Joints with "Pizza Cutter" roller	Public Carpool Lot	Entire Site Plowed, Sand Applied to Half	Water Sampling
Site 3	Maple Ridge, BC	Spring 2008	Hand Placement and Roller, Joints with "Pizza Cutter" roller	Driveway for Trucks and Personal Vehicles	None	Strain Gauges, Moisture Trees
Site 4	Barrie, ON	Fall 2008	Asphalt Paver, No Joints	Staff Parking Lot	Entire Site Plowed, Sand Applied to Half	Moisture Trees
Site 5	Laval, QC	Summer 2009	Hand Placement and Roller, Joints were Saw Cut	Staff Parking Lot	Entire Site Plowed	Moisture Trees

Table 2: Field Site Pavement Structures

Site	1	2	3A	3B	4A	4B	4C	5A	5B	5C	5D
Site Size (m^2)	630	1800	50	10	250	250	250	72	72	72	40
Pervious Concrete Thickness (mm)	300	240	250	250	200	200	200	200	200	200	200
Pervious Concrete Mix Details	Fibres, Air[1]	Fibres, Air[1]	Control[2]	Higher W/C than 3A	14mm Gravel	20mm Gravel	20mm Gravel and 20mm Crushed Limestone	Fibres	Latex	Control[2]	Latex
Clear Stone Base Thickness (mm)	600	100	200	200	250	250	250	200	200	200	200
Subbase (mm)	100 (Mud Slab)	200 (19mm gravel)	Not Applicable								

[1] Air entrainment admixture
[2] Control Mix for particular site

Table 3: Field Site Surface Condition

Site	**Surface Condition (Age - months)**							
	1 – 4	**4 – 8**	**8 - 12**	**12 – 16**	**16 - 24**	**24 – 28**	**28 – 32**	**32 – 36**
1	Slight raveling in slabs, 10 – 20%		Moderate raveling in slabs and joints, 20 – 50%,			Moderate raveling 50 – 80%, slight aggregate fracturing 10 – 20%,moderate joint raveling 20 – 50%		Moderate joint and slab raveling 50 – 80%, <10% surface abrasion, severe raveling <10%
2	Slight raveling in slabs and joints, 20 – 50%	Moderate and severe raveling in slabs and joints, 20%, slight surface abrasion, 10%	Moderate and severe raveling in slabs and joints, 70%,	Slight raveling in slabs and joints, 80%	Moderate raveling in slabs and joints, 80%	Moderate raveling in slabs and joints 80%, slight surface abrasion <10%		Not Yet Available
3A	Surface sealing, 20%, slight raveling, <10%		Slight cracks, <10%, moderate raveling, 20% - 50%		Moderate raveling in slabs and joints, 50% - 70%	Not yet available		
3B	Surface sealing, 20%		Surface sealing, 50%			Not yet available		
4A	Construction joint slight to severe raveling, 40%	Aggregate failure, 10%		Moderate joint raveling 20-50%, moderate slab raveling <10%, aggregate failure <10%	Severe joint raveling 80%, moderate surface abrasion <10%, aggregate failure 20-50% - *Under wheels of vehicles*, very slight crack	Not yet available		
4B		Aggregate failure, 20% - 50%, Moderate raveling, 20% - 50%		Moderate joint raveling 80-100%, moderate slab raveling <10%, slight surface abrasion <10%	Moderate joint raveling 80-100%, moderate slab raveling <10%, slight surface abrasion <10%			
4C		Slight raveling, 20%		Moderate joint raveling 20 – 50%, aggregate fracturing <10%, slight surface abrasion <10%	Moderate joint raveling 20 – 50%, slight surface abrasion 10-20%, aggregate fracturing <10%			
5A	Slight crack, <10%, Very slight raveling, <10%	Not yet available						
5B	Very slight raveling, <10%							
5C	Very slight to slight raveling, 10% - 20%							
5D	Uneven surface							

Table 4: Slab Characteristics

Characteristic	Average	St Deviation
Slump (mm)	0	0
Density (kg/m^3)	1972.1	58.1
Air Content (%)	4.5	0.7
Compressive Strength R Samples 7 Days (MPa)	12.4	3.5
Compressive Strength PH Samples 7 Days (MPa)	9.6	2.3
Compressive Strength R 28 Days (MPa)	14.4	3.7
Compressive Strength PH Samples 28 Days (MPa)	11.5	2.2
Compressive Strength of Cores (MPa)	13.6	1.4
Permeability of Slabs (cm/sec)	5.7	2.3
Permeability of Cores (cm/sec)	2.8	0.4
Void Content (%)	29.1	0.8

Table 5: Slab Loading

Slab Group	Winter Maintenance Type	Winter Maintenance Level	Precipitation Level
1	Sand	High	High
2	Sand	Average	Average
3	Sand	High	Average
4	Sand	Average	High
5	Salt	High	High
6	None	N/A	High
N/A - Not Applicable			

Table 6: Slab Surface Condition

Slab	Age	
	1.25 Years	2.5 Years
1A	Very slight paste loss	<10% paste loss, 50% raveling in multiple areas (1.5cm x 2cm x 6cm)
1B	Fractured aggregate, Slight paste loss	<10% paste loss, raveling 1cm in depth
1C	Fractured aggregate, very slight paste loss	slight aggregate fracturing, <10% raveling 1cm in depth
2A	Moderate paste loss	40% raveling in one deep area (2cm x 3cm x 3cm), 10% paste loss

2B	Moderate paste loss	40% raveling in localized 1cm deep areas, <5% paste loss
2C	Moderate paste loss	<5% aggregate fracturing, <10% raveling 1cm in depth
3A	Very slight paste loss	<5% raveling 1cm in depth
3B	Fractured aggregate, Slight paste loss	<5% aggregate fracturing, <20% raveling area (1.5cm x 5cm x 4cm)
3C	Very slight paste loss	<5% aggregate fracturing, <10% raveling 1.5cm in depth
4A	Very slight paste loss	<5% aggregate fracturing, <5% paste loss, 20% raveling 2 - 2.5cm in depth
4B	Very slight paste loss	<10% paste loss, <5% aggregate fracturing, <10% raveling 1.5cm in depth
4C	Moderate paste loss, fractured aggregate	<5% aggregate fracturing, <10% paste loss, <5% raveling
5A	<5% Fractured aggregate, <10% Moderate paste loss	75% paste loss, <5% aggregate fracturing
5B	<5% Fractured aggregate, 50% moderate paste loss	50% paste loss, <5% aggregate fracturing, salt building up on surface
5C	<5% Fractured aggregate, 50% Moderate paste loss, 10% Severe paste loss	60% paste loss, <5% aggregate fracturing, salt building up on surface
6A	<5% Fractured aggregate, 10%-20% slight paste loss	<10% raveling 1.5cm in depth
6B	<5% Fractured aggregate, 10% - 20% moderate paste loss	<5% aggregate fracture, <10% raveling 1cm in depth, <5% paste loss
6C	<5% Fractured aggregate, <10% Moderate paste loss	<5% paste loss, <5% raveling 1cm in depth

Table 7: Slab Group Permeability

Cycles	**Permeability (cm/sec)**												
	0	**4**	**12**	**24**	**31**	**46**	**51**	**51[1]**	**62**	**99**	**132**	**132[2]**	**153**
Group 1	7.12	7.04	1.39	0.77	0.41	0.30	0.30	0.32	0.41	0.21	0.11	0.07	0.24
Group 2	6.53	4.38	1.65	0.73	0.39	0.31	0.47	N/A	0.51	0.17	0.14	0.21	0.25
Group 3	7.96	2.55	0.82	0.50	0.21	0.34	0.33	0.45	0.40	0.17	0.13	0.16	0.22
Group 4	5.74	3.91	1.59	0.52	0.28	0.41	0.33	N/A	0.36	0.19	0.12	0.17	0.32
Group 5	2.64	3.32	4.02	3.04	2.46	4.36	3.49	N/A	4.06	2.63	1.86	N/A	1.15
Group 6	4.18	5.11	6.39	5.57	5.57	10.15	7.27	N/A	8.20	5.60	6.91	N/A	6.85
N/A – Not Applicable 1 – Samples Swept 2 – Samples Vacuumed													

Figures

Figure 1: Field Site Locations

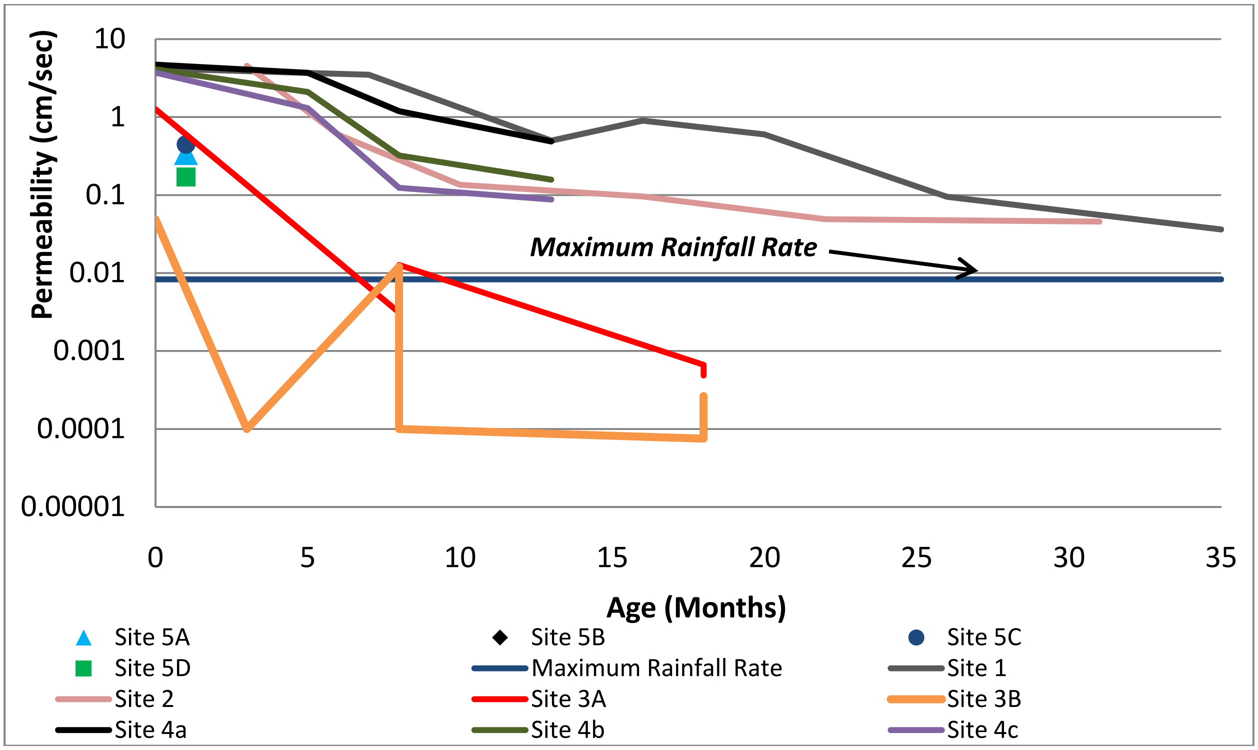

Figure 2: Site Permeability

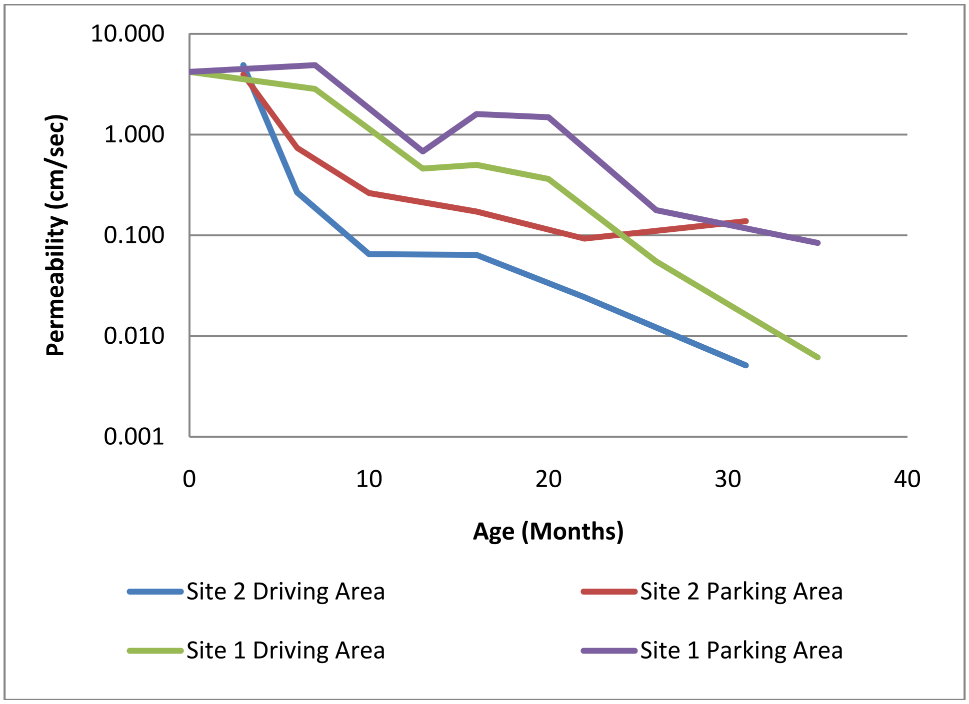

Figure 3: Comparison of Driving and Parking Areas of Sites 1 and 2

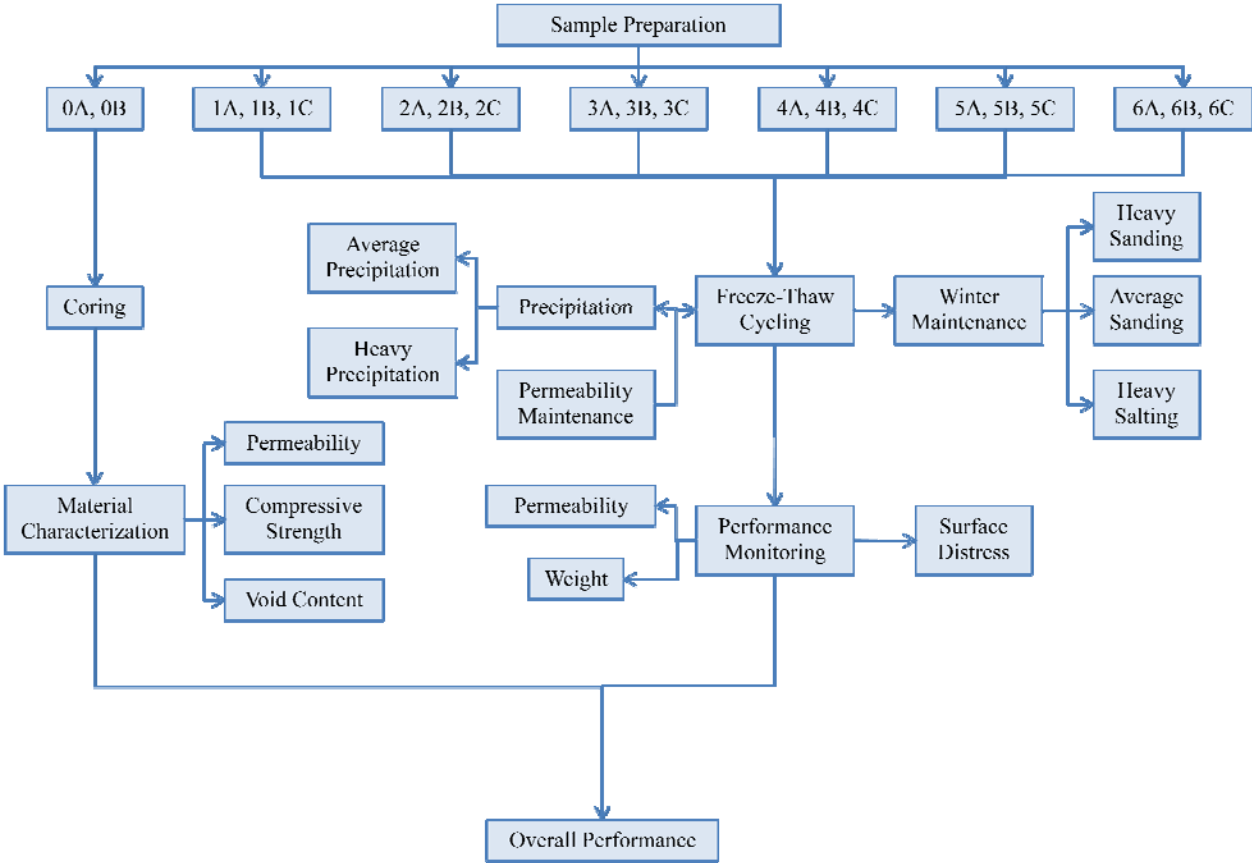

Figure 4: Laboratory Methodology.

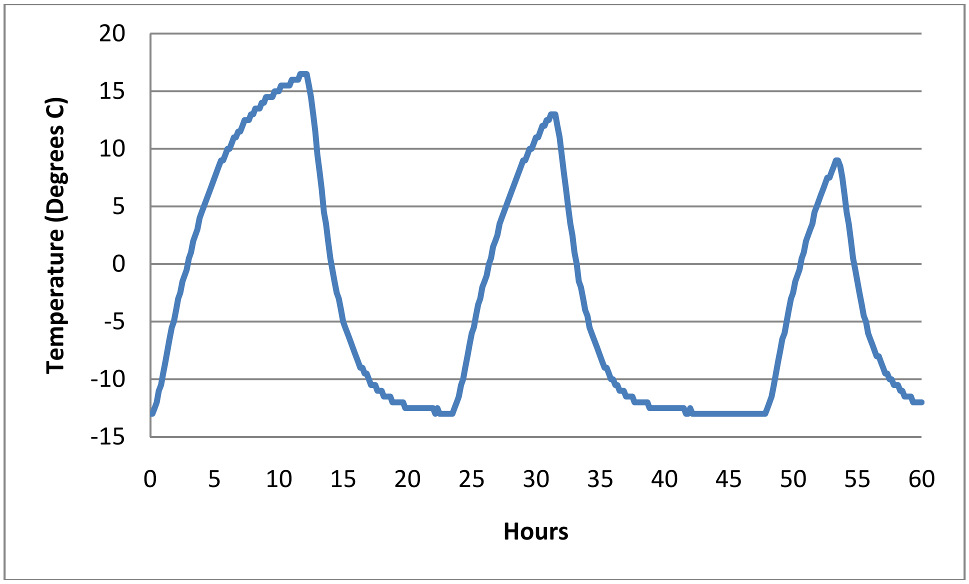

Figure 5: Freeze-Thaw Cycle Monitoring using Maturity Sensors

Figure 6: Slab condition during cycling