Development of the Canadian Design, Construction and Maintenance Guide for the Use of Pervious Concrete Pavement

Vimy Henderson, Ph.D., P.Eng., Golder Associates Ltd., Mississauga, Ontario
Susan L. Tighe, Ph.D., P.Eng., Canada Research Chair in Sustainable Pavement and Infrastructure Management, Norman W. McLeod Professor of Sustainable Pavement Engineering, University of Waterloo, Waterloo, Ontario
Rico Fung, P.Eng., LEED® AP, Cement Association of Canada, Toronto, Ontario

Paper prepared for presentation
At the Design, Construction and Maintenance of Permeable Pavements Session

Of the 2014 Conference of the
Transportation Association of Canada
Montreal, Canada

ABSTRACT

Pervious concrete pavement is an environmentally friendly pavement alternative for low speed, low volume applications. The high void content of the material allows moisture to drain from the surface and naturally infiltrate into the subgrade or be collected and drained away from the site. By draining moisture through the pavement structure the natural water cycle can be maintained while reducing the demand on stormwater management infrastructure.

The Cement Association of Canada (CAC), industry members and Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo (UW) partnered to develop a Design, Construction and Maintenance Guide for the use of pervious concrete pavement in Canada. This paper will present many of the recommendations in the guide as well as briefly discuss the research that was carried out in developing the recommendations.

A multi year integrated laboratory and field study was carried out to evaluate the performance of pervious concrete pavement in Canada. Five field sites were constructed across Canada. The field sites were used to evaluate alternative pavement structures, materials and construction practices. The performance of each field site was monitored from the surface as well as using instrumentation that had been included during construction. Winter maintenance methods were carried out at the field sites and the outcome of these activities was assessed. Permeability renewal maintenance methods were used as needed and also trialed for research purposes. The field sites were each unique and provided information for a variety of scenarios and conditions. The performance observed and data collected at the field sites was used to develop many of the recommendations provided in the guide.

In addition to the full scale field sites, laboratory research was also carried out. This research focused on the performance of pervious concrete pavement when exposed to freeze-thaw cycling and varying winter maintenance activities. Large pervious concrete samples were exposed to continual freeze-thaw cycling using a walk-in freezer. The controlled environment of the testing created fewer variables than the field sites and the opportunity to link observations between the field and laboratory results.

The guide presents recommendations from the design to maintenance aspects of pervious concrete pavement use in Canada. The research for this project indicated that pervious concrete pavement could be used successfully in southern Canada when the necessary factors were considered and addressed throughout the life of the pavement.

INTRODUCTION

Pervious concrete pavement is a sustainable solution to a challenge that often exists in urban areas. The challenge is handling the large amount of existing impervious area in urban environments and additional area created during urban growth and development. Impermeable areas produce runoff and requires an infrastructure system for adequate control (Walker, 2009). Pervious concrete pavement has two functions: a paved surface available for low volume, low speed traffic applications with the current technology; and a stormwater management alternative. This technology has been used for some higher speed applications e.g. highway shoulders at Missouri DOT and highway off ramps in Australia, but these applications are still under further development. The rigid concrete creates a paved surface for various uses while the open voids in the concrete allow water to drain from the surface. Research has been completed to develop pervious concrete mixes for high volume applications (PCA, 2009). At this time, only low volume and low speed applications have been considered for the Canadian climate. The low volume, low speed applications that are generally considered for pervious concrete pavement are:

- Sidewalks;
- Paths;
- Driveways;
- Parking lots;
- Shoulders; and
- Residential streets.

Pervious concrete can be used in active or passive drainage applications. Active drainage occurs in scenarios when runoff from surrounding impermeable areas is drained through the pervious concrete pavement structure in addition to the precipitation falling directly on the pavement. Passive drainage occurs when only precipitation falling directly on the pervious concrete pavement system is being drained through the pavement structure (PCA, 2012).

The consistency of pervious concrete includes interconnected voids, generally ranging from 15% to 35%. These voids and the connectivity of them allow moisture to be drained from the surface. The moisture drained from the surface can then infiltrate into the groundwater or can be directed to a collection system where it can be harvested or alternatively drained to conventional drainage systems.

Pervious concrete pavement is a Low Impact Development (LID) offering many benefits when integrated into urban areas. The ability for pervious concrete to drain water from the surface offers benefits which span various sectors including the environment, society and economy.

The LEED Canada Rating System awards points for new construction and major renovations (Canada Green Building Council, 2009). Pervious concrete pavement, as a type of permeable pavement is directly eligible or can contribute to points being earned under the following categories:

- Stormwater Design Quantity Control;
- Stormwater Design Quality Control;
- Heat Island Effect: Non-Roof; and
- Contribute to Regional Materials Use.

The Ontario Ministry of Transportation (MTO) has developed a program called GreenPave which allows owners to compare the sustainability of different project alternatives. Within GreenPave there are credits awarded for permeable pavements which pervious concrete pavement would fall within. There are also additional credits directed towards concrete pavement that pervious concrete pavement maybe eligible for (MTO MERO, 2012).

The low impact of using pervious concrete pavement is one of the main factors attributing to the environmental benefits of this material. The drainage capabilities of pervious concrete pavement lead to developments that have minimal to no effect on the natural water cycle in the area. The reduction or often elimination of runoff in areas paved with pervious concrete pavement, in comparison to the use of an impermeable pavement, can be a tremendous environmental gain. Permeable pavements are commonly referenced as Best Management Practices (BMP) for source control measures of urban stormwater management. Permeable pavement is referenced by many cities and municipalities throughout Canada as being a stormwater management alternative (City of Toronto, 2003) (Devereauz & Lorant, 2006) (Bozic, Deong, & Fesko, 2007).

Projects have been carried out by many groups to evaluate the ability of pervious concrete pavement to remove particulate from water that moves through the pavement structure. Pollutants that would otherwise remain in runoff and contaminate runoff have been shown to be removed during filtering through the voids in a pervious concrete pavement (Tennis, Leming, & Akers, 2004) (Drake, Bradford, Van Seters, & MacMillan, 2012).

Often the environmental benefits of sustainable infrastructure alternatives are more apparent to the user than those that improve society. Pervious concrete has several attributes that can improve the quality of life for the local community. Many of the societal benefits that pervious concrete exhibits are shared by conventional concrete pavements as well. These include minimizing heat islands and increased reflectivity. Both of these benefits are attributed to the colour of concrete, light grey, in comparison to asphalt pavement which is black in colour. The urban heat island effect occurs in urban areas with many dark surfaces that lead to the localized air temperature being higher than it would be on a comparable day in a rural environment. Research indicates that the air temperature in urban areas can be up to 4°C degrees higher than it would be in a rural setting (Pon, 2000). The effect of this increased temperature is a higher frequency of heat related illness, especially in the susceptible population: children; and seniors (EPA, 2008). While the effects of urban heat islands on humans are of great concern to communities and cities, reductions of urban heat islands also benefit the environment and economy. By maintaining the natural air temperature and not increasing it unnecessarily, due to dark areas, the demand for resources is not accelerated. Therefore, additional resources and funds are not spent cooling buildings because of increased outdoor temperature (Pon, 2000). Pervious concrete allows for the development of paved surfaces without hot areas.

A benefit that is easily recognizable by users is the dry surface that is constant on pervious concrete pavement. The high drainage rates of pervious concrete pavement lead to immediate movement of stormwater off the surface, therefore resulting in splash and puddle free areas. In addition, there is the potential to harvest the rainwater for various uses. While the benefit of a continually dry surface, or at least puddle free, may seem minimal, it is a reflection of the local area and presents an inviting environment to the clients of the surrounding businesses. The benefits that pervious concrete provides to the local community are significant and a key reason why this material can be used in applications to achieve sustainable results.

Pervious concrete pavement can offer economical benefits to individuals using it on their own property as it maintains the natural water cycle. Since pervious concrete is a low impact development it ensures that surrounding vegetation, such as gardens and lawns, receive natural moisture. This limits expenses for the home owner related to watering. In the case of both private and commercial properties pervious concrete can be used in a water harvesting system which reduces the water demand.

In order to accommodate stormwater management systems, additional land is often required for stormwater retention ponds. Stormwater management systems involve water being collected and drained to conventional drainage systems. The use of pervious concrete pavement can eliminate or reduce the need for land and infrastructure to support stormwater management systems (NRMCA, 2010).

Pervious concrete has been used in climates without regular freeze-thaw cycles for decades; however, use in freeze-thaw climates such as Canada has been only in recent years (ConcreteNetwork, 2010). The climate in Canada presents additional challenges for optimizing pervious concrete performance. Some of the challenges to using pervious concrete pavement are present in all climates. These challenges include: ensuring appropriate site design; achieving adequate mix performance; and complete compliance by involved parties to use educated staff for construction. All three of these elements are essential in achieving a quality pervious concrete pavement in any climate (Delatte, Miller, & Mrkajic, 2007).

While pervious concrete offers exceptional drainage capabilities, designers and managers should be conscientious of the limitations of this material. Land uses such as commercial nurseries, automobile recycling facilities, gas stations and outdoor liquid container storage areas should not include pervious concrete pavement as these are stormwater hot spots. These areas create runoff with high levels of contamination and pervious concrete can provide a path for the contaminated runoff to enter the groundwater (ACPA, 2006).

The anticipated traffic loading for a pervious concrete application should be considered in the design. Similar to all paving materials, when pervious concrete is placed in a location where it experiences more loading than the design considered, the result is surface distress development and poor performance for the owner.

The greatest challenge of implementing pervious concrete pavement throughout Canada is the concern related to the durability of the material in freeze-thaw conditions. Work carried out in the northern United States indicated that freeze-thaw cycles are not necessarily damaging to pervious concrete (Kevern, Wang, Suleiman, & Schaefer, 2005; Wang, Schaefer, Suleiman, & Kevern, 2006; Delatte, Miller, & Mrkajic, 2007). The research completed at the University of Waterloo had similar findings, suggesting with proper materials, construction and maintenance adequate performance of pervious concrete pavement in cold weather climates such as Canada is possible (Henderson, 2012). Distresses caused by freeze-thaw cycling could occur if water is trapped in the voids when these changes in temperature occur. The high permeability rate of pervious concrete reduces the opportunity for water to remain in the voids. It is anticipated that water would only become trapped in the voids if the debris has accumulated. The system must be design to prevent any water storage in pervious concrete.

BACKGROUND

The Cement Association of Canada (CAC), Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo (UW) and industry members partnered in 2007 to carry out a multiyear project to evaluate the potential for use of pervious concrete pavement in Canada. The project included the construction of five field sites within Canada and laboratory testing at the CPATT facilities. Figure 1 shows the locations of the five field sites:

1. Georgetown, Ontario;
2. Campbellville, Ontario;
3. Maple Ridge, British Columbia;
4. Barrie, Ontario; and
5. Laval, Quebec.

Figure 1: Field site locations

Each field site presented a unique scenario to evaluate various aspects of pervious concrete. More specifically, each site evaluates various aspects including: mix design; pavement structure; application; traffic; maintenance; and climate. Table 1 summaries of the field site features and experimental design aspects, including the key climatic attributes (Henderson, 2012).

The laboratory portion of the project involved two major engineering aspects: material characterization; and evaluation of the effect of freeze-thaw cycling and cold weather maintenance. Pervious concrete material characteristics were measured on samples cast during the construction of the field sites as well as from core samples extracted from the field sites. Freeze-thaw cycling was performed at an accelerated rate. In essence, all samples were exposed to typical Toronto area freeze thaw cycling using the walk-in freezer at the CPATT laboratory. The winter conditions in the Toronto area are harsher on pavements than those experienced in other southern portions of Canada, such as southern British Columbia. Freeze-thaw cycling was performed on laboratory cast slabs that were also loaded with various cold weather maintenance scenarios. The research in the laboratory was complimentary to that at the field sites and has gone into the development of this guide (Henderson, 2012).

DESIGN, CONSTRUCTION AND MAINTENANCE GUIDE FOR THE USE OF PERVIOUS CONCRETE PAVEMENT IN CANADA

The objective of the guide is to provide guidelines and recommendations for the design, construction and maintenance of pervious concrete pavement in Canada. The guide is intended to provide practical information that is applicable to all projects where pervious concrete pavement is being considered. The scope of the guide includes the various aspects of design, construction and maintenance such as application, pavement structure, mix design, construction methods, warm and cold weather maintenance and permeability renewal maintenance.

Table 1: Field Site Characteristics

Site	Location (Climate Zone)	Construction Date	Construction Method	Size (m^2)	Application	Pavement Structure	Comments
1	Georgetown, Ontario (Dfa)	Summer 2007	Automated Vibrating Roller	630	Employee Parking at Concrete Plant	Pervious Concrete (300 mm) Clear Stone Base (600 mm) Impermeable Slab (100 mm) Existing Subgrade	Two maintenance strategies were applied to the parking lot
2	Campbellville, Ontario (Dfa)	Fall 2007	a. Bidwell Bridgedeck Paver b. Razorback Paver	1800	Public Car Pool Lot	Pervious Concrete (240 mm) Granular O (OPSS) Base (300 mm) Subdrain across width of site Existing Subgrade	Two methods used for construction and two methods of maintenance were employed
3	Maple Ridge, British Columbia (Cfb)	Spring 2008	Manual Roller Compacted	60	Entrance and Exit Driveway of Concrete Plant	Pervious Concrete (250 mm) Clear Stone Base (200 mm) Existing Subgrade	Two variations of mix design (3A, 3B) Instrumented with moisture gauges and static strain gauges
4	Barrie, Ontario (Dfb or Dfa)	Fall 2008	Asphalt Paver and Vibratory Plate Compactor	750	Employee Parking at Concrete Plant	Pervious Concrete (175 mm) Clear Stone Base (350 mm) Existing Subgrade	Three vairations of mix design (4A, 4B, 4C) Each mix instrumented with moisture gauges
5	Laval, Quebec (Dfb)	Summer 2009	Automated Vibrating Roller and Vibratory Plate Compactor	255	Employee Parking at Concrete Yard	Pervious Concrete (200 mm) Cement Stabilized Clear Stone Base (Popcorn Concrete) (200 mm) Existing Subgrade	Three variation of mix design (5A, 5B, 5C) Two variations of construction method (5B, 5D) Instrumented with moisture gauges (5B, 5C)
W. Köppen Climatic Classifications (Schultz, 2004)		Dfa	Cold winter, hot summer, adequate moisture throughout the year				
		Dfb	Cold winter, warm summer, adequate moisture throughout the year				
		Cfb	Mild wet winter, short warm moist summer				

DESIGN

The design of a pervious concrete pavement involves the consideration of the application, pavement structure and materials. Initially in designing a pervious concrete pavement the objectives of the site in terms of pavement and stormwater management need to be identified. The objectives can then be compared and used to develop a design that is suitable for both types of infrastructure. The following aspects of design are discussed below: application; pavement structure; and mix design.

Application

Pervious concrete pavement is a combination of two types of infrastructure: pavement; and stormwater management. Because pervious concrete pavement has the characteristics and functionality of two types of infrastructure it is only suitable for particular applications. Pervious concrete pavement is appropriate for low volume, low speed pavement and stormwater management applications. Also, pervious pavement is under development for higher speed applications, e.g highway shoulders and off ramps, but this guide will only focus on low speed applications. During the planning of a pervious concrete pavement project the objectives of the infrastructure in terms of its functionality as a pavement and as a stormwater management tool should be considered. After recognizing the objectives it is possible to integrate pervious concrete pavement suitably.

A pervious concrete pavement application has the same geometry options as a conventional concrete pavement, in a comparable scenario. Typically it is recommended that concrete be geometrically designed such that it is square. By designing concrete as square as possible, it allows for consistent movement and minimizes the opportunity for random cracking. During the planning of the site is it important to consider geometric restraints and incorporate them into the design.

Pervious concrete pavement is generally constructed flat but can be constructed on slopes. The pavement structure may require adjustment depending on the extent of the slope. Pervious concrete pavement has been used in applications with slopes up to 16 % (NRMCA, Hydrological Design Considerations, 2010).

Pavement Structure

The pavement structures used for pervious concrete pavement must meet the demands of the two functional purposes that it is intended for. The functional purposes include providing a rigid pavement surface and a stormwater management solution. The general pavement structure used with pervious concrete pavements to achieve both functions is shown in Figure 2. Figure 2 shows the pervious concrete surface, a granular reservoir storage base layer and the existing subgrade.

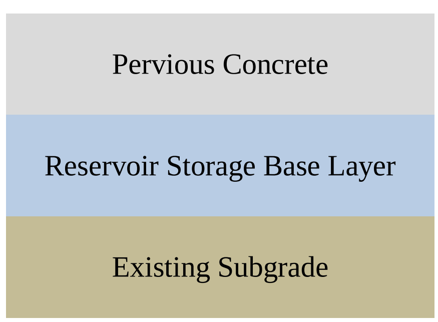

Figure 2: Pervious Concrete Pavement Structure

The pavement structure shown in Figure 2 can be altered for site specific requirements. The requirements for the pavement structure need to be considered and optimized for both purposes of the pavement. The granular base layer is recommended in freeze-thaw climates in all scenarios (NRMCA, 2004). The granular reservoir storage base layer is intended to act as a short term reservoir, allowing water to accumulate and infiltrate into the existing subgrade and groundwater. In 2006 the typical pavement structure of pervious concrete pavement in the United States was 100 mm to 150 mm of pervious concrete, and up to 450 mm of permeable granular base on a permeable subgrade (Schaefer, Wang, Suleiman, & Kevern, 2006). The typical pavement structure for low volume pervious concrete applications in the State of Vermont is 150 mm pervious concrete, 50 mm of AASHTO #57 stone choker course, minimum 850 mm AASHTO #2 stone granular storage base layer and geotextile on the existing subgrade (McCain & Dewoolkar, 2010; AASHTO, 2008).The choker course can provide a solution to construction challenges. A geotextile can be incorporated if there is a concern about fine material migrating into the reservoir base layer.

Subgrade

The characteristics of the subgrade beneath a pervious concrete pavement structure will determine whether water that drains through the structure can naturally infiltrate into the subgrade in an adequate amount of time or if a drainage system needs to be included. The NRMCA suggests that subgrades with percolation rates of 12 mm/hour or more are suitable for pervious concrete pavement structures. Therefore, a subgrade with a percolation rate of less than 12 mm/hour would require additional reservoir thickness to accommodate the slower percolation rate. The determination of the percolation rate of the subgrade is important in developing the design of the entire pavement structure (NRMCA, 2010).

Pervious concrete pavement structures can be used on soils with low permeability rates by incorporating a drainage system. The drainage system would include an underdrain in the reservoir layer of the pavement structure. The inclusion of the underdrain would provide drainage of the water that was not able to dissipate into the existing subgrade or would be too slow. The positive benefits of using pervious concrete as a stormwater management tool would still exist as runoff would be mitigated and drainage from the underdrain would not generate substantial peaks.

When possible samples should be taken from the natural subgrade that the pavement structure will be constructed on as they will provide the most reliable information for the design. The frost susceptibility of the subgrade material should be evaluated during the geotechnical investigation. Pervious concrete pavement structures should not be constructed on frost susceptible soils, similar to all pavement structures. If frost susceptible soils are present they should be removed prior to construction of the pavement structure or they can be treated with cement to change the plasticity index.

A geotextile can be included between the base layer and the subgrade. The base layer is intended to hold moisture as a storage area continually throughout the year. The constant moisture in this area is anticipated to lead to the top of the existing subgrade being in a moist condition as well. The inclusion of a geotextile with a silty soil prevents fines from the subgrade soil from migrating into the storage layer. If fines do migrate into the storage layer the amount of storage capacity available over time would be reduced and soil support capacity would decrease (NRMCA, 2005).

Granular Base

The granular base layer of a pervious concrete pavement structure is intended to provide structural support to the pavement, as would be the case in a conventional concrete pavement. Additionally, base layers need to be at least free draining and also incorporate an area where storage of water can occur in order for a pervious concrete pavement structure to behave as a stormwater management solution. The suggested material for the granular base layer of a pervious concrete pavement structure is an open-graded clean stone with 20% - 40% void space or porosity (PI, 2010; ACPA, 2006; NRMCA, Hydrological Design Considerations, 2010; OPSS, 2012). Table 2 provides gradations recommended for the granular base layer by different users of pervious concrete throughout North America.

Table 2: Granular Gradations for Storage Base Layer (AASHTO, 2008)

Sieve Size	Types of Materials						
	AASHTO No. 2	**AASHTO No. 3 (30% Porosity)**	**AASHTO No. 4 (30% Porosity)**	**AASHTO No. 57 (40% Porosity)**	**Granular O (OPSS 1010)**	**Clear Stone Type II (OPSS 1004)**	**AASHTO No. 67 (40% Porosity)**
	Percent Passing Sieve (%)						
75mm	100						
63mm	90-100	100					
50mm	35-70	90-100	100				
37.5mm	0-15	35-70	90 – 100	100	100		
25.0mm (26.5mm*)		0-15	20 – 55	95 – 100	95-100	100	100
19.0mm	0-5		0 – 15		80-95	90 – 100	90 – 100
16.0 mm						65 – 90	
12.5mm (13.2mm*)		0-5		25 – 60	60-80		
9.5mm			0 - 5		50-70	20 – 55	20 – 55
4.75mm				0 – 10	20-45	0 – 10	0 – 10
2.36mm				0 – 5			0 – 5
1.18mm					0-15		
300µm							
150 µm							
75 µm					0-5	0 – 2	
	* Used in Granular O gradation only						

The choker course is included in a pervious concrete pavement structure to provide a construction platform. The clear stone material in the reservoir base layer is generally not stable enough for loading from construction equipment and concrete trucks. To create a surface that provides support for construction equipment a choker layer can be placed on top of the clear stone reservoir base. The choker layer should be free draining but have less voids than the reservoir layer. The intent is for water to drain through the thin choker course and be stored in the voids in the reservoir layer (Bush, et al., 2008)

Design Tools

Software programs are available for use in developing pervious concrete pavement structure designs. PerviousPave has recently been developed by the American Concrete Pavement Association (ACPA) (ACPA, PerviousPave, 2012). PerviousPave allows users to design both the hydrological and structural aspects of a pervious concrete pavement. The hydrological portion is based on modifications to the Los Angeles County method (LACDPW, 2002). The structural design portion is a modified version of StreetPave. Details of the equations and assumptions within PerviousPave are described in the user's manual (ACPA, 2012). PerviousPave determines the pavement structure required based on the structural inputs by the user. The hydrological requirements are then determined. The reservoir base layer thickness determined to the meet the structural requirements is compared to that required for the hydrological demands. The thicker of the two reservoir layer options (structural and hydrological) is used for the design (ACPA, 2012).

Constructability

As has been noted earlier in Section 2, it is important to consider the feasibility of constructing the intended pervious concrete pavement structure. Constructability challenges often include the use of construction equipment on the reservoir base layer, generally for the placement of the pervious concrete. This can be overcome by designing a more stable base, either with a choker course or by stabilizing the base. Both options noted previously would provide a construction platform for equipment. Alternately the pervious concrete can be moved on a conveyor. A stabilized base was used with success at Site 5.

Mix Design

A pervious concrete mix design needs to provide a void structure that allows water to drain from the surface. It also has to provide a pavement with adequate durability for the intended users, to minimize the development of surface distresses. The durability of a pervious concrete mix can be jeopardized if there are too many voids and not enough strength develops. The ability to continue to perform under exposure to freeze-thaw cycling and regular traffic is critical in the Canadian climate. The traffic currently considered for pervious concrete pavement in Canada is low speed and low volume.

A pervious concrete mix design may include either a coarse and fine aggregate or only a coarse aggregate based on overall gradation, and, cement, water and chemical admixtures. Both the coarse and fine aggregate contribute to the overall void content of the hardened concrete. Various supplementary cementitious materials, admixtures and fibres can also be included if deemed suitable by the concrete producer (Kevern, Wang, Suleiman, & Schaefer, 2005). A significantly higher dosage of air entraining admixture is recommended to accommodate for potentially higher paste content and often increased difficultly entraining air into this type of concrete mixture. Effective air entraining of this paste can only be identified thorough petrographic evaluation.

The size of coarse aggregate used in a pervious concrete mix will alter the appearance of the pavement and the void structure. Use of 13.2 mm aggregate or less is recommended. Larger aggregates can create the same void content; however the voids will be larger in size and have fewer contact points. The reduction in contact between aggregates reduces the opportunity for strength development and long term durability. In addition, the flexural strength of a specimen cut from the test slab should be in the range of 1.5 to 4 MPa.

The aggregates used in the mix design should meet the physical properties requirements for aggregates typically used in concrete pavements in the surrounding area.

The mix design intended for use should be trialed in a test pad using the planned construction method. Cores should be extracted from the test pad to indicate the anticipated material characteristics of the hardened concrete. Cores should be accepted based on void content only. During construction, quality assurance testing should include density. Acceptance should not solely be based on compressive strength and it may not be included in some projects. Current test methods of pervious concrete pavement are discussed later in the guide.

CONSTRUCTION

The efforts put in during the construction phase of a pervious concrete pavement project will be reflected in the performance of the material. It is very difficult to correct errors made during construction later in the lifetime of the pavement. As pervious concrete is unique from conventional concrete it is essential that the construction crew be familiar and educated about the material. Over compaction can result in sealing of the surface which eliminates the permeability characteristics. Slight compaction of the surface is necessary to develop strength in the material and minimize future ravelling. In addition, the mix should be handled minimally and efficiently in order to achieve optimum quality (NRMCA, 2010). The surface of the pervious concrete should not be finished. The points noted previously are examples of the differences between pervious concrete pavement and impermeable pavement and reinforce the importance of training for crew members. Construction of pervious concrete pavement can be achieved with routine, available equipment and can be successful if the crew understands the material being placed.

Constructability or feasibility of construction of the designed pervious concrete pavement needs to be considered in the design phase and again in the construction phase. One of the primary challenges in constructing pervious concrete pavement arises from the open structure of the base material. As discussed earlier, since the base is intended to store water it has numerous voids which may decrease the stability of the material for loading with construction equipment. This challenge can be over come by using a stabilized base layer, a choker course or a conveyor belt which would eliminate the need to drive on the base layer.

Staging of a pervious concrete pavement project involves both the construction of the pervious concrete itself as well as other construction that maybe occurring in adjacent areas. Staging of the pervious concrete pavement construction primarily needs to consider the concrete surface layer. If more than one lane of pervious concrete pavement is being placed then it is important to allow for sufficient time for the edges of the pervious concrete pavement poured earlier to cure before placing adjacent material. If the edges are not given sufficient time to cure then distresses, primarily ravelling will develop in these locations. At Site 1 initial pervious concrete pavement was placed using metal forms. The forms were removed the following day and pervious concrete was placed. No ravelling has developed at the construction joints.

A test pad is often required prior to the construction of the pervious concrete pavement. Many provincial and state specifications require that a test pad be placed prior to the construction of the entire project to verify material characteristics and effectiveness of the planned construction methods. A test pad provides the contractor an opportunity to evaluate if the planned staging will be feasible.

Conditions

The forecasted weather conditions should be reviewed prior to placement of pervious concrete pavement. The OPSS 356 requirements are that the air temperature remain below 28 °C during the placement of pervious concrete pavement and that no pervious concrete pavement be placed in cold weather. Pervious concrete pavement is not to be placed against anything (such as granular base material) that is below 5 °C. Within the OPSS 356 document it is also highlighted that pervious concrete pavement is not to be placed while it is raining (OPSS, 2010). Windy conditions can lead to the pervious concrete pavement drying out prematurely if it is not protected. Placement of pervious concrete pavement should be avoided on frozen material or in winter conditions. At this time methods used for cold weather placement of impermeable concrete have not been trialed with pervious concrete pavement.

Pervious concrete pavement can be hauled in an agitated or non agitated truck. If hauling in an agitated truck then it should be placed within 90 minutes of mixing. If hauled in a non agitated truck then it should be placed as efficiently as possible. Use of a non agitated truck is only recommended when the pervious concrete can be placed efficiently after mixing, such as on site or following a short travel time.

Method

Construction of a pervious concrete pavement involves the following steps:

1. Preparation of the subgrade;
2. Placement of the reservoir base layer;
3. Placement of the pervious concrete;
4. Compaction of the pervious concrete; and
5. Curing of the pervious concrete.

The subgrade should be evenly compacted during construction. It is important to ensure that the permeability of the subgrade is not lost during construction. Areas with organic, soft and/or inconsistent material should be removed. The reservoir base layer should be placed consistently throughout the site.

Pervious concrete can be placed either directly from the chute of the concrete truck, from a conveyor, from a non-agitated truck, front end loader or other available means. Pervious concrete should be drop as close to the surface a possible to avoid separation and segregation of the mix and within 1.5 m of its final location (OPSS, 2010). The pervious concrete should be handled and moved as little as possible to minimize disturbance to the mix. The intended placement method should be used in the trial placement. There are a variety of methods that can be used effectively, depending on the specific project. The most common options are from the chute of the concrete truck, conveyor or through a paver (asphalt).

Compaction of the pervious concrete layer should be carried out immediately following placement. Compaction promotes contact between the aggregates, therefore, providing more opportunity for strength development in the pervious concrete layer. Compaction can be achieved with a variety of methods: striking off the surface with a wooden board; vibrating roller; manually operated roller; vibrating screed; vibratory plate compactor; and asphalt paver. A combination of the equipment noted above can also be used. Similar to the placement, it is important to use the intended compaction method during the construction of the trial pad, in order to evaluate the effectiveness and the end result. In addition to identifying a suitable compaction method based on mix, pavement structure and site layout, it is important to know the required extent or repetitions required to achieve the desired compaction. Ultimately the compaction required in the field should be linked to the desired void content established in the laboratory.

Curing

The same curing method was used throughout the research at CPATT and when planned prior to construction was very effective. The curing method used in the research and recommended is to place a plastic sheet on the pervious concrete efficiently after any compaction and joint forming has been completed. The plastic sheeting should be left on the pervious concrete for at least seven days and only pedestrian traffic allowed on the pervious concrete surface during this time. Pedestrian traffic if possible should be limited and only occur as necessary, likely during the construction of adjacent pavement.

Keeping the plastic sheeting secured on the pervious concrete surface proved to be a challenge during the construction of the field sites. The appropriate method for keeping it secured is highly dependent on the particular site conditions. In some cases the sheeting was secured to the wood forms using staples which was effective. When the wood forms were removed for adjacent construction they would be placed on the plastic sheeting to hold it in place. Overall the sheeting should be secured as it is important that the plastic remain in place for at least seven days. Wind may get under the plastic and lift it off the pervious concrete. Therefore the condition of plastic should be monitored throughout the seven days if possible. Curing is deemed to be a critical aspect in the construction of pervious concrete pavement should be planned in advance of the placement of the pavement.

Joints

The use of joints in pervious concrete pavements is optional. If joints are not included it is anticipated that limited cracking will occur although they will not likely be very visible and will not impact the serviceability of the pavement. limited cracking was observed at Site 4 where no joints were constructed. The joints provide a location for cracks to develop in the pervious concrete pavement if used. If joints are used they can be formed or saw cut. Joints that are formed should be done so using a joint former, also referenced as a “pizza cutter”. Joints should be formed within minutes of the pervious concrete being placed. If joints are saw cut this should be done within 24 hours of the placement of the pervious concrete; however, cutting joints can increase the risk of ravelling

Construction joints are joint locations that occur for constructability purposes. They can occur at the location where work ends on one day and is resumed the next day or when the pervious concrete is constructed in adjacent sections, either in one day or over several days. In some cases no construction joints are needed within a pervious concrete project. The number of passes required to place the pervious concrete is dependent on the width of the area being constructed and the equipment being used in the construction. In the case when only one pass is required to construct the pervious concrete then a joint is formed between the pervious concrete and the adjacent materials, which could be asphalt, concrete curb, concrete pavement or other materials. Pervious concrete can be constructed with the adjacent material being soil with vegetation, such as grass provided consideration has been given to avoid infiltration/contamination of adjacent fine materials (e.g. soils, etc.) into the pervious pavement. Construction joints can be handled using various methods with the key factors for consideration including:

- Complete construction method is carried out to the end of the paved section;
- Pervious concrete pavement edges are provided adequate support to maintain shape during curing; and
- Sufficient time is allowed for pervious concrete to cure and gain strength before being loaded or disturbed by adjacent construction.

Testing

Specifications and test procedures are currently available specifically for pervious concrete pavement. These specifications and test procedures should be used whenever possible. Conventional concrete test procedures have not been shown to represent the pervious concrete constructed in the field. If conventional concrete test procedures are used, the results should be considered with caution, remembering that pervious concrete is different than conventional concrete. Currently there is no method for casting pervious concrete cylinders that reflect the material placed in the field. Drilling of core samples is therefore the most accurate and reliable method of sampling pervious concrete. Further details regarding current test methods for pervious concrete pavement are provided in the guide.

MAINTENANCE

Maintenance for warm and cold weather is discussed in the guide. A limited discussion is provided regarding maintaining surface distresses should they develop. To date there has been minimal work carried out regarding surface distresses in pervious concrete and hence only initial discussion is included. Given that pervious concrete is a concrete material, the anticipation is that when designed and constructed well, a life cycle with little surface distress development is possible. Warm weather maintenance, debris removal, is necessary throughout the lifetime of a pervious concrete pavement. The type of equipment and frequency required for warm weather maintenance is dependent on the site and the surrounding conditions. Throughout Canada the winter season varies and therefore the amount of maintenance required in the winter or cold weather is anticipated to vary. However, it is assumed that some conventional maintenance will be required during the winter season if the pervious concrete pavement is in use, such as removal of snow from the surface.

Warm Weather Maintenance

Warm weather or permeability renewal maintenance is intended to remove debris from voids in the pervious concrete pavement. The required frequency for this maintenance is dependent on the site. Aspects of the site such as users of the pavement, mix design of the pavement, surrounding conditions and climate will influence the required frequency of maintenance. It is recommended that maintenance be performed from a pro-active perspective, at least initially following construction. By performing the maintenance more often it will avoid debris accumulating that is challenging to remove.

At minimum maintenance should be carried out in the fall and spring seasons. During the fall, maintenance will remove debris that has accumulated and eliminate areas where water can be trapped and freeze in cold weather. Maintenance in the spring will remove material that was placed on the surface throughout the winter, as winter maintenance. Various methods can be used for warm weather maintenance. Below is a list of methods. Each method is described further in the guide.

- Sweeping;
- Washing;
- Vacuuming; and
- Blowing.

The environment can improve the permeability of the pavement structure as well. Research has shown that an intense rain storm can clear voids and result in an increase in permeability (Henderson, 2012).

Cold Weather Maintenance

The extent of necessary cold weather or winter maintenance varies across Canada with the changing climate regions. Nonetheless, cold weather maintenance to an extent is required throughout. There are two primary aspects of winter maintenance: snow removal; and maintaining a safe surface.

Snow can be removed from the surface using conventional equipment such as a personal truck mounted snow plow blade, highway grade snow plows or a front end loader. It is important that the operator of the equipment is aware that the pavement is not typical (asphalt or impermeable concrete). The equipment can be operated as normal, however, the height of blade should be monitored to ensure it is not directly scraping the surface. A snow blower, either a manually operated or mounted on a tractor can be used as well. While using either of these types of equipment it is important to ensure that the blades of the blower are not contacting the surface (agitating the aggregate in the pervious concrete pavement). When possible, a rubber blade should be used.

It is recommended that sand or salt be applied to the surface if necessary. Sand can be applied at the rate recommended locally for cold weather use on pavements. The laboratory research carried out at CPATT demonstrated that regular application of salt can negatively impact the performance of the pervious concrete, leading to the development of distresses throughout the concrete layer. Sand has not been found to cause development of surface distresses. It is recommended that whether sand or salt is used for skid resistance on the surface, it be applied only when required (Henderson, 2012).

Distress Maintenance

At this time, minimal work has been carried out regarding the appropriate treatment for surface distress development in pervious concrete pavement. The following comments reflect the current knowledge of pervious concrete pavement performance and available maintenance techniques for various pavements. The distresses noted below have been observed in pervious concrete and maintenance recommendations for each are provided:

- Cracking – A low severity crack should be monitored to evaluate if it widens or leads to ravelling of the surrounding aggregate. Medium and high severity cracks can be sealed using conventional sealant. The crack should be saw cut, creating a reservoir for the sealant. A low viscosity sealant should then be applied. The low viscosity of the sealant will minimize the amount of sealant that fills adjacent voids, if any. The use of the sealant will create a small area with in the pavement surface that is impermeable. Assuming the majority of the surface is still permeable, this is not an issue.
- Sealed surface – Areas of the surface may have become sealed during placement. This can be a result of the characteristics of the mix in this area or the construction method that was used in the

area. Assuming that the surface is only sealed in localized areas, water can drain through adjacent areas and the pavement structure will continue to function sufficiently.

- Ravelling – Ravelling in localized areas that is low in severity should be monitored to ensure it does not expand or worsen. Medium to high severity ravelling in localized areas can be repaired in that area. The area should be saw cut such that it is square and suitable for placement of a patch. The bottom of the area to be patched should be level. A patch can be placed with pervious concrete or conventional impermeable concrete. If impermeable concrete is used, it is important that the patch is sloped to provide positive drainage to the adjacent, permeable areas. If the ravelling is of medium to high severity throughout the site then an overlay can be placed. An overlay using pervious concrete pavement can be constructed. The reason for the development of the ravelling should be identified before proceeding with the overlay. If the ravelling is due to traffic loading then it may be suitable to place a portion of the overlay with impermeable material and the remainder with pervious concrete. The impermeable material can be constructed such that drainage is directed toward the pervious concrete for active drainage.

CONCLUSIONS

The research carried out by the University of Waterloo has shown promising results for the future use of pervious concrete pavement in Canada. The successful aspects of the various field sites, when combined, suggest the ability to effectively plan, design and construct pervious concrete pavement in Canada. From the results generated during the monitoring period of the field sites and the laboratory testing it is anticipated that pervious concrete pavement in Canada can achieve a successful design life when used in a suitable application.

It is recommended that the application of pervious concrete and the geometry of the site be considered during the planning. The objectives of the site should be identified and then an assessment should be carried out regarding the potential debris sources and commitment to maintenance by the owner. Pervious concrete is not suggested for use in industrial applications that have substantial amounts of debris such as concrete plants or stormwater hot spots, such as gas stations, where there is high probably of a contaminant spills. It is important for this planning phase to be a joint effort with stormwater management representatives to ensure that the interests of both parties are achieved.

The pavement structure design should reflect the traffic loading and stormwater requirements. The mix design would be handled by the concrete supplier.

Multiple methods are available for successful construction, as demonstrated in this research. The important considerations include the constructability of the pavement, ensuring some compaction of the surface and being prepared for curing. It is recommended that a test strip be placed ahead of time using the complete system that will be used for the project. This will provide an opportunity to evaluate the effectiveness of the methods as well as the hardened material that is produced.

Maintenance should be considered from a proactive perspective and it is anticipated to be one of the key factors in achieving performance of pervious concrete pavement in Canada. It is apparent though, that if the pavement is not planned, designed and constructed well then maintenance will not change the performance characteristics. At a minimum, maintenance to remove debris from the surface should be performed in the fall and spring seasons.

Owners should be educated about winter maintenance. Snow removal with conventional plowing equipment is deemed to be suitable for pervious concrete pavement. The ideal winter maintenance scenario would involve the removal of snow and allow any remaining ice or snow to melt and drain through the pervious concrete pavement. It is acknowledged that this is not always a suitable alternative. If necessary snow should be removed and if sand is used for winter maintenance, the surface should be cleaned in the spring.

REFERENCES

AASHTO. (2008). Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes M145 - 91. In AASHTO, *AASHTO Standard Specifications* (pp. 145-1 to 145-8). Washington, DC: American Association of State Highway and Transportation Officials.

ACPA. (2006). *Stormwater Management with Pervious Concrete Pavement.* American Concrete Pavement Association Concrete Paving Technology.

ACPA. (2009). *Stormwater Management with Pervious Concrete Pavement.* Skokie, IL: American Concrete Pavement Association.

ACPA, A. (2012). *PerviousPave*. Retrieved July 2012, from American Concrete Pavement Association: http://acpa.org/PerviousPave/

ACPA, A. (2012). *PerviousPave Background, Purpose, Assumptions and Equations.* USA: ACPA.

ASTM. (2010). *C1688/C1688M-10 Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete.* West Conshohocken, PA: American Society for Testing and Materials International.

Beatty, D. (2007). *Report - 2007-04-18 - Drowning Prevention in Young Children.* Perth County: Board of Health.

Bozic, L., Deong, Y., & Fesko, P. (2007, June 22). Stormwater Management Strategy for Calgary. *Innovative Stormwater Management Conference.* Vancouver, BC. Retrieved February 18, 2012, from http://research.ires.ubc.ca/projects/ISM/include/pdfs/Bozic_ISM_June2007.pdf

Bush, E., Cawley, B., Durham, S., MacKenzie, K., Rottman, J., & Thomas, D. (2008). *Specifier's Guide for Pervious Concrete Pavement Design Version 1.2.* Centennial, CO: Colorado Ready Mixed Concrete Association.

Canada Green Building Council, (. (2009). *LEED Canada for New Construction and Major Renovations 2009.* Ottawa: Canada Green Building Council.

Cement Association of Canada. (2011). *Building Sustainable Highways in Canada*. Retrieved February 18, 2012, from Cement Association of Canada: http://www.cement.ca/en/Highways/Building-Sustainable-Highways-in-Canada.html

City of Toronto. (2003). *Wet - Weather Flow Management Master Plan.* Toronto, ON: City of Toronto.

ConcreteNetwork. (2010). *Where Pervious Concrete is Being Used*. Retrieved May 2010, from Concrete Network: www.concretenetwork.com/pervious/being_used.html

Delatte, N., Miller, D., & Mrkajic, A. (2007). *Portland Cement Pervious Concrete Pavement: Field Performance Investigation on Parking Lot and Roadway Pavements, Final Report.* Cleveland, Ohio: Cleveland State University.

Devereauz, S., & Lorant, F. I. (2006). *Stormwater Management Guidelines.* Halifax, NS: Dillion Consulting Ltd.

Drake, J., Bradford, A., Van Seters, T., & MacMillan, G. (2012). *Evaluation of Permeable Pavements in Cold Climates.* Kortright Centre, Vaughan, Ontario: Toronto and Region Conservation Authority.

EPA. (2008). *Effluent Limitations Guidelines and New Source Performance Standards for the Construction and Development Category.* Environmental Protection Agency.

Gilson Company Inc. (2007). *AP-1B Asphalt Field Permeameter Operating Instructions.* Lewis Center, OH: Gilson Company Inc.

Henderson, V. (2012, April 30). *UWSpace: Evaluation of the Performance of Pervious Concrete Pavement in the Canadian Climate.* Retrieved May 31, 2012, from UWSpace: http://hdl.handle.net/10012/6686

Henderson, V., & Tighe, S. L. (2011). Pervious Concrete Pavement - A Sustainable Alternative. *Transportation Research Board Annual Meeting.* Washington, DC.

Heron, M. P., Hoyert, D. L., Murphy, S. L., Xu, J. Q., Kochanek, K. D., & Tejada-Vera, B. (2009). *Deaths: Final Data for 2006, National Vital Statistics Reports.* Hyattsville, MD: National Center for Health Statistics.

Instrotek®, Incorporated. (2011, February). Corelok (R) Operator's Guide. Raleigh, North Carolina, USA.

Kevern, J. (2010). Maintenance and Repair Options for Pervious Concrete. *Low Impact Development 2010: Redefining Water in the City* (pp. 113 - 125). San Francisco, CA: American Society of Civil Engineers.

Kevern, J., Wang, K., Suleiman, M., & Schaefer, V. (2005). Mix Design Development for Pervious Concrete in Cold Climates. *Mid-Continent Transportation Research Symposium.* Ames, IA.

LACDPW, L. (2002). *Development Planning for Storm Water Management.* Los Angeles: Los Angeles County Department of Public Works.

McCain, G. N., & Dewoolkar, M. M. (2010). Porous Concrete Pavements: Mechanical and Hydraulic Properties. *Transportation Research Board Annual Meetings.* Washington, DC.

Montes, F., Valavala, S., & Haselbach, L. (2009). *Test Method for Porosity Measurements of Portland Cement Pervious Concrete.* Mississauga, ON: RMCAO.

MTO MERO. (2012). *Greenpave Green Pavement Design Rating System Version 1.0.* January: Ontario Ministry of Transportation Materials Engineering and Research Office.

NRMCA. (2004). *Freeze-Thaw Resistance of Pervious Concrete.* Silver Spring, Maryland: National Ready Mixed Concrete Association.

NRMCA. (2005). *Pervious Concrete When it Rains it Drains.* Retrieved February 27, 2012, from Green Concrete National Ready Mixed Concrete Association: www.greenconcrete.info

NRMCA. (2010). *Construction*. Retrieved July 13, 2011, from National Ready Mixed Concrete Association Pervious Concrete: http://www.perviouspavement.org/construction.htm

NRMCA. (2010). *Economic Benefits*. Retrieved July 13, 2011, from National Ready Mixed Concrete Association Pervious Concrete: http://www.perviouspavement.org/benefits_economic.htm

NRMCA. (2010). *Hydrological Design Considerations*. Retrieved July 13, 2011, from National Ready Mixed Concrete Association Pervious Concrete: http://www.perviouspavement.org/hydrological_design.htm

OPSS. (2003). *Material Specification for Aggregates - Base, Subbase, Select Subgrade and Backfill material, OPSS 1010.* Ontario Provincial Standard Specifications.

OPSS. (2010). *Construction Specification for Pervious Concrete Pavement for Low-Volume Traffic Applications, OPSS 356.* Ontario Provincial Standard Specifications.

OPSS, O. (2012). Material Specification for Aggregates - Miscellaneous. *Ontario Ministry of Transportation*, OPSS.PROV 1004.

PCA. (2009, July 6). *Heavy Duty Pervious Concrete Breaks the Mold in New Jersey - Executive Report.* Retrieved July 6, 2009, from Portland Cement Associatrion: http://www.cement.org/exec2/07-06-09.htm

PCA. (2012). *Pervious Concrete*. Retrieved February 18, 2012, from Portland Cement Association: http://www.cement.org/tech/cct_con_design_pervious_hydro.asp

PI. (2010, September). *Permeable Pavements*. Retrieved July 2011, from Pavement Interactive: http://pavementinteractive.org/index.php?title=Permeable_Pavements#Porous_Concrete

Pon, B. (2000). *Heat Island Group*. Retrieved May 2010, from High Temperatures: http://eetd.lbl.gov/heatisland/hightemps/

RMCAO. (2009, May). *Pervious Concrete Specifier's Guidelines.* Retrieved February 19, 2012, from Ready Mixed Concrete Association of Ontario: http://www.rmcao.org/sites/default/files/RMCAO%20Pervious%20Concrete%20Specifiers%20Guidelines,%20May%202009.pdf

Roa-Espinosa, A., Norman , J., Wilson, T. B., & Johnson, K. (2003). Predicting the Impact of Urban Development on Stream Temperature Using a Thermal Urban Runoff Model (TURM). *National Conference on Urban Stormwater: Enhancing Programs at the Local Level*, (pp. 369-389). Chicago, IL.

Schaefer, V., Wang, K., Suleiman, M., & Kevern, J. (2006). *Mix Design Development for Pervious Concrete in Cold Weather Climates.* Ames, IA: Center for Transportation Research and Education, Iowa State University.

Schultz, R. B. (2004). *Koppen Climate Classification.* Retrieved February 27, 2012, from Geography 101: http://www.elmhurst.edu/~richs/EC/101/ http://www.elmhurst.edu/~richs/EC/101/KoppenClimateClassification.pdf

SKC. (2007). *Child and Youth: Unitentional Injury: 1994 - 2003 10 Years in Review*. Sick Kids Canada.

Tennis, P. D., Leming, M. L., & Akers, D. J. (2004). *Pervious Concrete Pavements.* Skokie, IL: Portland Cement Association.

Tyner, J. S., Wright, W. C., & Dobbs, P. A. (2009). Increasing exfiltration from pervious concrete and temperature monitoring. *Journal of Environmental Management*, 2636-2641.

UDFCD. (2008). *BMP Monitoring Sites.* Retrieved August 2011, from Urban Drainage and Flood Control District: www.udfcd.org/sw_quality/SQMP.pdf

Walker, J. (2009, December 21). Sustainable Stormwater Management. *Water Canada*.

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

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