Development of Durability Performance Related Test Methods for Pervious Concrete Pavement

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Sustainability has become one of the most important design factors for pavement engineers over the last several years. Much of this focus has been on reducing material costs for pavement infrastructure by using innovative materials into traditional pavement design. Pervious concrete pavement has the ability to offset the typical requirement for stormwater management ponds for large paved areas. It can be considered as an alternative to impervious pavement systems as the open void structure of pervious concrete pavement allows water to infiltrate very quickly through it and join the natural ground water table. As a result, it does not disturb the natural hydrological cycle or increase the demand on the local stormwater management. Besides stormwater management, pervious concrete can also provide environmental and economic benefits such as removing water pollutants, reducing noise pollution, lowering the heat island effect, lowering light demand, and increasing driver safety through improved visibility.

Pervious concrete pavement is receiving more and more interest recently due to the pressure by environmental agencies and environmental acts to reduce the quantity of stormwater runoff from urban areas. The introduction of pervious concrete pavements in cold weather climatic regions, specifically Canada, was driven by their sustainable benefits. However, there has been caution in the pavement industry to use pervious concrete in climates that experience freeze-thaw cycles. Literature shows that there is no dedicated test method to assess the performance of pervious concrete, which is structurally substantially different from conventional concrete pavements. The increased use of pervious concrete in roads, walkways, and parking lots demands improved specifications, performance criteria, and acceptance test methods for evaluating structural performance and durability of this innovative concrete product.

The main objective of this research is to recommend specifications and performance criteria for pervious concrete based on the results of experimental investigations and field experience in Ontario, Canada. Above all, this study attempts to establish test procedures for evaluation of durability and performance of pervious concrete pavement. Initially the test methods available for conventional concrete were performed, the gaps were identified and the test methods were modified. Field samples were also collected and the modified test methods were performed on the field cores to define correlation between the laboratory and the field samples.

Several pervious concrete field sites were constructed by the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, the Cement Association of Canada, and several other industry members from 2007 to 2011. Initial results from this work have been published previously. This research described herein involved continued collection of drainage data from instruments such as the moisture gauge measurements, strain gauge at three sites that are still being monitored. This field/laboratory study provides insight into the longer term drainage performance of pervious concrete pavement. This study has also involved an evaluation of the latest mix design, which has also built upon previous research. In addition new test methods have been evaluated and now that the pervious test sections are more than seven years old, the longer term drainage monitoring has been assessed.

Barriers to implementing this technology are being solved, as the research is assisting designers on the various functional and structural design aspects. In this research, a framework is also developed to identify how pervious concrete can be integrated into low-volume infrastructure for cold climate such as Canada.

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Finally I would like to thank my family. I also would like to thank all my friends from Bangladesh and Canada for their support.

Dedication

This thesis is dedicated to my family; whose support and love have made this a possibility. Special thanks to my husband Kaiser and my son Dayyan, who are my inspiration and provide me with all the support.

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Chapter 1
INTRODUCTION

1.1 Introduction

Sustainability has become one of the most important design factors for pavement engineers over the last decade. As resources become scarcer and pavement costs increase, methods to make pavement infrastructure cost-effective yet durable and more sensitive to the environment, there is an opportunity to provide alternative designs.

Much of this focus has been on reducing material costs for pavement infrastructure, by incorporating recycled materials or using local materials which reduce transportation costs to the construction site and reduce the need to use non-renewable resources such as virgin aggregate. While these may be good solutions, it is important to take a holistic approach to designing pavement infrastructure to ensure that all possible benefits are realized without compromising pavement performance.

One such benefit is in the area of stormwater management. Pervious pavements, such as pervious concrete, have the ability to offset the typical requirement for stormwater management ponds for large paved areas. It can be considered as an alternative to impervious pavement systems as the open void structure of pervious concrete pavement allows water to infiltrate very quickly through it and join the natural ground water table. As a result, it does not disturb the natural hydrological cycle and it reduces the demand on the local stormwater management. This characteristic makes pervious concrete pavement a sustainable alternative and is identified as a Low Impact Development (LID).

The use of pervious concrete in pavements is relatively new in northern climates. However, it has been extensively used in the southern United States for many years (Henderson 2012). Traditionally, pavement structures are designed to be impermeable. Usually, pavement designers explicitly try to keep the water out of the pavement structure. The pavement surface therefore is generally considered to be impervious. The impervious pavement results in an increase in direct runoff and a corresponding decrease in infiltration. With increased urbanization, this has resulted in a significant alteration of the natural water cycle. For example, generally there is 10% runoff, 25% infiltration and 25% deep infiltration into the soil in a situation with natural ground cover. For many urban areas where 75-100% of the surface is impervious, only 10% has shallow infiltration and 5% of the area is deep infiltration (Van Seters 2006). This results in significantly higher runoff than 10% that must require extensive Stormwater Management Practices (SWMP). To reduce the load on stormwater management systems, pervious concrete pavement can be a viable and effective option.

Besides stormwater management, pervious concrete can also provide environmental and economic benefits such as removing water pollutant, reducing noise pollution, heat island effect, lowering light demand compared to asphalt pavement, and increasing drivers' safety. Literature suggests that pervious concrete pavement has a very high water pollutant removal rate (Tennis et al.). Removal of 82% to 95% total suspended solid was also reported (Goede 2009). As water drains directly through pervious concrete, it reduces hydroplaning and glares which ultimately increase driver's safety (Wanielista and Chopra 2007). It reduces road noise by allowing the air between the tire and pavement (Hendrickx 1998). Pervious concrete could also decrease the heat island effect of urban areas by decreasing the temperature above pavement (Henderson 2012). The drained water through pervious concrete could be utilized in water harvesting in the area where pervious concrete is installed (Roa-Espinosa et al. 2003).

Pervious concrete pavement is receiving more and more interest recently due to the pressure by environmental agencies and environmental acts to reduce the quantity of stormwater runoff from urban areas. However, this technology can be improved to ensure a good quality consistent product is achieved in the field. Pervious concrete has certain functional considerations that need to be addressed so that it is durable, especially under typical Ontario conditions. One potential consideration is that it should only be used on low volume roads or where there is limited truck traffic. At the present time, pervious concrete pavement is mostly used in low volume low speed roads, with personal vehicle at a speed 50 km/hour or less (Henderson, 2012). Such examples for its application include:

- Sidewalks

- Parking lots
- Walkways
- Driveways
- Shoulders
- Residential Streets

However, it should be noted that there has been successful usage of pervious concrete in Eastern Canada under heavy track loading (Henderson 2012). In addition, pervious concrete typically has lower flexural strength than conventional concrete. However, given the typical proposed design locations, the relevancy of this performance indicator is questionable. Pervious concrete is also more susceptible to freeze-thaw damage based on its open pore structure and since there is limited long term performance data available, it is difficult to fully define performance criteria and specified acceptance test procedures for pervious concrete. In order to achieve the potential benefits of pervious concrete, it is vital to ensure that the pavement performs well under typical Ontario conditions. The proposed research is intended to recommend specifications and performance criteria for pervious concrete based on the results of experimental investigation and field experience.

1.2 Knowledge Gap

The introduction of pervious concrete into pavements in cold weather climatic regions, specifically Canada, was driven by their sustainable benefits (Henderson and Tighe 2011). However, there has been caution in the pavement industry to use pervious concrete in climates that experience freeze-thaw cycles (NRMCA 2004). The Ministry of Transportation of Ontario (MTO), in addition to other cities and municipalities, have used pervious concrete pavement on carpool parking lots and low volume roads. More interest on using pervious concrete pavements is rapidly growing in the municipal, the conservation, and the sustainable development sectors. The increased use of pervious concrete in roads, walkways, and parking lots demands improved specifications, performance criteria, and acceptance test methods for evaluating structural performance and durability of this innovative concrete product.

There are some standard test methods currently available to determine the density and void content of freshly mixed pervious concrete (ASTM C1688/C1688M), density and void content of harden pervious concrete (ASTM C1754/C1754M), the water infiltration rate of in-place pervious concrete (ASTM C1701/C1701M), and the abrasion/raveling resistance of pervious concrete (ASTM C1747/C1747M). A draft test method for compressive strength testing for pervious concrete is also available to date. However, there is no specific test method and performance criteria/specification available at present to use particularly for determining the durability of pervious concrete. The test methods established for conventional concrete are being used for pervious concrete with or without some modifications to study the structural and durability properties, though pervious concrete is structurally completely different than conventional concrete. The experience has proven that the existing test methods do not appear to be very effective in quantifying the durability performance, such as salt scaling, freeze-thaw resistance, cracking, roughness and raveling potential of pervious concrete. Therefore, there is a lack of confidence in using the conventional concrete test methods for pervious concrete, particularly in cold climatic regions like Canada.

The Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, the Cement Association of Canada (CAC), and other industry leaders partnered to carry out a Canada-wide project to evaluate the performance of pervious concrete pavement in the Canadian climate (Henderson et al. 2009, Henderson and Tighe 2010, Henderson and Tighe 2011, Henderson 2012). The study included the construction of several test sections in partnership with industry members across Canada. In total, five test sites were constructed to study the performance of pervious concrete pavement. In addition, several other previously constructed pavements were reviewed and assessed. The five main test sites were constructed in Georgetown, Ontario; Campbellville, Ontario; Barrie, Ontario; Maple Ridge, British Columbia; and Laval, Quebec. The locations of the test sites are provided in Map in Chapter 6 and 7. The project emphasized several key aspects related to pervious concrete pavement, including mix design (gradation and additives), structural design of the pavement, construction placement, winter maintenance activities, in-service monitoring, and summer maintenance techniques. Research into proper specifications for materials and mixes, performance criteria, and acceptance test methods for pervious concrete still remain in need for the successful application of this concrete for usage in Ontario. This research described herein to examine which test methods should be used to ensure a high quality pervious concrete pavement is believed to be achieved. It is being funded by the Ministry of Transportation Ontario (MTO) under Highway Infrastructure Innovation funding Program (HIIFP).

1.3 Research Objectives

This research project aims to develop acceptance test methods for evaluating performance and durability of pervious concrete. The objectives are as follows:

- To establish performance criteria for pervious concrete pavement tested for compressive and flexural strength, cracking, roughness, raveling, abrasion, permeability, scaling resistance, and freeze-thaw resistance.

- To develop recommendations to form quality assurance acceptance test methods applicable to Ontario conditions

1.4 Research Methodology

The research methodology is presented in Figure 1-1. The first step involved defining the problem and identifying gaps in the current state-of-the-art practice related to pervious concrete pavement test methods with specific interest in clod climate such as Ontario. As this project was funded by MTO and supported by industry partners, several meetings were held to ensure current state of the art practice was reflected in this research. This feedback was useful in establishing the methodology of assessment. This thesis aims to develop the test methods related to performance and durability of pervious concrete pavement. Thus mix design was not taken into consideration in this research. Accordingly, the mix design selected for this research was from one of the well performing pervious sites located in Ontario. Industry partners collaborated with MTO and the research team and donated the material used for this research.

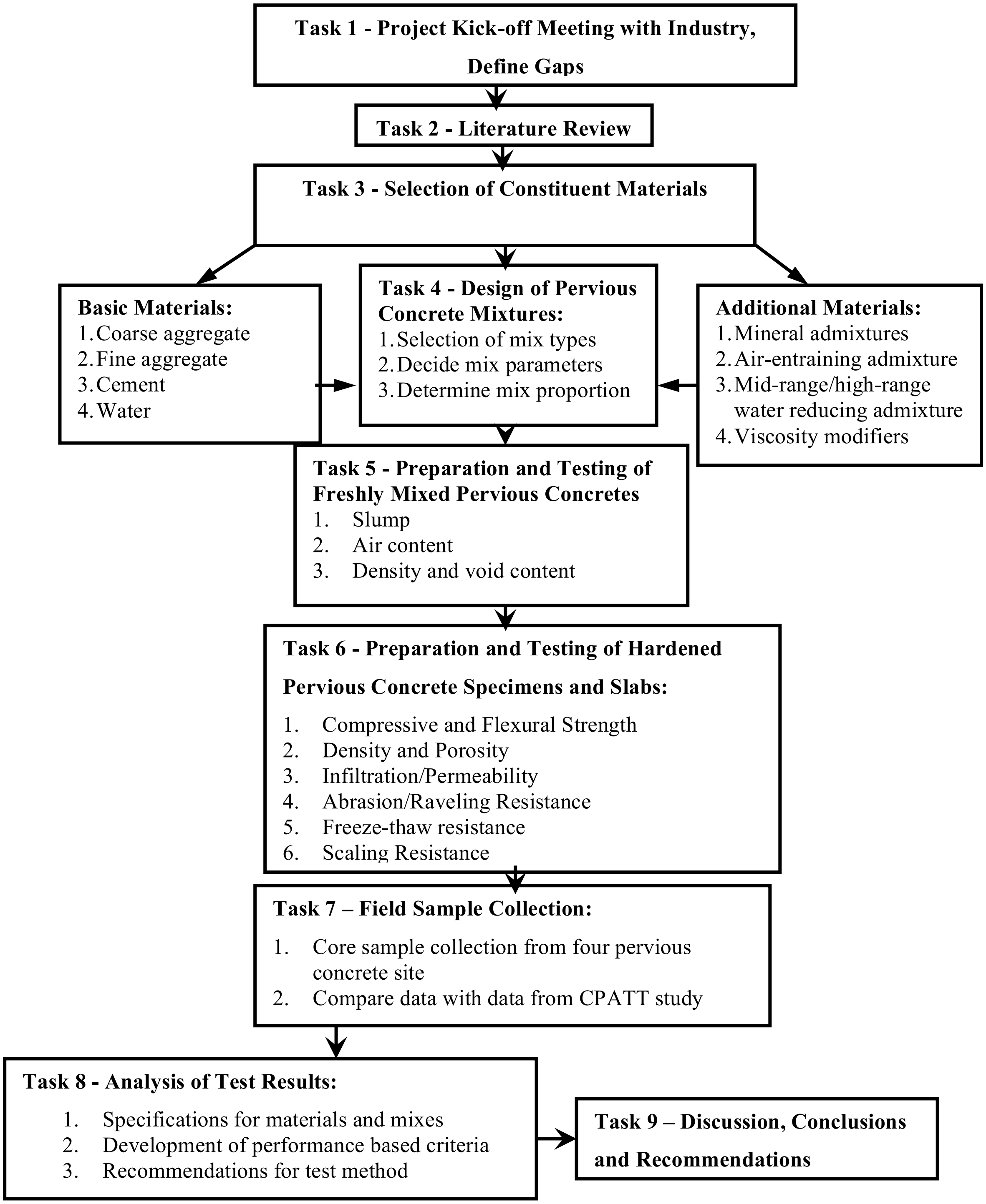


Figure 1-1 Research Methodology

The next stage of the research involved the development of a laboratory experimental design plan. The idea was to perform the test methods available for conventional concrete, identify the existing gaps, modify the test methods as necessary for pervious and correlate the test results by applying the modified test methods on field samples.

Specific tests including compressive strength, flexural strength, permeability, abrasion resistance, freeze thaw resistance, Hamburg wheel rutting and scaling resistance testing were performed in the laboratory and modified. Field samples were collected from several selected pervious sites and tested to define correlation between lab cast samples and cores. Finally, the results and conclusions were summarized and incorporated into this thesis

1.5 Organization of Thesis

This thesis consists of eight chapters. A brief description of each chapter is included below.

Chapter 1 provides an introduction to the topic of pervious concrete pavement as well as the scope, objectives and research methodology of this work are presented.

Chapter 2 provides a compilation of the knowledge available in literature related to this research is presented. This chapter discusses the state of the practice in terms of pervious concrete pavement and demonstrates the need for the research that was performed in this project.

The sources of material for this project are described in Chapter 3. This includes the effect of mix design on pavement; mix design for this project and aggregate description.

Chapter 4 includes the description of the test methods used in lab and field as well as calculation procedure are also discussed. Also the modification and how the modification was made are described.

Chapter 5 presents the test results and the necessary explanation regarding the results.

Chapter 6: The long term drainage behavior of pervious concrete is presented in Chapter 6. The movement of moisture through the pavement structure of the pervious concrete field sites was monitored with instrumentation. The details of instrumentation, data collection, rainfall event and functionality measurement is also described.

Chapter 7: The prospect of pervious concrete in low volume roads is discussed. A framework for pervious concrete usage is also presented.

Chapter 8: The conclusions drawn throughout the analysis of data in this project are presented in Chapter 8. Recommendations for future research related to the use of pervious concrete pavement in freeze-thaw climates, specifically Canada, are presented.

Chapter 2

LITERATURE REVIEW

2.1 Pervious Concrete Pavement

2.1.1 Definition

As presented in Figure 2-1, pervious concrete is visibly different than conventional concrete as it has interconnected pores, generally ranging from 15% to 30%, which allows water to drain directly through the structure and infiltrate into the ground water table or can be directed through pipe network to the existing stormwater system.

Figure 2-1 Pervious Concrete Core

2.1.2 Design Layout

To achieve effective long life performance from the pervious concrete pavement, it is important to design in accordance with the site geometry. For successful construction, each layer in the pavement structure, i.e. subgrade, base, reservoir layers and surface should be prepared and materials need to be carefully selected to ensure the design meets all the structural and functional requirements. More details about preparation are described in the following section.

2.1.2.1 Subgrade Layer

The subgrade layer should be constructed to be level and undeviating, in order to provide uniform support. Compaction of the subgrade should be 90%-95% of the Standard Proctor

Maximum Dry Density (SPMDD). Further compaction is not required, as it would reduce the draining capacity of the layer (Bush et al. 2008). Some of the literature suggested that subgrade should not be compacted to an extreme level before placement of coarse aggregate reservoir bed. Generally a cut as opposed to fill is better to take advantage of natural drainage patterns in the subgrade. However, sometimes fill is also needed for leveling and at that time, some compaction approximately 92% of Proctor is sufficient. Subgrades can also be scarified to improve the rate of percolation (Handbook for Pervious Concrete Certification in Greater Kansas City). Geotextile is typically placed on the subgrade soil after compaction is completed (Bush et al., 2008). Although, geotextile is not mandatory and can be used at the designer's discretion (NRMCA, 2004).

The thickness and required support by base layer depends on the strength of subgrade soil and required water storage capacity. The modulus of subgrade reaction (K value) of subgrade material provides the design information on strength and support capacity (Tennis et al., 2004).

2.1.2.2 Base Layer

The main function of the base layer of the pervious concrete pavement is to provide a storage layer for the percolating water and it also provides structural support. The base layer is generally recommended for pervious concrete in a cold climate with frequent freeze thaw cycles (NRMCA, 2004). This layer should be constructed to be uniform. Pervious concrete can be constructed even on the subgrade soil with low permeability. However, the higher the permeability of the subgrade the faster the water drains. To expedite drainage in low permeability subgrade, subdrains can be placed in base layers. This subdrain then assists to the drainage.

As described earlier, geotextile (filter fabric) should be placed on subgrade before placing the base material. The filter fabric keeps fine aggregate away from migrating into the storage layers. Sometimes it is suggested that filter fabric can be placed up and over nearly 610mm to 915mm (2-3 feet), which can control the erosion by holding the soil until the project is completed. The filter fabric can be cut to the edge of the pervious concrete pavement after the soil is secured (Handbook for Pervious Concrete Certification in Greater Kansas City). To provide a construction platform, sometimes a crushed stone or choker coarse can be used but it is not also mandatory, it depends on site characteristics (NRMCA, 2004). The granular base should be rolled (Bush et al., 2008).

Handbook for Pervious Concrete suggests to follow standard specification of concrete aggregate (ASTM C33) for the material specification of base layer. The specification describes how the material should be capable of having a minimum void of 38% by weight measured in accordance with Standard test methods for bulk density and air voids (ASTM C29). Dirt free cleaned rock with less than 2% retained on the sieve# 100 (0.15mm) and a maximum top size of 38mm can be used (Handbook for Pervious Concrete Certification in Greater Kansas City). NRMCA (2004) recommended AASHTO No. 67 (19mm -4.75mm) for the pervious concrete base layer, which can render 40% porosity. The Urban Drainage and Flood Control District (UDFCD) in Colorado suggested using AASHTO No. 3 (50mm-25mm) or AASHTO No. 4 (37.5mm -19mm) stone for the base layer, and 30% porosity can be anticipated (UDFCD, 2008). The New Jersey Stormwater Best Management Practice Manual suggested AASHTO No. 2 (63.5mm -38mm) is suitable for the base layer (New Jersey Stormwater BMP Manual, 2004). Other literature suggests that open graded clean stone with 20%-40% void space is required in the base layer of pervious concrete pavement (PI, 2010; ACPA, 2006; NRMCA, Hydrological Design Considerations, 2010). The summary of this study is provided in Table 2-1.

Table 2-1 Base Layer Material By Different Agency

Agency	*Base Layer Material*
Greater Kansas City Handbook	Rock with less than 2% is retained on the sieve# 100 (0.15mm) and a maximum Top size of 38mm
NRMCA	AASHTO No. 67 (19mm -4.75mm)
UDFCD	AASHTO No. 3 (50mm-25mm), AASHTO No. 4 (37.5mm -19mm)
The New Jersey Manual	AASHTO No. 2 (63.5mm -38mm)

The thickness of the base layer depends on the hydrological condition of the site and for that a true stormwater evaluation is also required for that design. The material should be placed and lightly compacted with equipment. At the time of pervious concrete placement, the base layer should be made wet to ensure that no water from the pervious concrete layer goes down to the base layer. Generally, water spraying is used to make the base layer moist, immediately prior to the pervious concrete placement (Handbook for Pervious Concrete Certification in Greater Kansas City).

2.1.2.3 Pervious Layer Thickness

The typical thickness of pervious concrete pavement is 150mm for parking lot areas with minimal truckload. For residential streets 200 mm of pervious concrete layer is recommended (Handbook for Pervious Concrete Certification in Greater Kansas City). The RMCAO also suggests a minimum pervious concrete layer thickness of 150 mm (RMCAO, 2009). Using the American Concrete Pavement Association (ACPA) Streetpave program concrete pavement design fatigue curves and assuming that pervious concrete had a flexural strength of 2.1 MPa to 2.8 MPa, it was proved that 150mm thick pervious concrete pavement is roughly equal to 100mm of conventional concrete pavement (Delatte & Cleary, 2006). A typical cross section of pervious concrete pavement is presented in the Figure 2-2

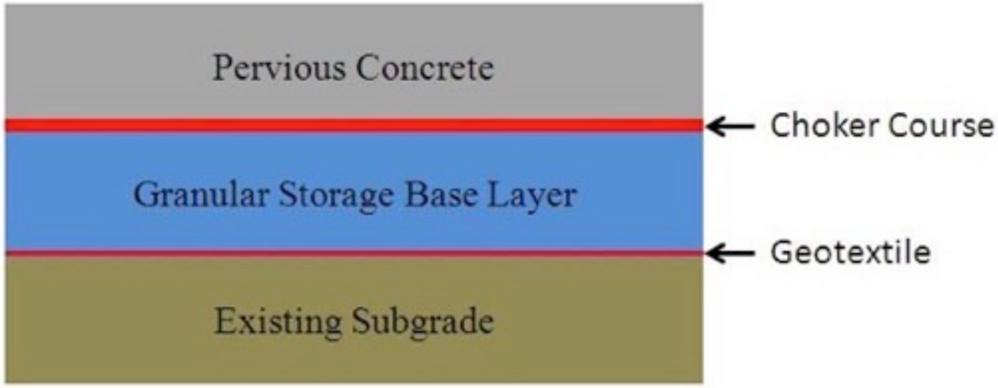


Figure 2-2 Typical Cross section of Pervious Concrete Pavement (Henderson, 2012)

2.2 Benefits of Pervious Concrete Pavement

There are many benefits associated with pervious concrete pavement. Some important ones are described in the following section.

2.2.1 Stormwater management

As pervious concrete pavement has a high drainage capability, it imposes the smallest impact on natural ground water level. Pervious concrete pavement is recognized as a Best Management Practice (BMP) for stormwater management by the United States Environment Protection Agency (Rhead, 2012). It eliminates the need of other stormwater management system (Lake Superior- Stormwater management- Pervious Pavement; Pervious Concrete Pavement- Burns and Sons Concrete Inc, 2006-07). It is reported that 70% to 80% of annual rainfall can percolate through the pervious concrete pavement towards the ground water recharge (ACPA, 2006). Wanielista et. al, (2007) in "Hydraulic Performance Assessment of Pervious Concrete Pavements for Stormwater Management Credit" reported that PCP allows water to infiltrate at a high rate typically 2.5m to 5m per hour whereas the underlying soils will infiltrate water at a lower rate of 1 to 2 orders of magnitude lower.

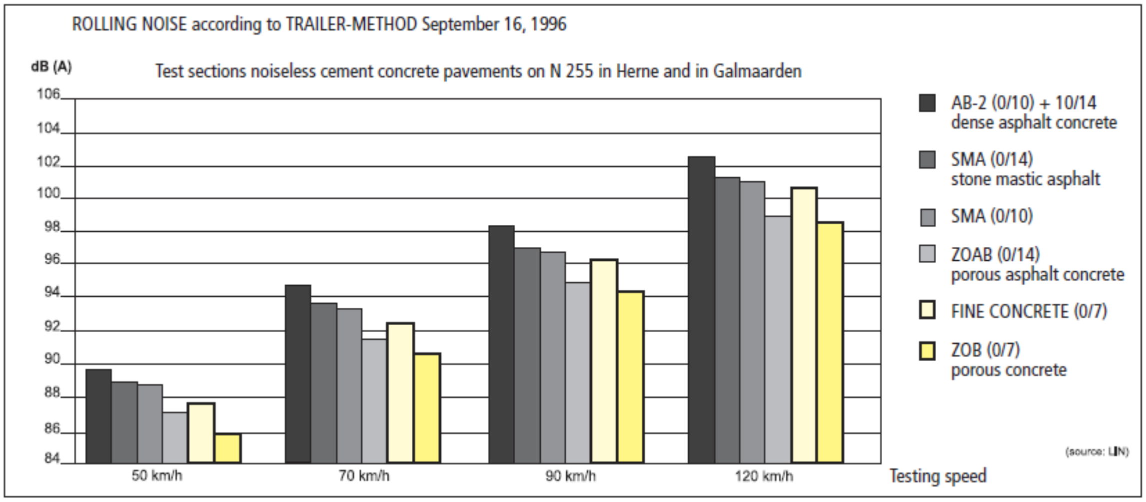
Two requirements by The United States Environmental Protection Agency (USEPA) in the recent development of the National Pollutant Discharge Elimination System (NPDES) are that private and public landowners need to reduce the amount of stormwater runoff on their property. In addition contaminants in the runoff water must be reduced to near pre-development levels. Detention ponds and vegetative buffers can achieve these reductions; however, pervious concrete pavement has also been recognized as an effective tool in reducing stormwater runoff and initially treating stormwater (Henderson, 2012).

2.2.2 Water filtration

Many groups have evaluated the ability of pervious concrete pavement to remove particulate from water that moves through the pavement structure. In essence, the pavement acts as a filter. Pollutants that would otherwise remain in runoff and contaminate groundwater have been shown to be removed during filtering through the voids in a pervious concrete pavement (Henderson, 2012). It effectively traps the dissolved heavy metal in the runoff (Calkins et al., 2010). Concentration reduction was found for the total suspended solids (92%), total lead (91%), total copper (47%) and the total zinc (75%) (Barrett et al. 2006). Thus pervious concrete pavement can potentially improve the overall water quality by reducing the amount of pollutant-carrying runoff as well as reducing the negative effects of hydrocarbon-based material such as grease, oil etc. CTC & Associates LLC, (2012) reported the removal efficiencies of pervious concrete pavement as 85-95% of sediments, 65-85% total Phosphorous, 80-85% total Nitrogen, 30% of Nitrate (N) and 98% of metal removal of the runoff. For Zinc, Lead and Chemical Oxygen Demand (COD), high removal rate was also reported. Generally the concrete contains the contaminants, then it is evaporated by the sunlight and the remaining carbon is absorbed by the plants and fungus (Charger Enterprises Inc, 2010). However if the pavement is not properly designed and the amount of pollutants is more than the soil can process, then the ground water can become polluted and unhygienic (Calkins et al., 2010).

2.2.3 Noise Reduction

As pervious concrete pavement has a porous structure with 15 to 25% of pores, it allows the sound waves to pass through and dissipate (Neithalath et al., 2005). These attributes can improve the quality of life for the local community (Henderson, 2012). The results of an experiment conducted in Belgium, taken directly from Hendrickx (1998), presented in Figure 2-3, show that pervious concrete produced the lowest decibel levels of all the pavements at all four traffic speeds tested.



(source: LIN)

Figure 2-3 Road Noise of Different Pavements (Hendrickx, 1998)

2.2.4 Heat Control

Other benefits of pervious concrete pavement include minimizing heat islands and increased reflectivity. The main reason of these benefits is attributed to the light grey colour of concrete, whereas the asphalt pavement 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 (Henderson, 2012). Another research paper reported that in hot weather conditions, conventional paving materials can reach 50°C to 65°C and transmit excess heat to the air above them as well as heat stormwater as it drains across the pavement structure. Porous parking lots have been shown to lower surface temperature and it allows unheated water to infiltrate directly to the ground water table minimizing the impact on aquatic ecosystem (Rhead, 2012). Also, the urban heat island effect impacts humans and is a great concern to communities and cities. Reduction of urban heat island effect is a great benefit to the environment and economy.

2.2.5 Night Light Requirement

Pervious concrete pavement has a lighter coloured surface which reflects more light and is brighter during the night. It offers reduced requirement of night light and has been shown to reduce the lighting requirement by 30% with light coloured permeable pavement (Cement Association of Canada, 2011).

2.2.6 Economic Benefit

The basic installation cost for conventional concrete is $34 - $45 per square meters and that for pervious concrete is $45 - $55 per square meters (CTC, 2012). Though the installation cost is slightly higher, it has the potential to exhibits a low life cycle cost depending on future maintenance costs (Henderson, 2012). Pervious concrete that is well designed and constructed properly should also exhibit similar life cycle performance as conventional concrete pavement (NRMCA, 2011). Again by using pervious concrete pavement, the requirement of stormwater retention ponds or infrastructure such as pipe network is eliminated (Rhead, 2012; Henderson, 2012). It also reduces property space requirements for the installation of stormwater ponds and thus reduces the probability of flooding (Rhead, 2012).

In the case of both private and commercial properties, pervious concrete can be used for water harvesting, which reduces the water demand. As water can infiltrate easily through pervious concrete pavement, it ensures that surrounding vegetation, such as gardens and lawns receive natural moisture. It can also limit the expense of watering the vegetation (Henderson, 2012).

As noted earlier, it can assist with heat control of porous pavement by cooling the surrounding area. The light colour of concrete also reduces the amount of lighting infrastructure required to create the desired brightness of parking lots and paths during evening and night use. The light colour of pervious concrete pavement is also expected to provide a similar benefit (Henderson, 2012; NRMCA 2010).

2.3 Major Challenges in Canada

Cold climates present various extra challenges including proper site design, appropriate mix design and complete compliance by involved parties to use educated staff for construction for pervious concrete pavement.

As pervious concrete pavement offers very high drainage capabilities, it should not be used to industry areas such as commercial nurseries, automobile recycling facilities, gas stations and outdoor liquid container storage areas, etc. These types of areas can create runoff with a high percentage of contaminants, which results in pollution of ground water (ACPA, 2006).

As freeze thaw cycles are frequent in Canada, precautions should be taken to avoid severe distresses such as spalling, cracking and ravelling. The following suggestions have been proposed in literature to avoid failures of pervious concrete pavement when used in freeze-thaw climates (Henderson, 2012; NRMCA, Freeze thaw Resistance of Pervious Concrete, 2004).

- Use of air entrainment in the mix design

- Use of latex in the mix design
- Use of fine aggregate in the mix design
- Use of a high void content granular reservoir base layer (clear stone)
- Ensure that the groundwater table is a minimum of one m from the bottom of the pervious concrete layer

2.4 Performance in Canadian Climate

Durability of pervious concrete exposed to freeze thaw cycles is one of the major concerns of its usage in Canada. However, literature of work being carried out in the Northern United States and Canada, shows that with proper design, pervious concrete can provide good performance (Henderson, 2012, Kevern et al, 2008).

Based on a large field site study in Canada, the most common problems that were observed were slight (80%-100%) to moderate ravelling (10%-20%). Very severe ravelling was observed in less than 10%. About 20% to 100% moderate joint raveling was found in some cases. In one site, paste loss problem was detected to an extent of 80% to 100%. Less than 10% surface abrasion was found. All of these data were collected five years after construction. Very few cracks were found in this age of pavement. Some other problems such as fractured aggregate, cracks with raveling and potholes were also found but to a very slight extend (Henderson, 2012).

Laboratory freeze thaw cycles were replicated by using the walk-in freezer and samples were placed there for several years of accelerated freeze-thaw cycling to monitor the effect of each. The laboratory study included accelerated testing such that samples which were exposed to five to eight years of freeze-thaw climatic conditions. On average, there are 50 freeze thaw cycles in Canada per year (E. Ho and W. A. Gough ,2006), so the samples had undergone 400 freeze thaw cycles to replicate eight years of freeze thaw condition. From the field and lab results, it was concluded that pervious concrete pavement in Canada can achieve a design life of 15 years, when used in a suitable application (Henderson, 2012). Pervious concrete pavement should be maintained well to perform properly and to achieve its expected life in Canada.

Kevrn et al. (2008) reported the effect of coarse aggregate on freeze thaw durability of pervious concrete pavement. In that study, seventeen different coarse aggregate samples from the United States and Canada were used. The majority of the aggregate fell into three main types: crushed siliceous granite; crushed or natural siliceous river gravel; and crushed limestone. From the results it was concluded that with an additional 5% to 7% of fine aggregate added to the coarse aggregate, gradation improves the mixture producing the greatest strength and durability responses (Kevern 2008; Schaefer et al. 2006). Granite or highly durable river gravel showed the best resistance against freeze thaw cycles. The following conclusions can be drawn from the literature:

- Aggregate absorption has the greatest effect on the freeze-thaw durability of pervious concrete. The absorption for the mixtures with acceptable freeze-thaw durability is recommended less than 2.5%, (with an average of 0.8%).
- Mixtures that contained angular aggregate tended to have porosity greater than the Design Void Content (DVC) compared to rounded or semi-angular aggregate.
- The freeze-thaw durability results showed that the concrete mixtures had a durability factor of >37%, as expressed by the relative dynamic modulus (RDM) value, generally had a mass remaining >95% at the end of the freeze-thaw test. When RDM ≥60% is used as a criterion, concrete weight remaining varied from 85% to 95%.
- Aggregate for high durability mixtures (i.e. heavy traffic loading or hard wet freeze environments) may need to have relative density (specific gravity) greater than 2.5, absorption less than 2.5%, abrasion mass loss less than 15%.

Generally, air entrainment improves compaction and freeze thaw durability of pervious concrete as noted in Kevern et al. (2008). Durability can also be improved by optimizing the ratio of cement to aggregate as well as adding fine aggregate and fibres. Increasing water to cement ratio to 0.35 -0.4 improves workability and consequently density and it is found that durability increases with an increase of density of the mixture. Binary mixtures including various replacement rates of fly ash and silica fume showed decreased freeze-thaw durability with replacement rate, while ternary mixtures including slag improved tensile strength and durability. Latex-based admixtures improved workability and strength, but had poor freeze thaw resistance (Kevern 2008).

2.5 Winter Maintenance

For winter maintenance special care should be taken for pervious concrete pavement. Sand should not be used as a de-icing material, as it may result in clogging the pavement structure. Pressure washing and vacuuming are effective maintenance technologies for restoring permeability (ACPA, 2006). Pressure washing can dislodge pollutants to the ground water; so vacuum sweeping is a better option (Wanielista et al., 2007). Literature suggests that for snow removal, plastic snowplow blade should be used rather than a conventional metal highway grade snow plow. Removal of snow with a metal blade can, in some cases, cause abrasion to the pavement surface or accelerates and increase ravelling (Henderson, Banfield, Bergsma, & Malleck, 2008).

2.6 State of Art Review of the Test Methods

This section outlines the state-of-the-art test methods applied to pervious concrete pavement to date in four categories: aggregate testing, fresh concrete testing, structural testing, and durability performance testing.

2.6.1 Aggregate Testing and Casting

Prior to preparing test samples, the first step is to test the quality of the aggregate. Aggregate size analysis (ASTM C33), determination of absorption and relative density (ASTM C127), bulk density (ASTM C29), and aggregate abrasion resistance (ASTM D6928) are the main initial tests performed. To date, all the tests available are for conventional concrete, and this creates a number of issues.

As many of these tests involve rodding or tamping, more care should be taken with pervious concrete, as over rodding can reduce the void content. This can lead to unrealistic results being obtained from the testing.

Abrasion resistance testing requires use of a Micro-Deval device, in which stainless steel balls rotate with the aggregate. As noted earlier, pervious concrete pavement contains single sized and comparatively larger coarse aggregate, so dropping steel balls increases the probability of breaking the aggregate rapidly compared to a graded sample. This, in turn, could result in lower abrasion values from testing due to the biasing of the aggregate size. An image demonstrating the before and after condition of conventional concrete aggregate subjected to Micro-Deval abrasion testing is shown in Figure 2-4.

Figure 2-4 Aggregate particles before and after Micro-Deval test (Pavement Interactive, 2011)

For casting samples, more care should be taken for pervious concrete as typically a number of admixtures are used to achieve the desired performance. Adding admixtures has been taken in consideration according to making and curing of concrete test specimen (ASTM C192), but in the case of pervious concrete pavement multiple admixtures are often used, making the procedure more complicated. As a result, a more specific casting procedure is required for pervious concrete pavement.

In addition, property comparisons between cast and cored samples have demonstrated that casting methods, which involve rodding or temping, can produce void contents that do not consistently match in-situ compaction. This is demonstrated in Figure 2-5, which shows cast and cored samples from the same pervious concrete mix and the correlating compressive strength.

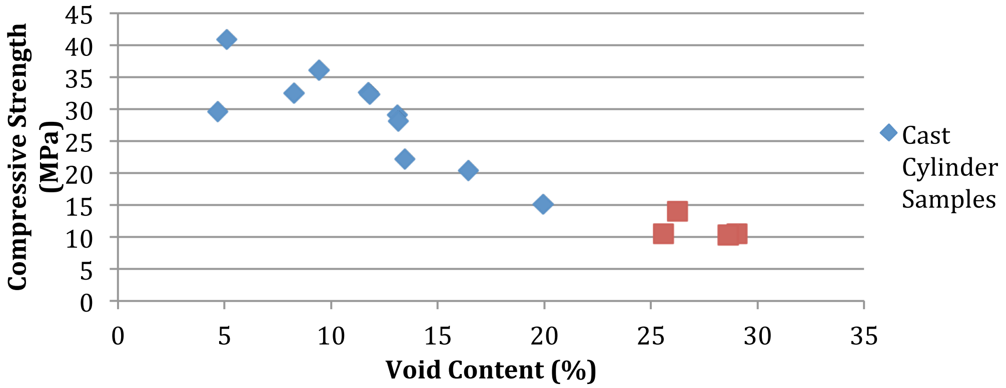


Figure 2-5 Compressive strength versus void content of cast and cored samples (Chai, 2011)

2.6.2 Fresh Concrete Testing

Slump, void content, and density are the main factors assessed during fresh concrete testing for concrete pavements, so these are also typically performed on pervious concrete pavements.

2.6.2.1 Slump Test

Slump testing is performed in accordance with the conventional concrete test method, "Slump and slump flow of Concrete" (CSA A23.2-5C, 2009). When performing it for pervious concrete, typically the same methodology is followed: placement of mix in the cone, number of layers in concrete placement, and rodding process for compaction. A sample tested for slump is shown in Figure 2-6.

Figure 2-6 Pervious concrete slump testing (Henderson, 2012)

As pervious concrete is structurally different from conventional concrete, a different procedure should be established for this test. Less compaction should be applied, as too much compaction decreases void content substantially and provides unrealistic results. Slump for pervious concrete is generally zero or very low (Henderson, 2012), and no range has been found from the literature.

2.6.2.2 Density and Void content for Fresh Mix

Recently a specific test method for density testing, ASTM C1688 Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete has been developed. Previously, when this method was not available and CSA A23.2-4C was used for air content measurement and CSA A23.2-6C was used for density measurement of fresh concrete (Henderson, 2012).

This new method ASTM C1688, which is specifically for pervious concrete, provides guidance in preparing pervious samples for testing. It is suggested to fill the mold in two layers and a Proctor hammer should be used for compaction of mix; 20 drops is suggested in each layer. After that, the weight of the mold should be taken and the density and void content should be calculated according to the specified equations.

2.6.3 Structural Performance Tests

There are many types of tests necessary to confirm the structural performance of pervious concrete such as compressive strength testing, flexural strength testing, permeability measurement, and void content in harden concrete.

2.6.3.1 Compressive Strength Testing

The test methods for compressive strength of conventional concrete, CSA 23.2-9C and ASTM C39, are also generally applied for pervious concrete pavement as shown by Henderson (2012) and Kevern (2008). A pervious concrete sample undergoing compressive testing is demonstrated in Figure 2-7.

Figure 2-7 Pervious concrete sample undergoing compressive strength testing

CSA A23.2-3C describes the preparation of concrete sample for the compressive and flexural strength testing. As strength is dependent on compaction, the compaction procedure should be followed carefully. Compaction of mix with rod is only considered in the available test methods, despite the Proctor hammer showing better results in ASTM 1688.

The end grinder and sulfur capping were used in the study to prepare the end of the sample for compressive testing. (Rizvi et al, 2009). This change can help to make lab samples that replicate field conditions and can provide a significant difference in the ultimate compressive/flexural strength results.

Another study proposed a draft for new compressive strength tests for pervious concrete pavement. It suggests that since the variability of compressive strength testing of pervious concrete pavement is three times higher than that of conventional concrete, the available tests for conventional concrete is not reliable for pervious concrete. This research proposed the use of 4X8 cylinder molds and collars. The mold was proposed to be filled in two layers with mix and 20 hammer drops were suggested per layer. A sulfur or gypsum cap collar should be provided on the second layer. A minimum six days curing time was suggested (Mitchell, 2010).

2.6.3.2 Flexural Strength Testing

For flexural testing, ASTM C78 is the standard for conventional concrete and also used for pervious concrete pavement. Preparation of the samples is similar as for compressive strength (CSA A23.2-3C). Henderson (2012) followed a slightly different method for preparing samples for flexural testing so that the sample characteristic is not different from field conditions. In this case, the first layers were rodded but the last layer was overfilled and then excess mix was struck off to replicate field condition. A flexural strength testing sample is shown in Figure 2-8.

Figure 2-8 Pervious concrete sample undergoing flexural strength testing (Henderson, 2012)

2.6.3.3 Permeability Measurement

Permeability is measured using the ASTM C1701 "Standard Test Method for Infiltration Rate of In Place Pervious Concrete", which was developed in 2009. According to this test method, an infiltration ring should be placed on pervious concrete surface with plumber putty underneath and around the bottom edge of the ring to create a watertight seal. Water should then be poured for prewetting, and once this is completed the test should be started within 2 mins. The test should be stopped when there is no free water on the surface. Infiltration rate is then calculated following the supplied equation.

Previously when no specific method was available, a variety of different methods (i.e. Gilson permeameter, falling head permeability test apparatus) were used for permeability measurement. Without proper specification, it was hard to define and compare which result is most accurate.

2.6.3.4 Density and Void Content for Hardened Concrete

To determine density and void content of hardened pervious concrete a specific test method, ASTM C1754/ C1754M, is available. Previously, when no test method for harden concrete was available, different types of test methods were used to determine the harden density and void content. Literature shows that Corelok® vaccum or T-040R can be used for void content measurement of harden concrete (Henderson, 2012).

The new pervious concrete test method is applicable to both cored and cast samples. First the sample should be weighed and then put in the oven for drying. Two different drying methods are presented here. Drying method A uses lower temperature 38± 3 °C [100 ±5 °F] and drying method B uses higher temperature 110± 5 °C [230 ± 10 °F] to determine the constant dry mass. After reweighing the samples, they should be put back in the oven and the process is repeated until the difference between two subsequent masses is 0.5%. Then density and void content is calculated according to the equation.

2.6.4 Durability Performance Tests

The most important durability tests performed on pervious concrete samples are freeze-thaw resistance, scaling resistance, and abrasion resistance testing.

2.6.4.1 Freeze Thaw Resistance Testing

For freeze thaw testing, the available test method for concrete pavement is covered by ASTM C666. Literature suggests that most of the pervious concrete research has applied this method for freeze thaw evaluation.

Henderson (2012) in her research followed this test method, procedure B, and evaluated the effect by determining the changes in weight of the core after freeze thaw cycles. In this case, the cores were submerged in water and then taken out of the water bath (all the water drained out of the samples) and put in the freezer for the freeze thaw cycle. After every 10 cycles, the cores were taken out of the freezer and weighed to examine the change in mass. This procedure was repeated until specimen failure or until 300 cycles had been completed.

Kevern (2008), followed the ASTM C666, procedure A, in which samples were frozen and thawed under saturated condition. In both research studies, 15% mass loss was considered as the failure.

2.6.4.2 Scaling Resistance Testing

To evaluate the effect of mixture proportioning, maintenance, and surface treatment on resistance to scaling, ASTM C672/C672M is typically followed. To use this method for pervious concrete pavement further research is required as this standard is appropriate for high slump, non air-entrained mixtures. The mix of pervious concrete generally contains two or more admixtures and the slump is very low to zero.

Scaling resistance testing is vital for pervious concrete installed in Canada or countries with a very severe cold climate with frequent freeze thaw cycles. In this climate, winter maintenance such as snow removal and application of salt or sand are mandatory. So, to install pervious concrete successfully in cold climates it is important to build a specific scale resistance testing for pervious concrete pavement.

In the research work by Henderson (2012), sand and salt were applied to pervious concrete pavement as winter maintenance work but it was a part of the freeze thaw test. Also magnesium sulfate and sodium sulfate were applied by Kevern (2008), but it was also in freeze thaw resistance testing.

2.6.4.3 Surface Abrasion Testing

For surface abrasion resistance typically ASTM C944 is used (Kevern, 2008). In that study, a rotary cutter with a speed of 200 rpm was rotated on the surface of the sample and applied a constant force of 98 N (22 lbs) for two minutes, after which mass loss is calculated. This is identical to the process used for conventional concrete testing.

Another study involves a testing with the Los Angeles abrasion testing machine for pervious concrete pavement. Cylindrical samples 100mm X 200mm (4”x8”) are selected for casting. Marshall hammer is proposed to consolidate samples to 100mm height, moisture cap to prevent moisture loss and seven days curing time is proposed. After finishing curing, three cylinders should be put in the LA abrasion machine with no charge for 500 revolutions. Then the percentage of mass loss should be calculated by weighing the retained material on a 25mm sieve (Mitchell, 2010). This proposed test method has recently been adopted as ASTM C 1747/1747M.

2.6.5 Summary of Test Methods

Table 2-1 provides a summary of the test methods outlined in this report.

Table 2-2 Summary of State of the Art of Pervious Concrete Test Methods

Category	*Test*	*Standard Type*		
		Dedicated	**Main**	**Other**
Aggregate	Abrasion Resistance	-	ASTM D6928	-
	Absorption and Relative Density	-	ASTM C127	-
	Aggregate Size	-	ASTM C33	-
	Bulk Density	-	ASTM C29	-
Fresh	Density and Air Voids	ASTM C1688	-	-
	Slump	-	CSA A23.2-5C	-
Structural	Compressive Strength	-	CSA A23.2-9C	ASTM C39
	Density and Air Voids	ASTM C1754	-	CoreLok, T-040R
	Flexural Strength	-	ASTM C78	-
	Permeability	ASTM C1701	-	Gilson Permeameter, Falling Head Permeameter
Durability	Freeze Thaw	-	ASTM C666	-
	Scaling Resistance	-	ASTM C672	-
	Surface Abrasion	ASTM C1747	ASTM C944	-

2.7 Summary: Existing Gaps in the State of Art of the Test Method

The first conclusion drawn from this review is that there is a necessity to establishing dedicated testing standards for pervious concrete materials. The standards that have been developed for fresh and hardened density and air void measurement, hardened permeability, and surface durability are not applicable evaluation tool for pervious concrete pavement. These benefits should be applied to the non-dedicated tests as well by continuing progress with developing new-dedicated standards.

Casting samples to accurately mimic the characteristics of cored or cut samples from field sites can be challenging. This is largely due to the artificial compaction methods applied to the cast samples, and while the Proctor hammer is showing promise as an ideal compaction method, there has been no formal consensus amongst researchers.

Lastly, it was found that there is a need to better understand pervious concrete pavement performance under freeze thaw and scaling conditions. Performance under freeze thaw and winter maintenance can be of great concern to practitioners looking to install pervious concrete in Canada as all Canadian infrastructure is exposed to these phenomenon. Clear test methods should be developed and evaluated to ensure the practicality of pervious concrete application in Canada.

Chapter 3

RESEARCH METHODOLOGY

This chapter describes the research methodology. This research involved both laboratory and fieldwork. Initially, the research started with performing the conventional concrete test methods and then afterward the methods were modified as needed. Integration of the laboratory and fieldwork provides the ability to compare the laboratory casted and field cored samples, and develops a correlation between lab results and field results.

3.1 Effect of Material and Mix Design

3.1.1 Mix Design

Mix design is very important for pervious concrete pavement to provide a void structure that allows water to drain from the surface for sufficient durability and to achieve the desirable design life. Generally, the pervious concrete mix design contains coarse aggregate, cement, water, and limited fine aggregate. Different types of supplementary cementitious material, admixtures and fibres are also added in some cases to get satisfactory performance (Kevern et al., 2005).

3.1.2 Aggregate

Aggregate size has an effect on the distribution of voids as well as on the characteristics of the pavement. Kringos et al. 2011, used x-ray scanning and found that smaller aggregate mix had a higher percentage of voids and mortar than the larger aggregate mix. But the permeability rate was lower in the smaller aggregate mix than the larger aggregate mix. The x-ray scan explained that though there were more voids in the smaller aggregate mix, the voids were smaller and more distributed throughout the sample than in the larger aggregate mix. The larger aggregate mix had larger voids and visibly small contact points between aggregates. Smaller aggregates have more surface area when a volume of space is considered than larger aggregates. Therefore there is more area for mortar coverage and opportunity for contact and bond development (Kringos et al., 2011). Another literature also suggests bigger sized voids are to be found with larger aggregate mix and therefore resulted in increased permeability (Neithalath et al., 2005).

3.1.3 Cement

Cement content affects the durability of pavement. With higher cement content, better performance in freeze-thaw cycling was observed. A water cement ratio of 0.25 showed less freeze-thaw durability in saturated conditions than a ratio of 0.35. It is suspected that with a water cement ratio below 0.30, there may have been excessive drying and shrinkage cracking (Yang Z., 2011).

3.1.4 Admixtures

Concrete admixtures can change the overall durability of the pervious concrete. To examine the effects of admixtures on freeze thaw resistance, concrete was cast with various cement contents, silica fume, polypropylene fibres and both silica fume and fibres. All types of concrete were exposed to saturated freeze-thaw cycling. The best freeze-thaw durability was experienced in the mix with the highest cement content, 5 % silica fume and 1.78 kg/m^3 fibres. It was concluded that the inclusion of fibres and/or silica fumes, increased freeze thaw durability and minimal improvement was found with higher cement content (Yang Z. , 2011).

The effect of high range water reducer and air entrainment on compressive strength and permeability were evaluated by McCain et. al, (2010). The largest compressive strength results were achieved with only high range water reducer and no air entrainment. The mix containing only air entrainment and no high range water reducer had the lowest compressive strength. Permeability results were similar for all three-mix variations. The mix with only high range water reducer had some results that were lower than the other two mixes (McCain & Dewoolkar, 2010).

Another literature suggests the effect of latex and fibres on pervious concrete. Four different mixes were prepared in the lab: control mix; control mix plus latex; control mix plus fibres; and control mix plus latex and fibres. Samples containing latex and those with latex and fibres had the lowest void content. The four mixes were prepared with #7 aggregate (nominal sieve size 12.5 mm to 4.75 mm) and again with #89 aggregate (nominal sieve size 9.5 mm to 1.18 mm). Larger void content results were measured for the mixes with #7 aggregate than those with #89, which is contradict of the result found by Kringos et al., 2011. Samples with latex or fibre and latex had low permeability results. Samples containing #7 aggregate had higher permeability values than those containing #89 aggregate (Wu et. al 2010).

Again, higher compressive strength and splitting tensile strength were found in mixes with #7 aggregate. Samples containing latex and #89 aggregate had higher results than the other mix combinations. The addition of fibres to the mix did not change the results substantially. Samples with #7 aggregate consistently had lower results than those containing # 89 aggregate (Wu et al., 2010).

Again, to assess the ravelling tendency of various pervious concrete mixes, the LA abrasion test was performed on pervious sample following ASTM C 1747/C 1747M. The test involved cycling samples for 300 cycles without the conventional steel balls. In all scenarios, samples containing #89 aggregate performed better than those with #7 aggregate. The addition of latex to the mixes improved the ravelling resistance the most. Including fibres in the mix also improved the performance; however, not as much as latex (Wu et al., 2010).

3.2 Pervious Concrete Mix Design

The mix design for this research was provided by one of the industry partners in partnership with the Ministry of Transportation Ontario. It had been successfully used at on MTO carpool parking lot. The pervious concrete mixture was designed based on the guidelines provided in ACI 522.1-13 (ACI Committee 522, 2013). A water to cement ratio of 0.35 was used in designing the concrete mixes. The design parameters for fresh mix were a minimum void content of 17% and minimum specified compressive strength at 28 days of 15.0 MPa. The admixtures doses were determined based on the range define by the supplier (BASF) and also using trial mixes that were fabricated in the beginning of this research.

The mix design contains:

- General Use Cement
- Slag Cement
- Coarse Aggregate
- Air Entrainment Admixture (AEA)
- High Range Water Reducing Admixture (HRWR)
- Viscosity Modifying Admixture (VMA)
- Set Retarding Admixture (SRA)
- Water/Cement ratio, (W/C) 0.35

The proportion of materials is presented in Table 3-1.

Table 3-1 Pervious Concrete Mix Design Parameters

Material (Weight/m^3)	*Water/Cement ratio (W/C) 0.35*
General Use Cement, Kg	265
Slag Cement, Kg	90
Water, L	124
Coarse Aggregate, Kg	1655
Viscosity Modifying Admixture, ml	1464.8
High Range Water Reducing Admixture, ml	2442.4
Set Retarding Admixture, ml	675
Air Entrainment Admixture, ml	600

The aggregate gradation is provided in Table 3-2 and shown Figure 3-1.

Table 3-2 Aggregate Gradations

Sieve	*Cumulative Weight Retained*	*Individual % Retained*	*Cumulative % Retained*	*Sample % Passing*	*% Pass Lower Limit*	*% Pass Upper Limit*
19mm	**0**	**0**	**0**	**100**	**100**	**100**
13.2mm	**1050**	**1.5**	**0.02**	**98.5**	**90**	**100**
9.5mm	**3050**	**29**	**0.31**	**69.5**	**40**	**70**
4.75mm	**9750**	**67**	**0.98**	**2.5**	**0**	**15**
Pan	**10000**	**2.5**			**0**	**0**

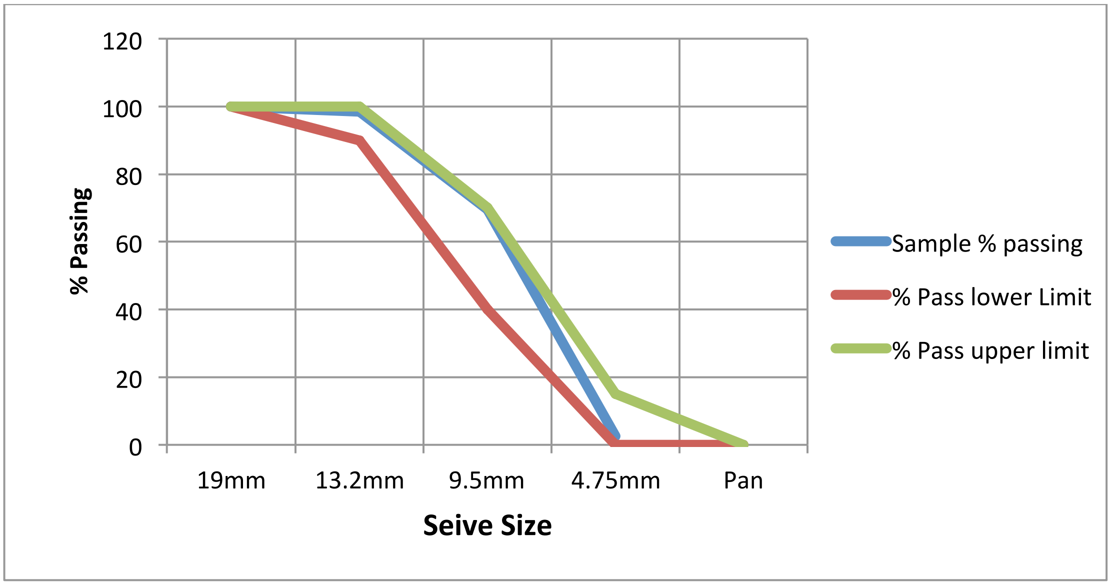


Figure 3-1 Aggregate Gradation Curve

3.3 Lab Testing

Test methods related to performance and durability was performed in lab on fresh mix and harden pervious concrete samples. The details about the tests are provided in Chapter 4.

3.4 Field Cores Collection

To relate lab data and apply modified test methods, field samples were collected from selected field sites. All the sites are located in Ontario. The sites are:

- Barrie Community parking lot, Barrie
- Kortright Centre, Vaughan
- Evergreen Brickworks, Toronto
- Georgetown Holcim Plant, Georgetown

All the sites are shown in the map in Figure 3-2. The details about the field sites are described in Chapter 4, section 4.4.

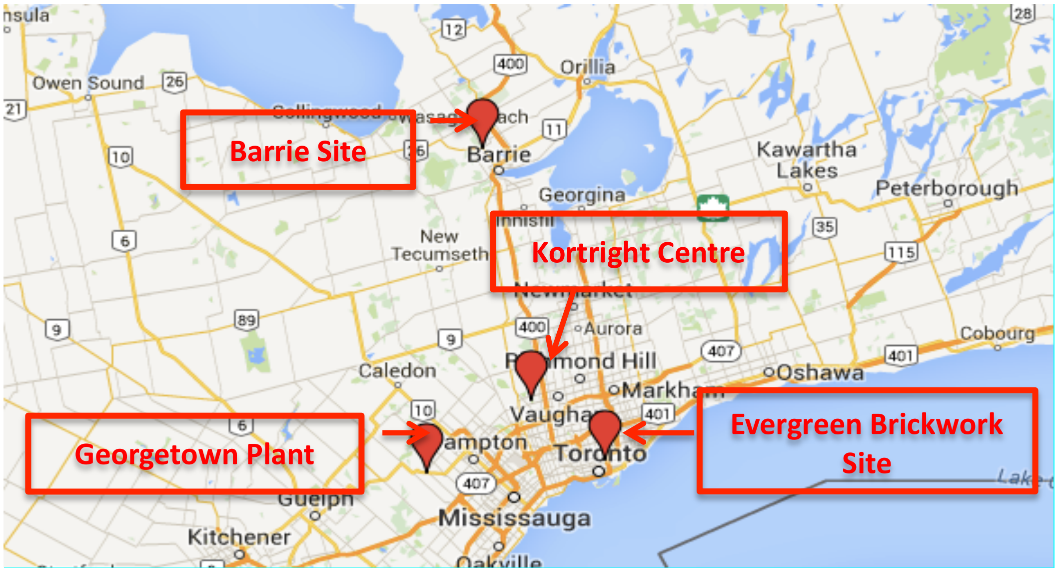


Figure 3-2 Field Sites

3.5 Summary

This chapter summarizes the methodology of this research project. The effect of mix design is also described here. Though mix design was not taken into consideration in this study, it plays a vital role in the performance of pavement. The mix design used for this project involves four admixtures. The effect of admixtures, amount and adding procedure is also important in the performance. The sequence of adding admixtures may change the ultimate behaviour. A trial and error process was followed in the mixing procedure and the optimum amount and adding time of admixture was determined. Cylindrical cores of 100mm and 150 mm were collected from all four pervious pavement sites. Field sample collection is described in detail in Chapter 4. Sample casting and all the test procedure on lab cast samples and field samples are also described in Chapter 4

Chapter 4

EXPERIMENTAL METHOD

This chapter describes the detailed methodology as well as the materials and methods of the tests conducted in this research.

4.1 Testing with Fresh Mix

4.1.1 Mixing Procedure

The fresh concrete mixes were prepared in a revolving pan-type concrete mixer with a capacity of 25 L. Materials were mixed in three steps in the lab as described below:

I. 70% of water, set retarding admixture, air entrainment admixture and aggregate: Mix for 1 minute to make the aggregate surface wet
II. Add cementitious material: Mix for 3 minutes
III. Add high range water reducing admixture, rest of the Water and viscosity modifying admixture: Mix for 5 minutes.

Figure 4-1 shows the mixing material in the mixer. At the end of mixing, it is recommended to place a small portion of the mix in the hand and rub the mix between two hands and hold the hand as shown in Figure 4-1. If the material sticks on the hands, it represents a good mix. If the mix falls, it represents a very dry mix. If only paste remains on the palm rather than the aggregate then it represent a very liquid mix and there is less cohession among the aggregate and paste. This test can assist in ensuring that the pervious concrete has been mixed suffiiently as the temperature in the laboratory and the temperature and moisture content of the material can impact the mixing capacity of pervious concrete. Thus this test can assist in preparing laboratory samples.

Figure 4-1 Mixing Materials in the Mixer

4.1.2 Slump Test

A slump test was performed by modifying the the standard CSA A 23.2- 5C (2009) "Slump of Concete". The slump cone was moistened inside and placed on a flat non absorbent surface. The cone then filled in two layers and each layer was compacted with a Proctor hammer, 20 evenly distributed drops across the layer. The second layer was filled over the cone and the excess material was removed with a flat plate. The cone is then lifted off the concrete, at a steady rate, in which takes approximately five seconds. The cone can then be placed upside down beside the concrete and the difference in height between the concrete and mould can be measured. This measured value is the "slump" of the mix. Figure 4-2 and Figure 4-3 presents the hammering and measuring the slump. For all of the batching the slump value found was 0 mm.

Figure 4-2 Hammering For Slump Test

Figure 4-3 Slump Measurement

4.1.3 Density and Void Content of Fresh Pervious Mix

After the mixing was complete, density and void content was determined following Standard test methods for density and void content of freshly mixed pervious concrete (ASTM C1688). The bucket in Figure 4-4 was filled in two layers and a Proctor hammer was used for compacting the material at 20 drops per layer. After finishing hammering on the second layer, a smooth wooden plate was used to strike off the access material as represented in Figure 4-5.The pervious concrete should at this point be level with the top of the cone container. All excess pervious concrete on the exterior of the container was removed with a damp sponge.

Figure 4-4 Compacting with Proctor Hammer

Figure 4-5 Striking off excess material

Prior to filling the bucket, the weight of the empty bucket was recorded. Once the bucket has been filled, the bucket with the materials was weighed. Equation 4.1 is used to determine the density of the pervious concrete mix.

$$D = M/V \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.1)$$

Where, D = is the density of the pervious concrete mix, kg/m^3,

M = Mass of the mix in the air meter bucket, kg,

V = Volume of the air meter bucket, m^3.

4.2 Casting and testing of Hardened pervious concrete specimens and slabs

4.2.1 Density and Void Content of Harden Pervious Concrete

ASTM C 1754 was used to determine density and void content of harden pervious concrete. Cylindrical samples of size 100mmX200mm (4”X8”) were cast in two layers and 20 drops of Proctor hammer per layer was used to compact. Samples were removed from the molds after 20±4 hours and put in the curing room for seven days. Samples were tested for void content and density after curing for seven days. The samples were grinded using the grinding machine presented in Figure 4-6. For determining the dry weight of the sample, procedure 'A' was followed. The specimens were dried in oven at 38^0C $\pm 3^0$C for 24 hours and then removed and weighed and returned to the oven for 24 hours. The procedure was repeated in 24 hours until the difference between the two subsequent masses is less than 0.5 % and the weight was recorded as the dry mass.

Then for the submerged mass, the specimens were completely submerged in the water bath and kept to sit upright for 30± 5 min. To remove air bubbles, the specimens were tapped 10 times with a rubber mallet equally spaced around the circumference while fully submerging the mallet below the water. The submerged mass was recorded. The harden density was determined in kg/m^3, using Equation 4.2

$$\text{Density} = \frac{K \times A}{D^2 \times L} \quad \text{...(4.2)}$$

Where:

A = dry mass of the specimen, g,

D = average diameter of the specimen, mm,

L = average length of the specimen, mm, and

K = 1 273 240 in SI units

The void content was determined using Equation 4.3.

$$\text{Void Content} = \left[1 - \left(\frac{K \times (A - B)}{\rho_w \times D^2 \times L}\right)\right] \times 100 \quad \text{.......................................(4.3)}$$

Where:

B = Submerged mass of the specimen, g, and

ρ_W = Density of water at temperature of the water bath, kg/m^3

Figure 4-6 Grinding Sample

To find out the relationship between compaction and harden density, samples were cast with different compaction (i.e. different number of drops per layer), which is described, in more detailed in Chapter 5.

4.2.2 Compressive Strength Testing

A compressive strength test was performed following the ASTM C09.49 (draft method which is available for pervious concrete). Cylindrical samples of size 100mmX200mm were cast in similar manner as for harden density and void content testing described in Section 4.2.1. Again, to define the effect of compaction on compressive strength, more samples were cast in the lab with different compaction. The results are presented in Chapter 5. Figure 4-7 presents compressive strength testing.

Figure 4-7 Compressive Strength Testing

4.2.3 Flexural Strength Testing

ASTM C78 was followed to determine flexural strength testing of pervious concrete. Pervious concrete beams of size 150mmx75mmx75mm (6"x3"x3") were cast. In this case, casting was done in two layers and 20 drops of Proctor hammer were applied to each layer of the samples. The density of the samples was determined afterwards and it was found to be consistent with samples cast for other testing. After demolding, samples were kept in the curing room for 28 days. After 28 days, samples were brought out and tested for flexural strength. The three-point load was applied as shown in Figure 4-8 and the load was applied at a displacement rate 0.144mm/min.

In total eight samples were tested and for all the samples fracture was initiated in the tension surface within the middle third of the span length, so the modulus of rupture was calculated using Equation 4.4

$$R = \frac{PL}{bd^2} \qquad \text{...(4.4)}$$

where:

R =Modulus of rupture, MPa,

P = Maximum applied load indicated by the testing machine, N,

L = Span length, mm,

b = Average width of specimen, mm, at the fracture, and

d= Average depth of specimen, mm, at the fracture

Figure 4-8 Flexural Strength Testing

4.2.4 Permeability Testing

The Gilson Permeameter was used to determine permeability of pervious concrete samples in the CPATT lab. Cylindrical samples of 100mmx200 mm were cast in a similar way as described in Section 4.2.1 were used for permeability testing after seven days of curing. The samples were wrapped with latex sleeves to avoid horizontal movement of water and plumber putty was used around the rim of the device to seal the device. It is assumed that water was moving only in a vertical direction. Figure 4-9 shows permeability testing in the lab.

Then the permeameter was filled with water and timed between two points and permeability was determined by Equation 4.5

$$K = \frac{aL}{At} ln\left(\frac{h_1}{h_2}\right) \qquad \ldots\ldots(4.5)$$

Where

K = Coefficient of permeability, cm/sec

a= Inside cross-sectional area of the permeameter, 167.53 cm^2 for the larger, bottom tier or 38.32 cm^2 for the smaller, upper tier

L =Length of the sample, the thickness of the core or pervious concrete layer, cm

A = Cross-sectional area of the drainage of the permeameter, cm^2 t is the elapsed time between h_1 and h_2, seconds

h_1 = initial head, cm

h_2 = final head, cm

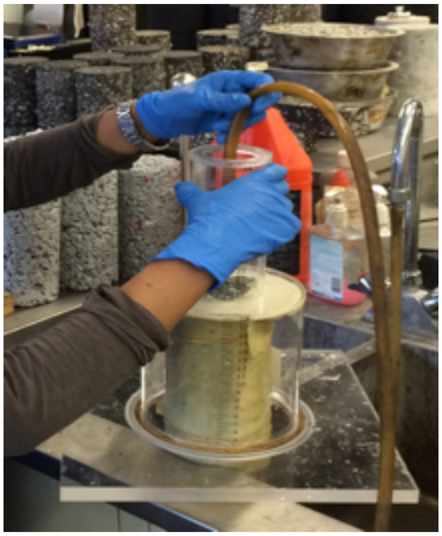


Figure 4-9 Permeability Testing

4.2.5 Abrasion Testing

Two types of abrasion test methods were used to determine abrasion resistance of pervious concrete: Drilled Pressed Rotary Cutter and Los Angeles Abrasion Device.

4.2.5.1 Drilled Pressed Rotary Cutter Abrasion Testing

ASTM C944 was followed to perform abrasion resistance testing with the drilled pressed rotary cutter device. The drill press device has a chuck capable of holding and rotating the abrading cutter at a speed of 200 r/min and exerting a force of either a normal load of 98±1 N [22±0.2 lbf] or a double load of 197±2 N [44±0.4 lbf] on the test specimen surface. For this project the normal load was applied to the samples and cured samples were tested for abrasion at 7 days and 28 days. Cylindrical samples of 150mmx75mm (6”x3”) were cast in two layers and 20 drops of Proctor hammer per layer were applied. At the end of each 2-min abrasion period, the test specimen was removed from the device and the surface were cleaned to remove debris using a soft brush or air blowing the surface with air and then the weight loss was determined. The test and sample after testing is presented in Figure 4-10 and 4-11.

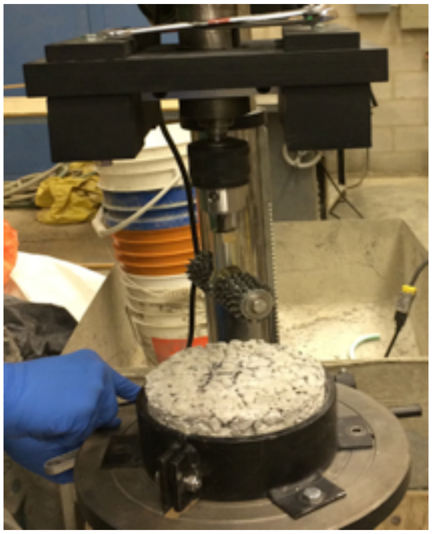


Figure 4-10 Abrasion Testing with Drilled Pressed Rotary Cutter

Figure 4-11 Sample after Testing

To find a relationship between compaction (or compressive strength) and abrasion resistance, samples with different compaction were also casted for this test. The test results are presented in Chapter 5.

4.2.5.2 Los Angeles (LA) Abrasion Testing

Following the ASTM C1747, the Los Angeles Abrasion test was performed. This is a specified test method particularly for pervious concrete pavement to find out ravelling resistance of the concrete, as ravelling is a major concern with pervious concrete pavement. The casting procedure is different in this case. From the density of fresh concrete, the amount of material required to fill the mold to a height of 100mmx100mm (4”x4”) was determined. Then 100mmx200mm (4”x8”) sized mold was placed on a balance on a flat surface and set to zero. In the next step, fresh concrete was placed in the mold with the scoop till the calculated mass was achieved. The mold was then moved from the scale, placed on a flat surface and the Marshall hammer was used to consolidate the sample to the specified height of 100mm ± 2mm (4”±1/16 “). If the sample was over compacted it should be discarded. For this project 40 to 45 drops of Marshall hammer was used to compact the sample to the specified height. Samples were cured at room temperature for two days after which they were placed in the curing room for seven days without removing from the mold. After seven days, samples were removed from the curing room, demolded, and wiped to remove excess water. Next three samples was placed on a balance altogether as one set, which provides a single test result, and the mass was recorded.

Within 30 min after removing the molds, the three specimens were placed in the Los Angeles machine without any steel spheres. The machine was allowed to rotate at 30 to 33r/min for 500 revolutions. After 500 revolutions, the material was discharged from the machine and hand sieved on a 25-mm (1-in.) sieve. The material that retained on the sieve was recorded, which was the weight after testing. The weight loss was also determined. The samples before and after testing are presented in Figure 4-12 and 4-13, respectively.

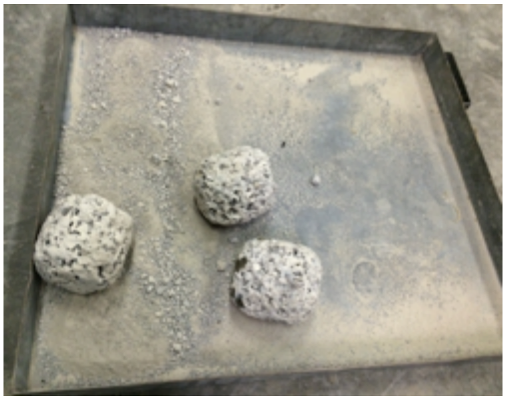


Figure 4-12 Sample set Before and Figure 4-13 Sample set After LA Abrasion Test

4.2.6 Ravelling Testing using Hamburg Wheel Rut Tester

The Hamburg wheel rutting (AASHTO 324-04) test is a test typically used for asphalt. But for this research project, Hamburg wheel testing was used to examine ravelling resistance, as ravelling is a common distress associated with pervious concrete pavement. The Hamburg Wheel Rutting Tester has two wheels and these two wheels move back and forth repeatedly on the samples for several thousands cycles (typically 10,000 for asphalt). There are two types of wheels, rubber tire wheels and steel wheels. The device is generally filled with water and run at a temperature of 50^0C. For this study, the water temperature was kept unchanged (50^0C) as it was assumed that temperature has minimal effect on concrete. After the cycles were complete the samples were examined to determine if rutting had occurred. For this research ravelling, cracking and removal of aggregate were checked. The CPATT research group started this testing allowing the rubber tire wheels to run on the samples for 30,000 cycles but no ravelling, cracking or aggregate loss was observed. After this test, the rubber tired wheels were replaced with the steel wheels and the device was allowed to run for more 20,000 cycles. Again no raveling was observed. Figure 4-14 shows the Hamburg wheel rutting testing.

Figure 4-14 Hamburg Wheel Rutting Testing

Thus there was no observed ravelling or cracking on the sample. This could be related to the fact that a good mix design was used in this research combined with proper curing of the samples in the lab. It also indicates that Humber wheel rut tester may not be an effective test for predicting raveling or cracking in pervious concrete.

4.2.7 Freeze Thaw Resistance Testing

Freeze thaw resistance testing has been performed following ASTM C666. Both of the procedures (i.e. procedure (A) and procedure (B)) were performed to find out the suitable method for pervious concrete. Procedure A is to conduct each freeze and thaw cycle in water, while procedure B is to freeze the specimens in air, but thaw them in water. Both procedures used the same sized beam samples. In both cases, 280mmx76mmx76mm (11”x3”x3”) samples were cast in two layers and 20 drops of Proctor hammer per layer was applied. Demolding occurred after 24 hours, the samples were placed in limewater in the curing room for 14 days. After that, the specimens were brought to thaw temperature and the transverse frequency and mass were measured before staring the freeze thaw cycles.

Since an automatic cabinet was used for procedure A, the specimens were placed in a container submerged in water and the temperature of the water was automatically adjusted with a timer to achieve each freeze thaw cycle. The freeze and thaw temperatures are dictated to be 0 deg F (-18^{0}C) and 40 deg F (4^{0}C) respectively, and each cycle must be conducted in two to five hours. In procedure A, a minimum of 25% of the time was used for thawing.

For procedure B the freeze thaw cycles were operated manually. The samples were placed on a cart, which has holes underneath and placed in the walk-in freezer. The time duration for the freeze thaw cycle was four to five hours. After a minimum of three hours of freezing cycle, samples were removed from the freezer and submerged in a water bath, while the water temperature was maintained at 4^0 to 6^0 C. The minimum thawing period was one hour to a maximum of two hours. After one hour, the samples were taken out of the water and drained for 10 minutes and put on the cart and placed in the walk-in freezer for the freezing cycle. The freezer temperature was maintained at -15^{0}C. On average three cycles were performed each day. Any remaining water in the sample after thawing would be drained through the holes in the cart.

Figure 4-15 presents the freeze thaw testing according to procedure (A), which is freezing and thawing in water and Figure 4-16 presents procedure (B), freezing in air and thawing in water.

Figure 4-15 ASTM C666 Procedure (A)

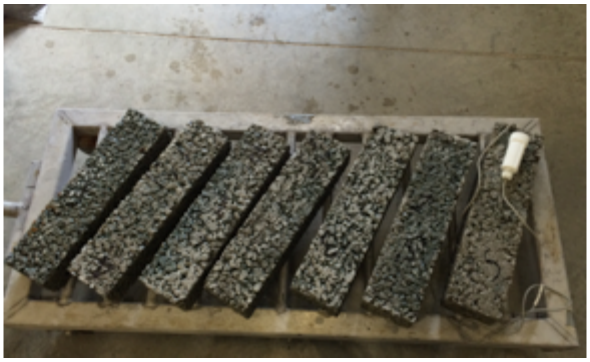


Figure 4-16 ASTM C666 Procedure (B)

For both procedures, fundamental transverse frequency was determined after each 36 cycles and the relative dynamic modulus of elasticity and durability factors were determined. Determining frequency of pervious beam samples is presented in Figure 4-17. As pervious concrete has a rough surface, caution should be taken at the time of transverse frequency determination. The needle of the vibrator is very sensitive and should be placed on a plain smooth surface. The needle is usually placed in the middle of the sample for conventional concrete. But, in some cases, no smooth place was available on the pervious sample. So, for this research, the needle was placed in three different positions and the average frequency was determined. The range for transverse frequency was found to be in 1000Hz to 1900 Hz.

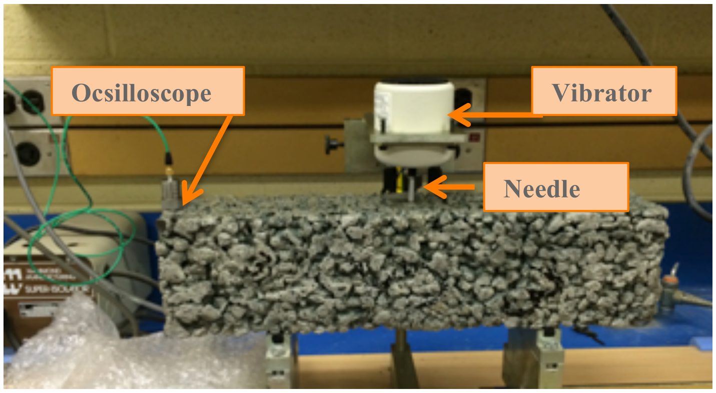


Figure 4-17 Determining Fundamental Transverse Frequency

The Relative Dynamic Modulus of Elasticity calculation involves the application of the following Equation 4.6.

$P_C = (n_1^2 / n^2) \times 100$ ……………………………………………………………………(4.6)

Where:

P_C = relative dynamic modulus of elasticity, after c cycles of freezing and thawing, percent.

n = fundamental transverse frequency at 0 cycles of freezing and thawing, and

n_1 = fundamental transverse frequency after c cycles of freezing and thawing

The Durability Factor calculation involves the application of the Equation 4.7.

$$DF = (P \times N)/ M \quad \ldots\ldots (4.7)$$

Where:

DF = Durability factor of the test specimen

P = relative dynamic modulus of elasticity, at N cycles, percent.

N = number cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less, and

M = specified number of cycles at which the exposure is to be terminated.

4.2.8 Scaling Resistance Testing

The ASTM C672/C672M was modified for scaling resistance testing of pervious concrete and slab samples of sized 300mmx300mmx75mm (12”x12”x3”) were cast. Samples were cast in two layers and 45 drops of Proctor hammer was applied per layer to achieve the required density and to maintain consistency with other samples. The samples were then cured for 14 days in he curing room and then cured for 14 more days in air at room temperature (23^0C). After completion of the curing time, samples were submerged in asalt-water solution (40g of salt per 1l of water) for 6-8 hours, which is the thawing period for this test. At the end of the submersion period, samples were taken out of the salt-water solution, drained for 20 minutes and placed in freezing environment for 16-18 hours. The CPATT research team continued this freezing and thawing regime until 50 cycles had been completed and after each five cycles the condition of the samples were examined according to ASTM C672. Two types of salts were used, sodium chloride (NaCl) and calcium chloride ($CaCl_2$), to determine and compare the effect of salt on scaling. Figure 4-18 shows scaling samples submerged in the water.

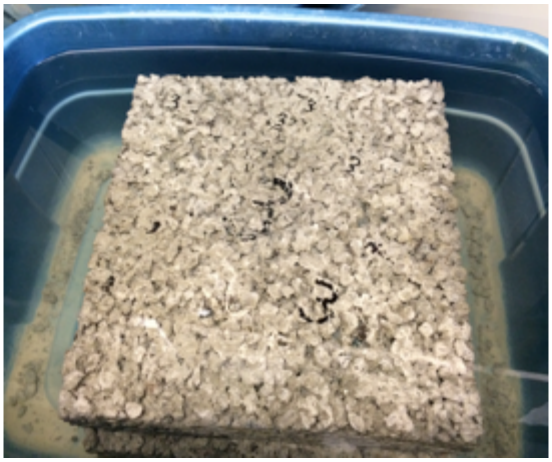


Figure 4-18 Scaling Samples submerged in the salt solution

A visual inspection was conducted using the rating system outlined in Table 4-1

Table 4-1 Scale for Scaling Evaluation (ASTM C 672)

Rating	*Condition of Surface*
0	No scaling
1	Very slight scaling (3 mm [1/8 in.] depth, max, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

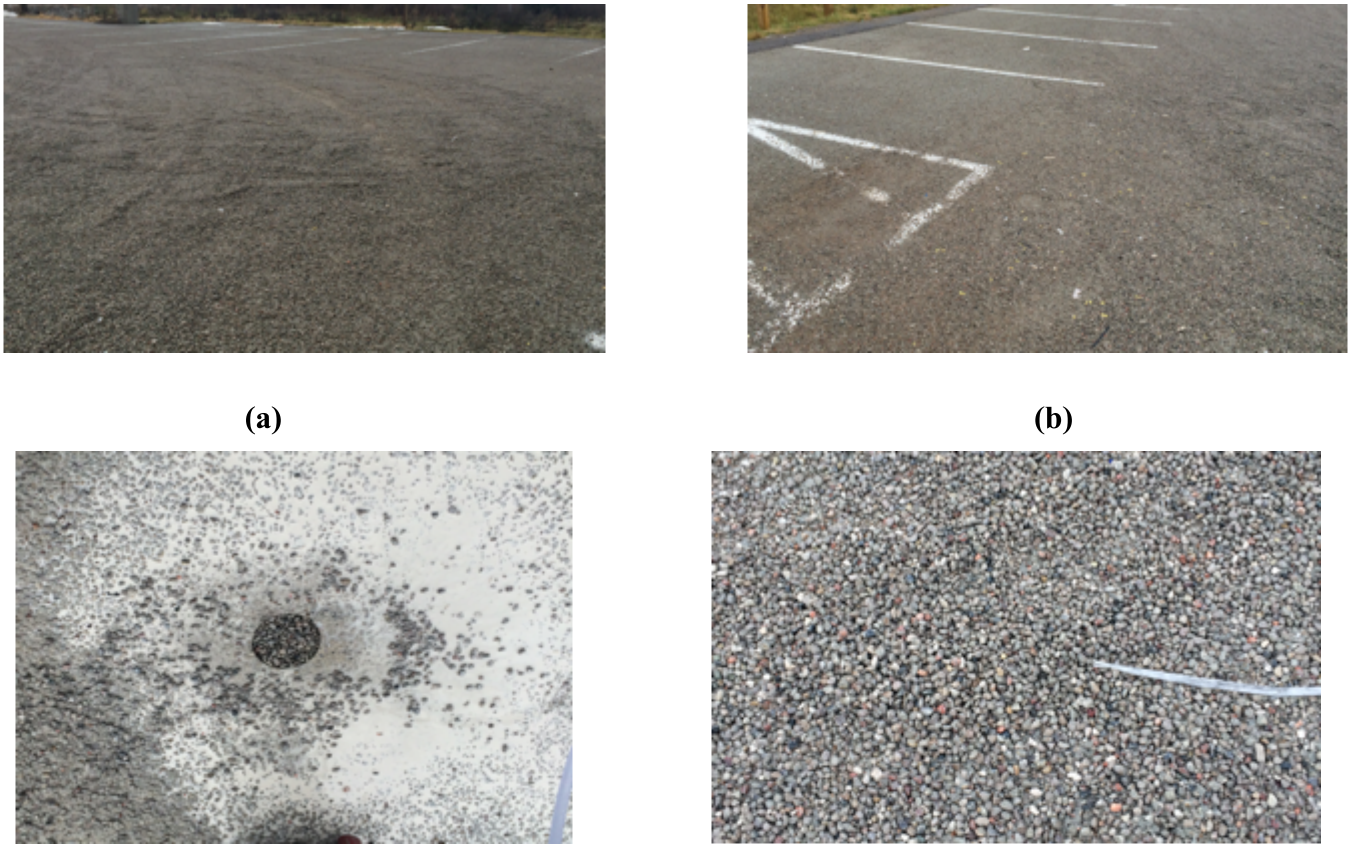
4.3 Field Sample Collection

A Map with the locations of the sites is presented in Chapter 3, Figure 3-2. More details about the sites are described in this section.

4.3.1 Barrie Commuter Parking Lot, Barrie

Barrie commuter parking lot is the third pervious concrete constructed by MTO (David Rhead, 2012). The construction began in September 2011 along Highway 26 at the Simcoe County Road 27 intersection in Midhurst, which is west of Barrie, Ontario, approximately 100 km north of Toronto. The mix design used in this parking lot is the same mix design that used in this research and described in Chapter 3.

Figure 4-19 (a, b, c and d) presents the pictures from this site.



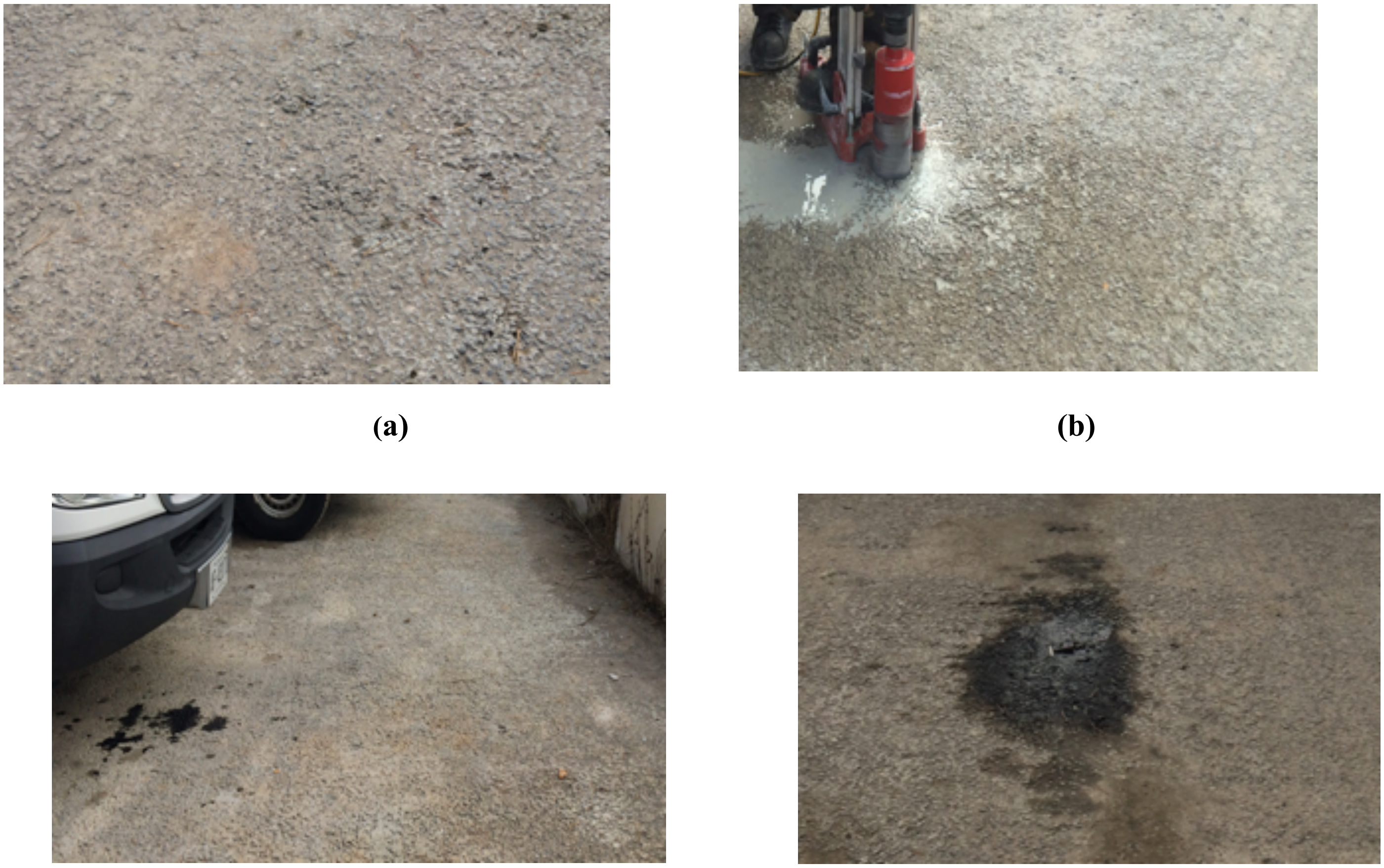
(a) **(b)**

(c) **(d)**

Figure 4-19 Field Condition and Coring at Barrie Commuter Parking Lot

4.3.2 Georgetown Plant, Georgetown

The Georgetown Plant is an employee parking lot at a concrete ready mix plant. The pavement was constructed in Summer 2007. The mix deign used here is 13.2 mm aggregate with no fines, 0.244 w/c, and admixtures: air entrainment admixture; super plasticizer; and set retarder. Vehicles turn in all areas of the parking lot, both driving and parking areas. The pavement surrounding the parking lot is generally sand. The conditions at this site are generally more aggressive in terms of loading from debris than would be recommended for the use of pervious concrete pavement. The pictures from this site are presented in the Figure 4.20 (a, b, c and d).



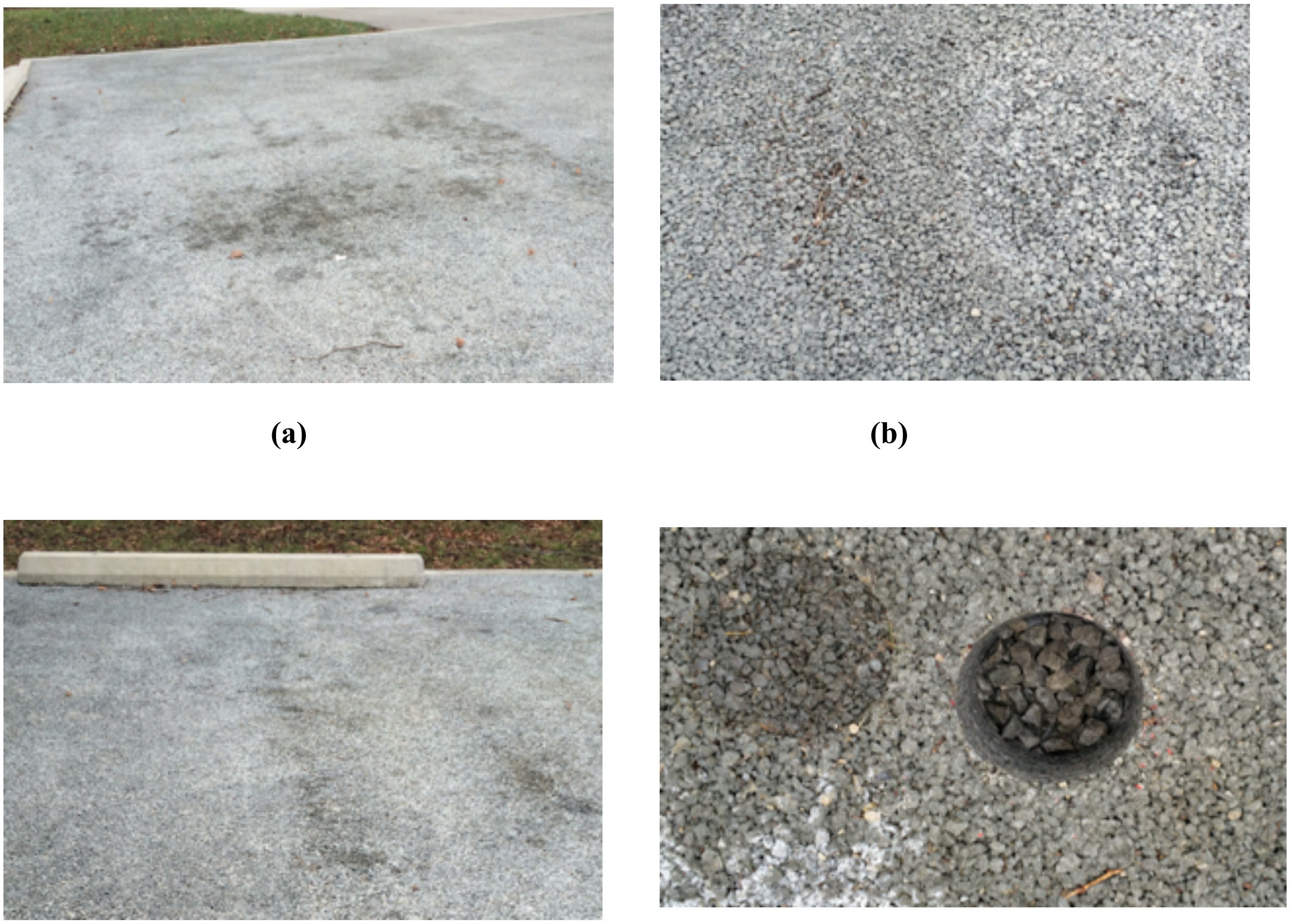
(a) **(b)**

(c) **(d)**

Figure 4-20 Field Condition and Coring at Georgetown Plant Pervious Parking Lot, Georgetown

4.3.3 Kortright Centre, Vaughan

Kortright Centre parking lot is located at Living City Campus at Kortright in Vaughan, roughly 8 km north of Toronto. The Living City Campus is a centre for education and research on sustainable technologies and, as such, generates frequent visitors interested in innovative approaches to building and urban design. This pervious pavement parking lot area is 230m^2. It was constructed in 2009. The mix design used here was Hydromedia provided by Lafarge. The pictures from this site are presented in Figure 4.21 (a, b, c and d).



(a) **(b)**

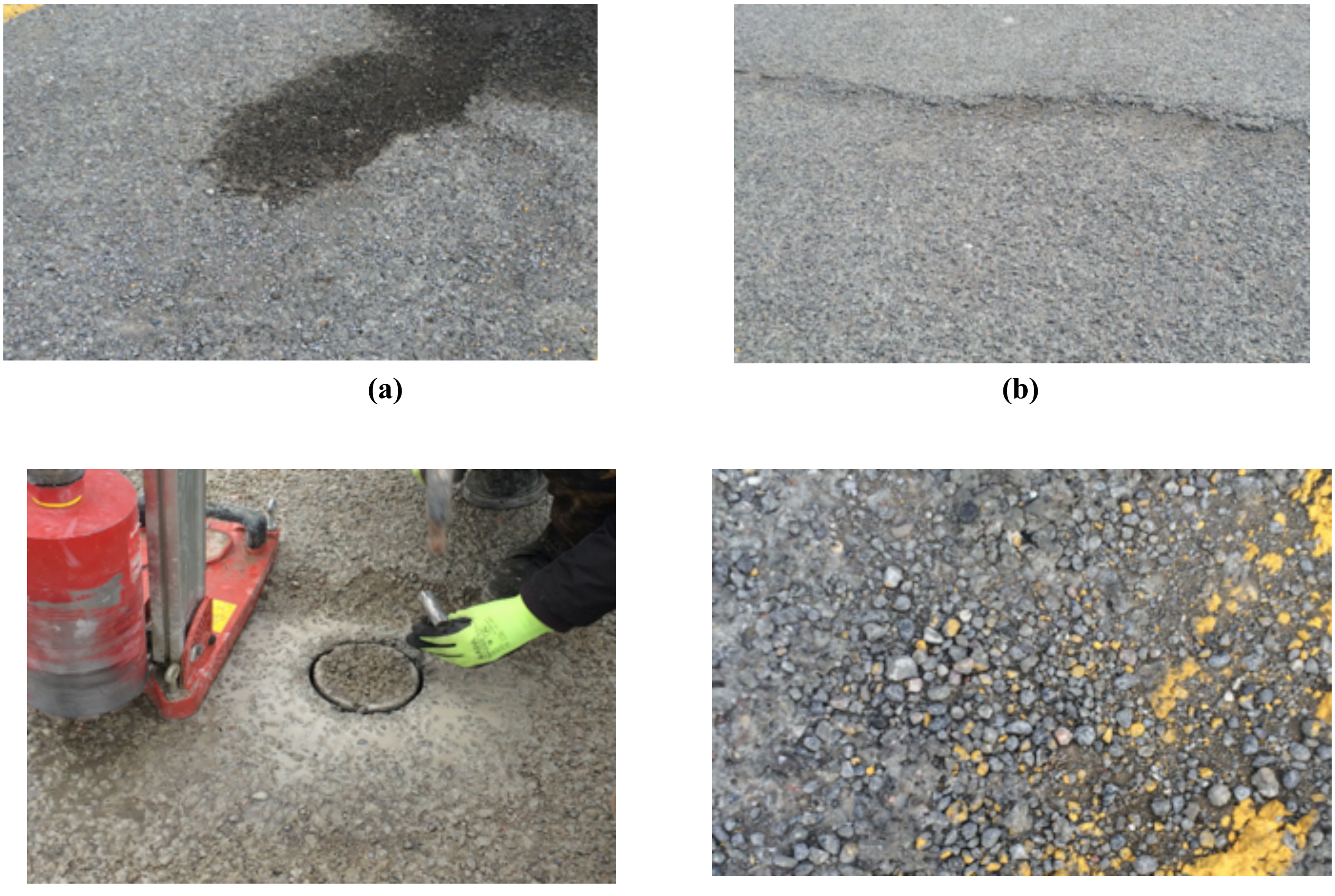
(c) **(d)**

Figure 4-21 Field Condition and Coring at Kortright Visitor Centre Parking Lot, Vaughan

4.3.4 Evergreen Brickworks, Toronto

The Evergreen Brick Works, also known as Don Valley Brick Works, is a former quarry and industrial site located in the Don River Valley in Toronto. In one section of the site, a large pervious concrete parking lot was constructed in 2010. The lot consists of 19 millimetres of clear stone underlying 150 millimetres of pervious concrete. The pavement is about 450 millimetres thick.

Figure 4-22 (a, b, c and d) represents field sample collection in this site.



(a) (b)

(c) (d)

Figure 4-22 Field Condition and Coring at Evergreen Brickworks Community Parking Lot, Toronto

4.4 Challenges in Collecting Cores in Pervious Concrete Pavement

There are some challenges associated with coring of pervious concrete. In general, with conventional concrete, when coring is completed, the mold is gently tamped with a metal hammer to remove the sample from the mold. As pervious concrete is porous, the tamping force is dissipated, so patience and gentle movement is important to distribute the tapping evenly. Aggressive tamping can easily break the sample. Again sometimes loose coarse aggregate could get stuck in the mold, making the situation worse. Several times the research group tried to take cores from the poor performing sections. It was challenging as the strength of the concrete was lower in those sections and very fragile and ready to break easily.

4.5 Testing with Field Cores

Selected tests were performed on the field cored samples. The tests were:

- Microscopic Analysis to find out distresses including micro cracking
- Petrographic Analysis
- Harden Air Void Testing
- Compressive Strength Testing
- Abrasion Resistance Testing

The detail of the test results and a brief comparison of the sites and mix design are described in Chapter 5.

4.6 Summary of Test Methods

Several materials and methods were described in this chapter. Some of the test methods were modified according to the test being performed. In the methodology, several tests were integrated to characterize performance and durability of pervious concrete pavement. Field samples collection was an important portion of this research. Test results from field samples allow evaluation of the applicability of the modified test methods and how the test results could be interpreting to correlate with the performance.

Chapter 5

RESULTS AND DISCUSSION

This chapter presents the results and discussion from the tests presented in Chapter 4.

5.1 Test Results of Laboratory Cast Sample

5.1.1 Density and Void Content of Fresh and Harden Pervious Concrete

As described in Chapter 4, after completing the mixing, density and void content of fresh concrete was determined following ASTM C1688. ASTM C 1754 was used to determine density and void content of harden pervious concrete. Fresh void content and harden void content results are presented in Figure 5-1.

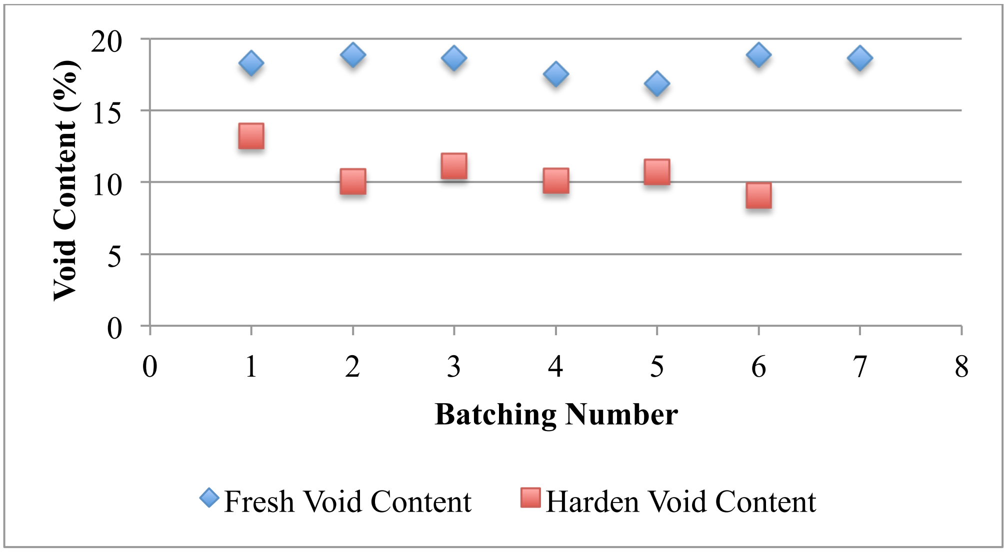


Figure 5-1 Fresh Vs. Harden Void Content

Figure 5-1 shows that harden void content is lower than the fresh void content. The difference observed in the fresh and hard void content relates to over compaction during the casting of the cylindrical samples. Therefore, to find out how compaction influences harden void content, more samples were cast in two layers as described earlier but with different level of compaction. The number of drops of Proctor hammer per layer was conducted at 5 drops, 10 drops, 15 drops and 20 drops/layer respectively. The results of the different compactions and void content are presented in Figure 5-2.

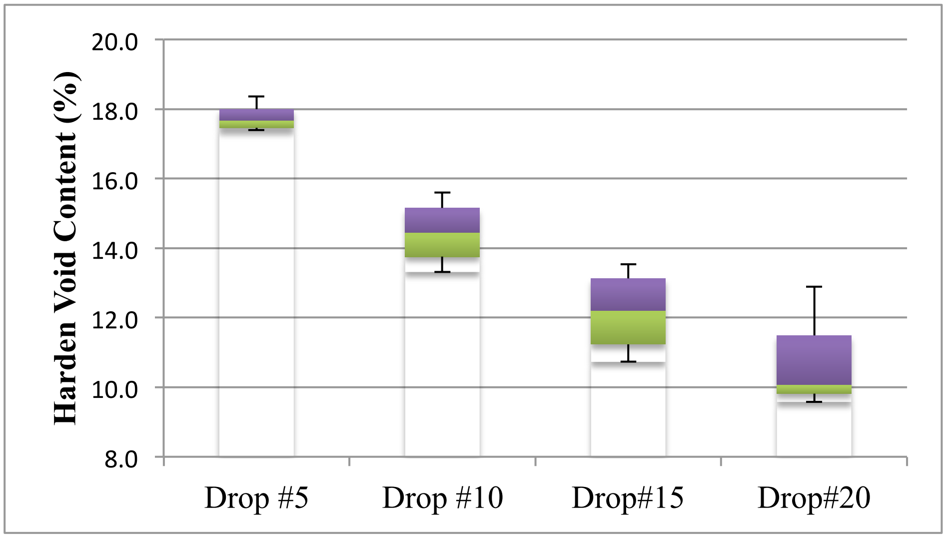


Figure 5-2 Harden Void Content with Different Compaction Effort

Figure 5-2 shows that with five drops of the Proctor hammer, the harden air void ranged from 17-20% with an average of 17.5%. With ten drops the air void ranged from 13-15% with an average of 15.5%. With fifteen drops the air void ranged from 11-13%, average 12% and with twenty drops the range was 9-13% (average 10%). The effect of compaction on harden air void and compressive strength is presented in Table 5-1.

It is clear that increasing the number of drops per layer decreases harden void content. The harden void content results were compared with the air voids of the core samples collected from Barrie site, as the mix design was same and from the comparison it can be recommended that 10 to 15 drops of the Proctor hammer per layer best replicate field compaction.

5.1.2 Compressive Strength Testing

The ASTM C09.49 (draft method) was followed to evaluate the compressive strength test results at 7 days, 21 days and 28 days. These results are presented in Figure 5-3. From the

Figure it can be shown that at the 21 day period, the compressive strength ranged from 19 MPa to 27 MPa with an average of 25 MPa. The 21 day compressive strength is higher compared to the 7 day values which ranged from 13MPa to 23MPa, with an average of 17MPa. The compressive strength at 28 day ranged from 24 MPa to 26 MPa with an average of 25MPa. The full compressive strength results including the number of samples tested, standard deviation and coefficient of variation are presented in Table 5-1.

Table 5-1 Compressive Strength Test Results

Test	*# of Samples Tested*	*Compressive Strength Results (MPa)*									*Average*	*STDEV*
		Sample Number										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**		
7day Comp St. Testing	9	21.5	23.3	22..4	16.8	20.3	18.8	16.4	16.2	17.2	19.2	2.8
21 day Comp St. Testing	7	27.0	26.8	23.8	23.1	18.2	26.3	24.7			24.3	3.1
28 day Comp St. Testing	6	24.9	25	24.5	24	26.1	24				24.8	0.8

As noted the 28 day strength is similar to the 21 day compressive strength. Theoretically the 28 day compressive strength should be higher than the 21day compressive strength. This could have resulted from variation in the process of manual compaction. Also in tested pervious concrete, most of the compressive strength was achieved by the 21 day. Therefore no significant difference was found between 21 and 28 days results. The compressive strength results with different age were compared further using ANOVA tables. At 95% confidence, tests were evaluated to determine if there was a significant difference amongst them. It was found that there was a significant difference among the 7 day compressive strength and the 21 day compressive strength but no significant difference is present among the 21 day compressive strength and the 28 day compressive strength. This result also explains the above stated situation. Table 5-2 presents the t-test results of compressive strength with different age.

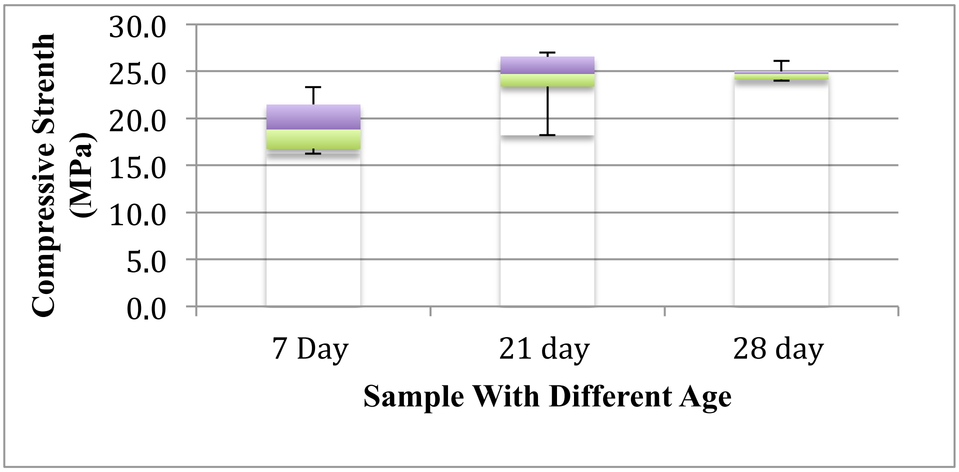


Figure 5-3 Compressive Strength at Different Age

Table 5-2 Statistical Analysis of Compressive Strength with ANOVA

	7 Day and 21 Day Compressive Strength Results (MPa)		*21 Day and 28 Day Compressive Strength Results (MPa)*	
	7 Day Comp St.	**21 Day Comp. St.**	**21 Day Comp St.**	**28 Day Comp St.**
Observation	**9**	**7**	**7**	**6**
Mean (MPa)	**19.2**	**24.2**	**24.2**	**24.7**
Variance	**7.57**	**9.44**	**9.44**	**0.61**
Hypothesized Mean Difference	**0**		**0**	
Pooled Variance	**8.37**		**5.43**	
df	**14**		**11**	
t Stat	**3.45**		**0.39**	
P (Two Tail Dist)	**0.0035**		**0.7**	
t_{crit} (5%)	**2.14**		**2.2**	
Outcome	**Statistically Different**		**Statistically Same**	

The compressive strength result of samples with different compaction is presented in Figure 5-4. With five drops of the Proctor hammer per layer, the compressive strength range was 13 to 15 MPA with an average of 14 MPa, 10 drops per layer provided 16 to 21 MPa with an average of 17 MPa, with 15 drops the range was found 19 to 22 MPa (average 20 MPa) and 20 drops of the Proctor hammer was 21 to 24 MPa (average 23 MPa).

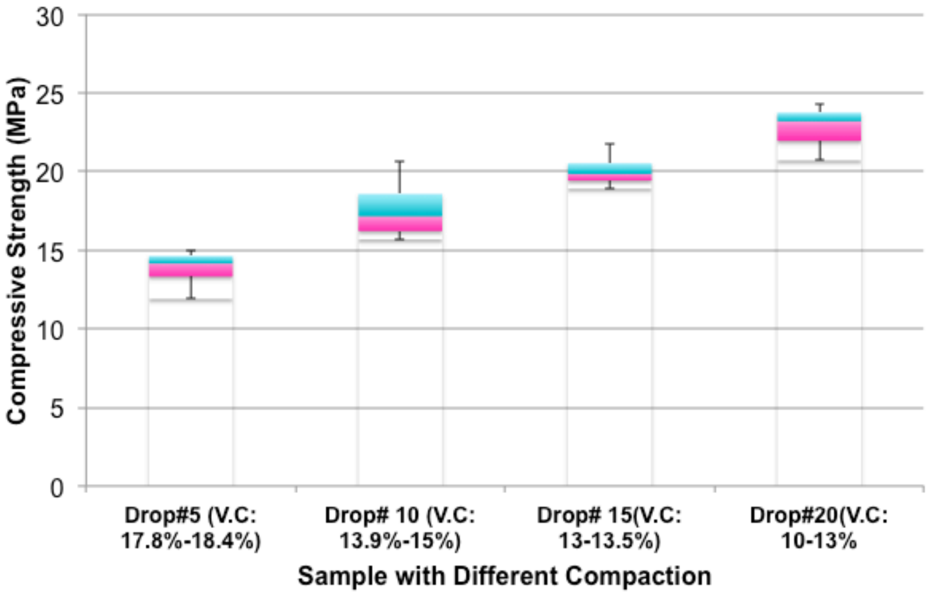


Figure 5-4 Compressive Strength of Samples with Different Compaction

The correlation among the compaction effort, air void and compressive strength is presented in Table 5-3.

Table 5-3 Compaction, Air Void and Compressive Strength

Number of Proctor Hammer drops per layer	*Harden Void Content Range (%)*	*Compressive Strength Range (MPa)*
5	17-20	13-15
10	13-15	16-21
15	11-13	19-22
20	9-13	21-24

5.1.3 Flexural Strength Testing

ASTM C78 was followed to determine the flexural strength testing of pervious concrete. The 28 day flexural strength results are presented in Table 5-4. The range was 3.4 to 4.0MPa with an average of 3.65 MPa and standard deviation of 0.2 MPa.

Table 5-4 Flexural Strength Test Results

Sample #	*Flexural Strength (MPa)*	*Mean (MPa)*	*STDEV (MPa)*	*COV (MPa)*
1	4.0	3.6	0.2	4.7
2	3.4			
3	3.8			
4	3.6			
5	3.6			
6	3.5			
7	3.6			
8	3.6			

5.1.4 Permeability Testing

Figure 5-5 presents the permeability test results of samples with different level of compaction. The highest permeability was found in the samples that were cast with five drops of the Proctor hammer per layer and the lowest permeability was observed in the samples that were cast with the 20 Proctor hammer drops per layer. Nevertheless, with 20 drops the permeability is reasonable and more than the average rainfall rate of Canada. In Canada the average rainfall rate is .0083cm/sec (Environment Canada, 2010). In general, permeability is not a major concern with pervious concrete as all the test sections constructed in different provinces in Canada showed satisfactory permeability performance initially. With time, clogging may affect it but with proper maintenance permeability can be regained to the satisfactory level (Henderson, 2012).

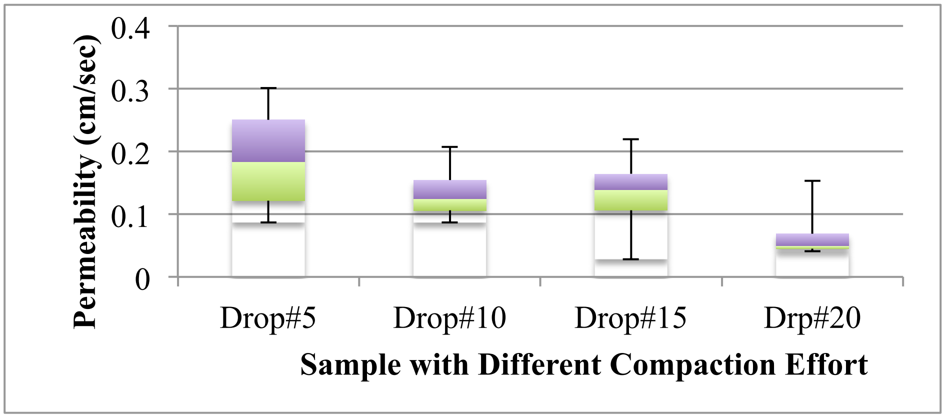


Figure 5-5 Permeability of Samples with different Compaction Effort

5.1.5 Abrasion Test Results

5.1.5.1 Drilled Pressed Rotary Cutter Abrasion Testing

ASTM C 944 was utilized to evaluate the abrasion resistance with the drilled pressed rotary cutter device. Weight loss was determined in the test. Figure 5-6 presents the weight loss results of samples with different ages. According to the standard, the single-operator coefficient of variation has been found to be 21% and the results of two properly conducted tests by the same operator on similar samples should not differ from each other by more than 59% of the average. For all the cases of this test, the coefficient of variation was found to be in the specified range (minimum was found with 7 days weight loss of 11.16% and maximum was found with 28 days weight loss of 20.08%).

The weight loss range for 28 days aged samples was shown to be lower than the 21 days aged samples. This is considered to be a good trend as it can be anticipated that with age compressive strength increases and abrasion resistance also increases, as a results weight loss decreases. The results between 7 days and 21 days samples were compared, and were not found to be following a similar trend. The average weight loss for the 21 days aged samples is higher than the average weight loss for 7 days old samples. The probable explanation could be compaction of the prepared samples. Some of the 7 days samples probably would be highly compacted than 21 days samples as the lower range of weight loss for both cases is almost in the same line. So it can be assumed that only a few of the 7 days samples cause the different result. To find out the statistical difference among the weight loss ANOVA at 95% confidence level (t-test) was performed. Table 5-5 presents the t test results.

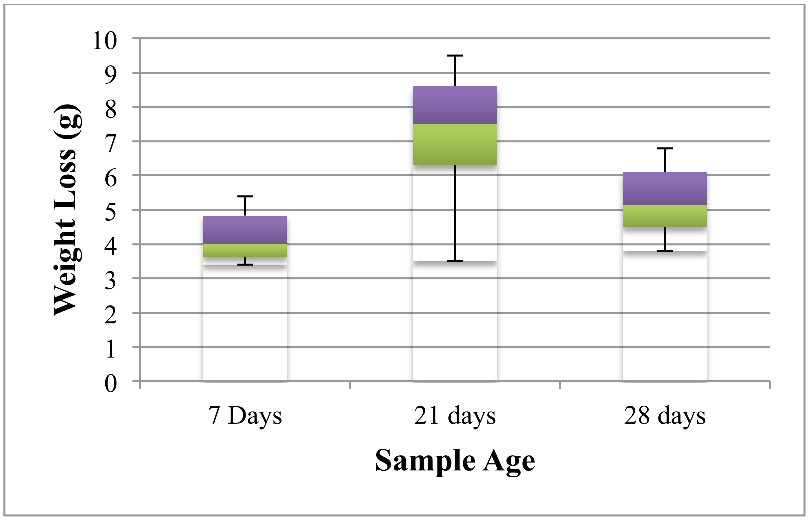


Figure 5-6 Abrasion Results of Aged Samples

Table 5-5 Statistical Analysis of Abrasion Test with ANOVA

	7 Day and 21 Day Abrasion Resistance Test Results (g)		*21 Day and 28 Day Abrasion Resistance Results (g)*	
	7 Day Wt. Loss	**21 Day Wt. Loss**	**21 Day Wt. Loss**	**28 Day Wt. Loss**
Observation	**6**	**5**	**5**	**7**
Mean	**4.22**	**7.08**	**7.08**	**5.3**
Variance	**0.67**	**5.4**	**5.4**	**1.13**
Hypothesized Mean Difference	**0**		**0**	
Pooled Variance	**2.7**		**2.85**	
df	**9**		**10**	
t Stat	**2.81**		**1.79**	
P (Two Tail Dist)	**0.02**		**0.1**	
t_{crit} (5%)	**2.26**		**2.22**	
Outcome	**Statistically Different**		**Statistically Same**	

To find a relationship between compaction (or compressive strength) and abrasion resistance, samples with different compaction were also casted for this test. The test results are presented in Figure 5-7.

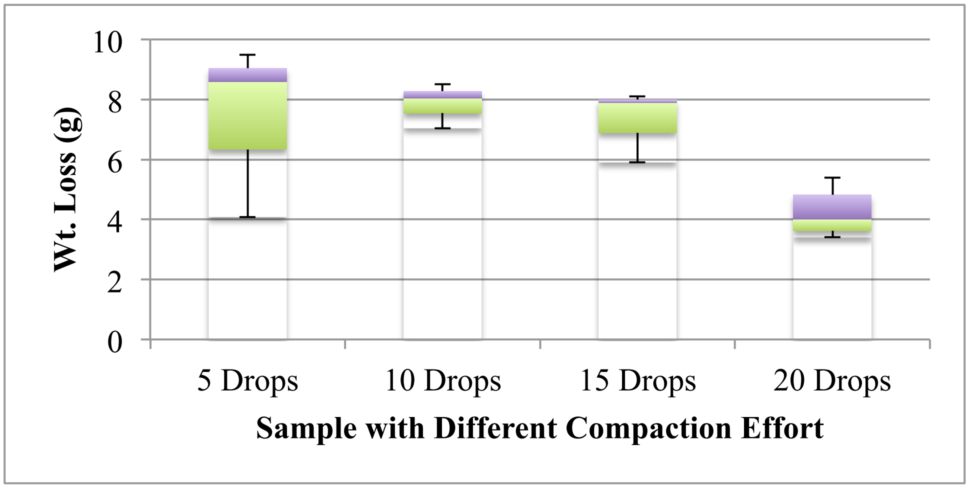


Figure 5-7 Abrasion Results of Samples with Different Compaction Effort

This result presents that the higher number of drops of the hammer results in increased compressive strength and also increased abrasion resistance. Therefore, the amount of weight loss decreases with the higher number of Proctor hammer drops per layer.

5.1.5.2 LA Abrasion Test Results

As stated earlier, the LA Abrasion test was performed following ASTM C 1747/C 1747M. The standard does not suggest any accepted or reference range of weight loss. For this project the range of mass loss found in the range of 21.6%-24.5% with a mean of 23% and coefficient of variation is 4.13.

The test results are presented in Table 5-6.

Table 5-6 LA Abrasion Test Results

Sample Set	*Mass Loss in %*	*Mean*	*STDEV*	*COV*
1	**21.6**	**23.0**	**0.95**	**4.13**
2	**22**			
3	**23.5**			
4	**22.9**			
5	**23.3**			
6	**24.5**			

5.1.6 Freeze Thaw Testing

The results of freeze thaw testing for both procedures are presented in Table 5-7. For each procedure, six samples were evaluated. The table includes the results for the relative dynamic modulus of elasticity and the Durability Factor (DF). As stated earlier in section 4.2.7, transverse frequency was evaluated at every 36 cycles. From transverse frequency the relative dynamic modulus of elasticity and durability factor were calculated using equation 4.6 and 4.7 respectively, presented in Chapter 4. Durability Factor (DF) is an indicator of the internal damage of the samples due to the thermal expansion and contraction effects of water (FHWA, 2012)

The ASTM C666 standard requires that for conventional concrete, the freeze thaw testing shall continue until the relative dynamic modulus reaches 60% or 300 cycles, whichever is lower. For this research, in several cases it was found that the relative dynamic modulus was lower than 60% of the initial results even just after 36 cycles for some of the samples but the physical condition of the sample was good (i.e. no aggregate loss, not brittle or damaged). So freeze thaw continued until the samples broke.

Table 5-7 Summary of Freeze Thaw Testing

Procedure	*Sample*	*Relative Dynamic Modulus of Elasticity (%)*								*Durability Factor (DF)*
		Number of Freeze Thaw Cycle								
		0	**36**	**72**	**108**	**144**	**180**	**216**	**252**	
A (Freezing and Thawing in Air)	**1**	**100**	**74.1**	**63.1**	**43.8**	**43.8**	**43.8**	**43.8**	**x**	**43.8**
	2	**100**	**64.4**	**63.3**	**63.3**	**44.7**	**44.7**	**x**	**x**	**44.7**
	3	**100**	**58.7**	**56.4**	**37.02**	**37.02**	**37.02**	**37.02**	**37.02**	**37.0**
	4	**100**	**57.9**	**43.7**	**36.1**	**36.1**	**x**	**x**	**x**	**36.1**
	5	**100**	**37.6**	**37.6**	**37.6**	**x**	**x**	**x**	**x**	**37.6**
	6	**100**	**58.6**	**44.7**	**44.7**	**x**	**x**	**x**	**x**	**44.7**
	Average	**100**	**59.0**	**52.8**	**44.9**	**42.8**	**41.8**	**40.4**	**37.0**	
B (Freezing in Air and Thawing in Water)	**1**	**100**	**84.3**	**84.3**	**78.2**	**66.08**	**x**	**x**	**x**	**66.1**
	2	**100**	**59.3**	**41.9**	**41.8**	**41.8**	**x**	**x**	**x**	**41.8**
	3	**100**	**68.9**	**44.1**	**x**	**x**	**x**	**x**	**x**	**44.1**
	4	**100**	**39.9**	**39.5**	**39.5**	**x**	**x**	**x**	**x**	**39.5**
	5	**100**	**93.9**	**46.9**		**x**	**x**	**x**	**x**	**46.9**
	6	**100**	**52.9**	**46.2**	**46.2**	**x**	**x**	**x**	**x**	**46.2**
	Average	**100**	**66.5**	**50.4**	**51.4**	**53.9**				

*x represents samples were broken

The average relative dynamic modulus of elasticity is presented in Figure 5-8.

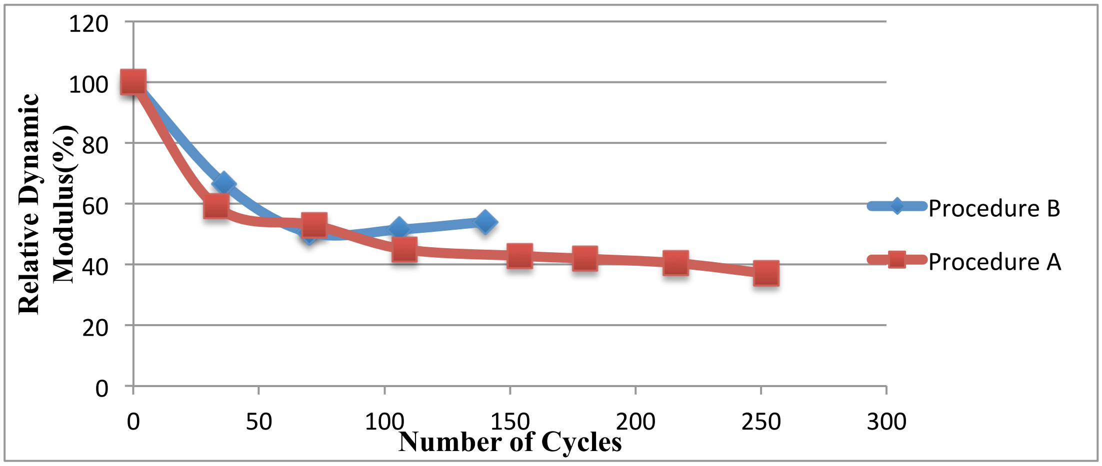


Figure 5-8 Relative Dynamic Modulus vs. Number of Freeze Thaw Cycle

The test results show that with procedure A (freezing and thawing in water) more cycles could be reached. However, it must be noted that procedure B better replicates field condition as it can be assumed that in the field, water generally does not get trapped in the void. But, at CPATT, procedure B was conducted manually and manual handling of samples might have caused extra damage to samples during handling which may have resulted an premature break up.

5.1.7 Scaling Resistance Testing

Modified ASTM C672/C672M standard test method was used for scaling resistance testing of pervious concrete. With Calcium Chloride ($CaCl_2$) better performance was observed than with Sodium Chloride (NaCl). The condition of the samples after 50 cycles is presented in Figure 5-10. Freeze thaw cycles with salts made the samples brittle compared with the initial condition.

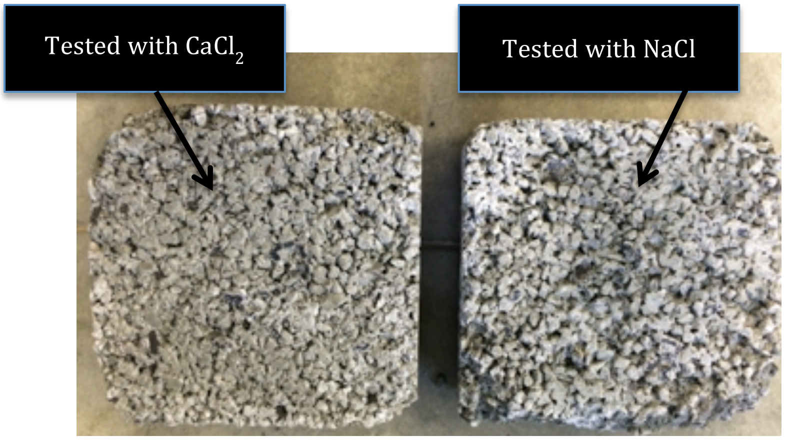


Figure 5-9 Scaling Samples after 50 Freeze Thaw Cycles

5.2 Test Results for Field Cores

A comparative study of the field condition is presented in Table 5-8, of the sites the cores were collected from.

Table 5-8 Overall Surface Condition and Observed Distresses of the Sites

Site	*Overall Condition*	*Probable Explanation*
Barrie Commuter Parking Lot	80-90% severe ravelling, 20-30% of abrasion, 20-30% of cracking	Improper Mix design
Evergreen Brickworks	80-90% severe ravelling, 40-50% of abrasion, 50-60% of cracking	Improper Mix design
Georgetown	80-90% of surface clogging, less than 10% ravelling, less than 10% cracking	Surrounding Condition
Kortright Centre	No ravelling, cracking or abrasion found	Proper mix design, Surrounding condition

5.2.1 Microscopic Analysis

To better understand the field performance a microscopic analysis was conducted. This involves slicing core samples into 25mm (1") thick samples. The samples were then evaluated for micro cracking, cracking pattern, and cracking frequency. Figure 5-11 to

Figure 5-14 present the pictures from the microscope. The cracking is marked with a red circle.

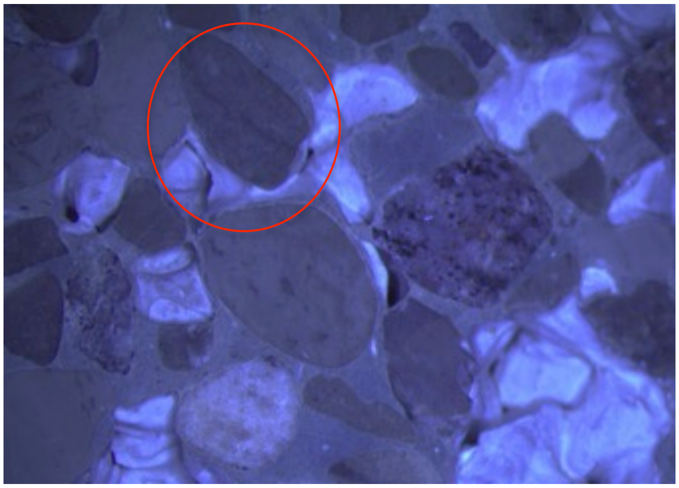


Figure 5-10 Microscopic Picture of Core from Barrie

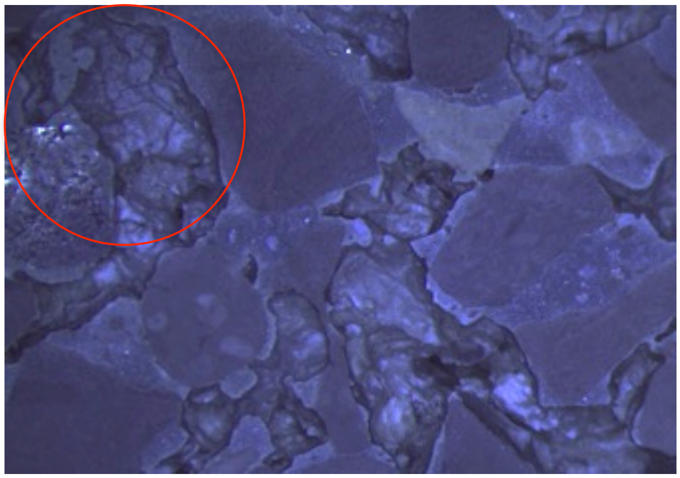


Figure 5-11 Microscopic Picture of Core from Evergreen Brickworks

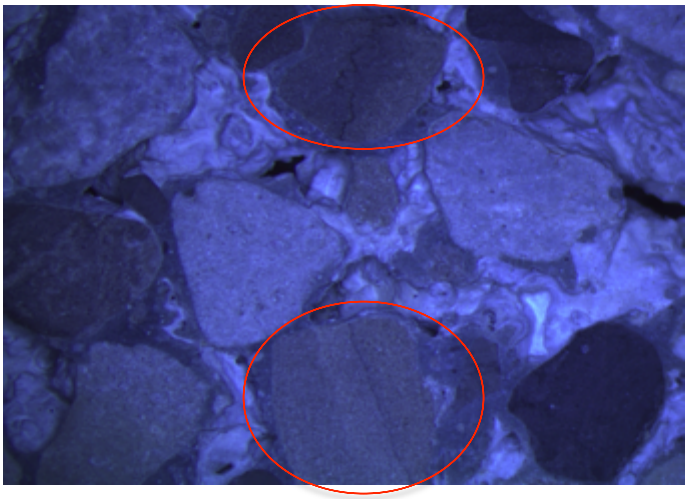


Figure 5-12 Microscopic Picture of Core from Georgetown

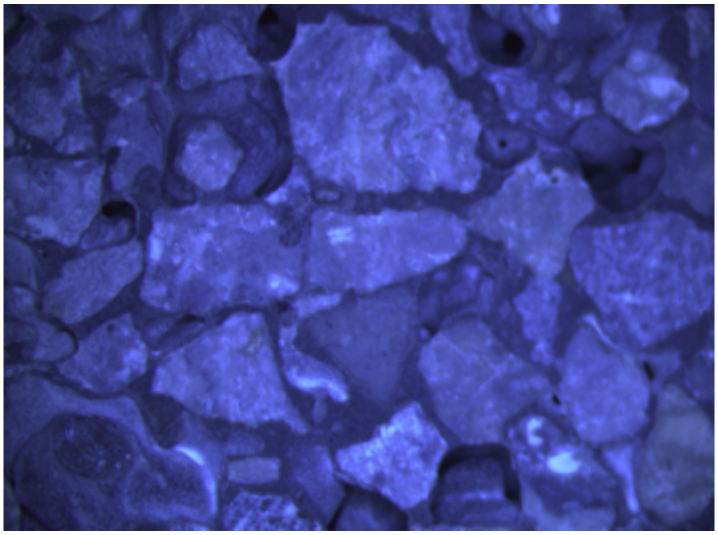


Figure 5-13 Microscopic Picture of Core from Kortright Centre (No cracking found**)**

From the microscopic pictures, it is found that aggregate cracking and, to some extent shrinkage cracking, is present in the cement paste in Barrie, Georgetown and Evergreen Brickwork sites. In the cores of Kortright site, neither shrinkage cracking nor fractured aggregate was found. According to the field performance, Kortright is performing well with no ravelling nor cracking. The three other sites that CPATT removed cores from, show ravelling, cracking and aggregate loss. It would appear that micro cracking in aggregate and within the cement paste could be the reason behind this observed field performance.

5.2.2 Petrographic Analysis

A petrographic analysis was performed on the field concrete samples to check if it can have any impact on the observed distresses in the field i.e. raveling and cracking. This test was performed in the University of Toronto under the supervision of Professor Karl Peterson. The procedure followed in this study is the petrographic method presented in the petrographic manual by the Federal Highway Administration, Research and Development, Turner-Fairbanks Highway Research Center, McLean, Virginia, U.S. (Walker, 2006). It was assumed that with Petrographic analysis, it would be easier to evaluate the existing concrete structure, the bonding characteristics between the aggregate and the paste, air void distribution, and distress pattern in the sample.

One cm thin-sections were sliced from the field samples. All the pores and cracks were filled with a fluorescent epoxy, and then 30-micrometer thick slices were cut from them, each covering an area of about 20 x 40 mm (a thin section). The thin sections then were put on an x-y mechanical stage, and recorded a mosaic of images covering the area of each thin section with a microscope equipped with a 1.25x objective lens. After collecting the images, they were stitched together using a plug-in written for ImageJ. In the pictures, places where there were cracks or pores, look bright because they were filled with the fluorescent epoxy. Blue light (430-510nm) was used to excite the fluorescent dye (Tigris Yellow D-043) and make the epoxy fluorescent. The fluorescent dye then emits green light (520-580 nm). A yellow blocking filter (allows only light with a wavelength >515nm to pass through) was used to block out the blue excitation source, so whatever is seen in the pictures is the green light produced by the fluorescent dye. The pictures are presented in Figure 5-14 to Figure 5-17. All the figures are fluorescent images, so those appears bright are porosity and cracks where the fluorescent resin has penetrated.

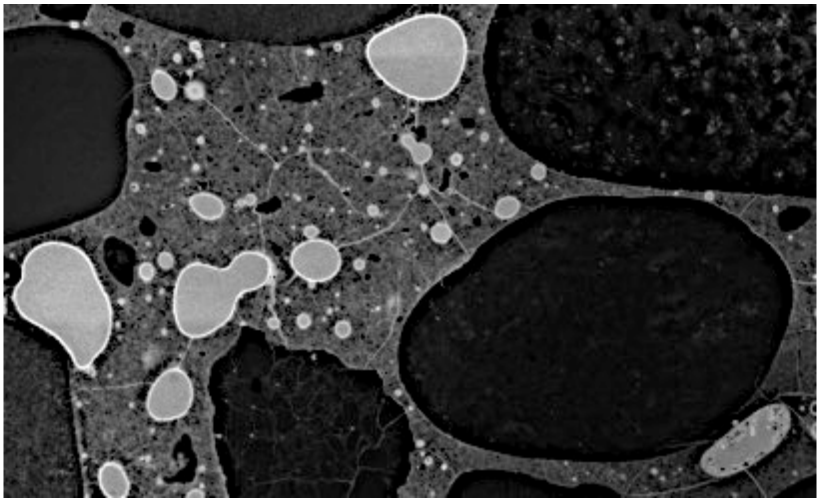


Figure 5-14 Fluorescent Image from Barrie Site

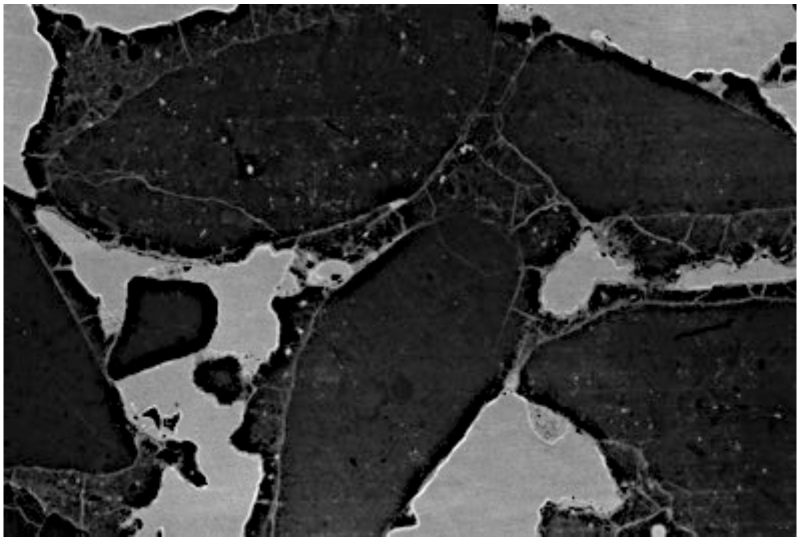


Figure 5-15 Fluorescent Image from Evergreen Brickwork Site

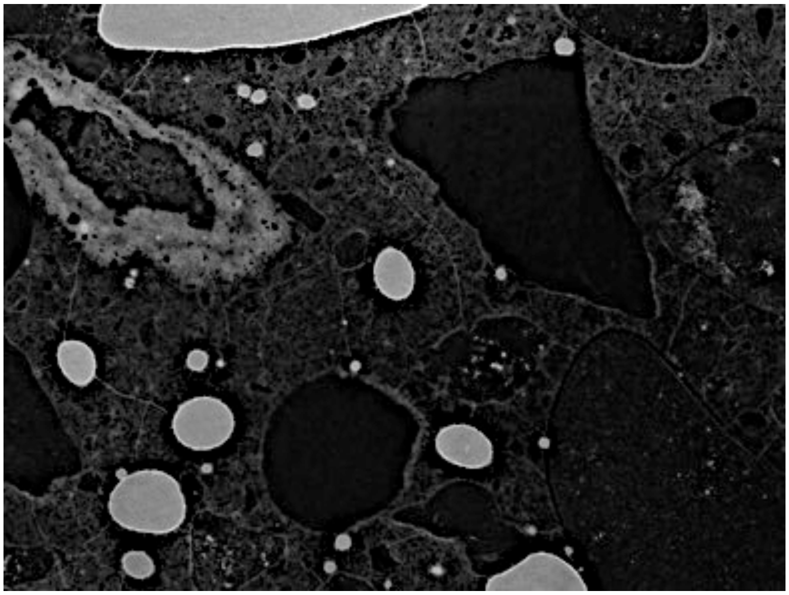


Figure 5-16 Fluorescent Image from Georgetown Holcim Plant

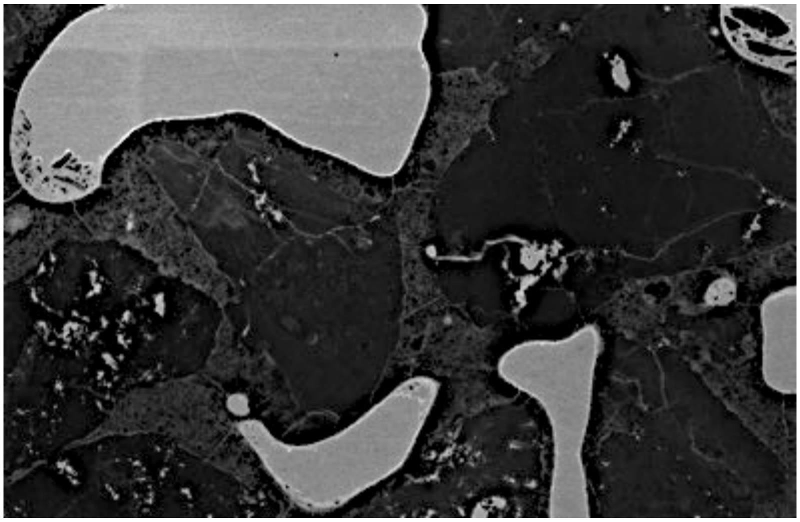


Figure 5-17 Fluorescent Image from Kortright Centre

From the petrographic analysis, it seems that all of the pervious concrete samples had freeze thaw related cracking issues. The samples from Barrie show addition of air entrainment in the mix, those from Georgetown and Evergreen Brickwork show that had some fines in the paste.

It doesn't appear that the raveling has much to do with the aggregate/paste bond, but more to do with the fact that the cement paste is all cracked up in the samples of Barrie and Evergreen Brickworks sites. For the Kortright Centre and the Georgetown plant, this type of cracking in the paste is minimal.

5.2.3 Density and Void Content

Density and harden void content of the cores from the four sites were determined and are presented in Table 5-9. Kortright centre shows a higher average void content of 26.7%, while Barrie also has close air voids but the performance of Kortright site is significantly better than Barrie possibly due to the mix design, traffic loading or traffic maneuver.

Table 5-9 Density and harden void content of Field Cores

Site	*Construction Year*	*Avg. Density(kg/m^3)*	*Avg. Void Content %(Harden)*
Barrie	2011	1907.5	24.9
Evergreen Brickworks	2010	2014.6	20.1
Georgetown	2007	2106.6	17.1
Kortright Centre	2009	1940.4	26.7

5.2.4 Compressive Strength Testing

Compressive strength testing was performed in a similar manner as done with the lab cast samples. The test results are presented in Table 5-10. From the results it can be shown that the highest average compressive strength was found for Georgetown site, while Barrie and Kortright Centre are also in the same range. Evergreen Brickwork shows consistent low results, with the lowest average compressive strength, which can be the probable explanation behind its poor performance. For Barrie, though average compressive strength is 19.1 MPa, but poor field condition was observed as described in Table 5-8. The compressive strength range for Barrie was found from 24.3 MPa to 15.8 MPa, with an average of 19.1 MPa, a standard deviation of 4.5 MPa and a coefficient of variation (COV) of 23.7 MPa, therefore, consistency was low. Again, for Georgetown site, only two samples were tested for compressive strength, the result was inconsistent (one result is the highest and the other one is the lowest) with a COV value of 73.6 MPa. For Kortright Centre, very consistent result was found. Thus it can be assumed that consistent compressive strength result can predict field performance. From the test results it can be anticipated that to achieve superior performance (i.e., minimal raveling, cracking, abrasion) minimum compressive strength should be 18 MPa and the results must be consistent.

Table 5-10 Compressive Strength Test Results of Field Cores

Site	*Sample*	*Compressive Strength (MPa)*	*Avg. Compressive St. (MPa)*	*Standard Deviation (MPa)*	*Coefficient of Variation (COV) (MPa)*
Barrie	1	17.3	19.1	4.5	23.7
	2	15.8			
	3	24.3			
Kortright Centre	1	19.8	19	0.8	4.4
	2	18.1			
	3	18.9			
Evergreen Brickworks	1	13.8	13.3	0.6	4.1
	2	12.7			
	3	13.4			
Georgetown	1	29.5	19.7	19.4	73.6
	2	9.9			

5.2.5 Abrasion Resistance Test

Abrasion resistance testing was performed in a similar manner on the lab cast samples. The test results are presented in Table 5-11. No direct relationship between the weight loss and the ravelling was found.

Table 5-11 Rotary Cutter Abrasion Test Results of Field Cores

Site	*Sample*	*Wt. Loss (g)*	*Avg Wt. Loss (g)*	*Site*	*Sample*	*Wt. Loss (g)*	*Avg Wt. Loss (g)*
Barrie	**1**	**12.4**	**13.2**	**Evergreen Brickworks**	**1**	**9**	**11**
	2	**15.2**			**2**	**12.8**	
	3	**12**			**3**	**11.2**	
Kortright Centre	**1**	**10.5**	**11**	**Georgetown**	**1**	**19.4**	**13.8**
	2	**9.3**			**2**	**14.2**	
	3	**13.2**			**3**	**7.8**	

5.2.6 Test Results Summary for the Field Samples

According to the field performance, Kortright is in very good shape with no ravelling or cracking. Georgetown site does not show much ravelling but it is clogged with surrounding debris. Barrie and Evergreen Brickworks site show drastic ravelling.

The summary of test results is presented in Table 5-12.

Table 5-12 Summary of Test Results on Field Samples

Sites	*Density (Kg/m^3)*	*Harden Air Void (%)*	*Avg. Comp. Strength (MPa)*	*Avg. Abrasion Wt. Loss (g)*
Barrie	1907.5	24.9	19.1	13.2
Kortright Centre	1940.4	26.7	19.0	11
Evergreen Brickwork	2014.6	20.1	13.2	11
Georgetown Plant	2106.6	17.1	19.9	13.8

From the test results, it can be stated that density is not directly related to the harden void content which was assumed from the laboratory test results. The field results also follow the similar trend. Harden void content depends on the compaction procedure.

Now if the Kortright Centre site is taken as a reference of well performing site, it can be predicted that the compressive strength should be minimum 18 MPa with consistency, to avoid ravelling. As minor raveling was observed in the Georgetown Plant and the compressive strength of this site is also high, so this statement is also valid here. But this statement is contrary with the Barrie site results. As explained in section 5.2.4, for Barrie,Do low consistency was observed among the data. The Evergreen brickwork site exhibits consistent lower compressive strength as well as drastic ravelling.

No direct relationship between abrasion test results and ravelling was found. Similar weight loss was observed in the samples from Kortright Centre and Evergreen Brickworks site. But one is performing well and the other is exhibiting drastic ravelling.

Cracking was not taken into consideration as in all the four sites minimal cracking was observed.

From the microscopic images and the petrographic analysis, it could be concluded that the paste characteristics in the structure affects the pavement performance. Ravelling could be directly related to it, as micro cracking is available in the paste of the samples from the poorly performing sites.

Chapter 6

Long Term Drainage Performance of Pervious Concrete Pavements

In this chapter the drainage methodology, rain event, movement of moisture in the pavement structure and analysis criteria are presented. The work presented in this chapter is a continuation of the work done by Dr. Vimy Henderson and could be found in Henderson, 2012. This extended study has also been presented in the conference of Transportation Association Canada (TAC), 2014.

6.1 Pervious Concrete Sites

Five pervious concrete test sides were constructed in different provinces of Canada, (Henderson, 2012). Initial performance and moisture movement in the pavement was observed till winter, 2011 and could be found in Henderson (2012). Instrumentation performance at the end of five years (till 2013) of the site constructed in British Columbia (BC) is presented in this Chapter.

6.2 Site Description

In the Spring of 2008, Rempel Brothers Concrete in partnership with CPATT and the Cement Association of Canada, constructed pervious concrete test areas in Maple Ridge, BC. Personal vehicles, loaded and unloaded concrete trucks, were the main vehicles in this parking area. There were two 1m wide sections in this site, addressed as 3A and 3B in this Chapter. 3A is located on the entrance and 3B is on the exit driveway of the concrete plant.

6.2.1 Instrumentation

This site was instrumented with 15 moisture gauges at different heights ranging from pervious concrete layer to existing subgrade. There are two sensor trees (A and B) in section 3A and two sensor trees in section 3B (C and D). Figure 6-1 to Figure 6-4 represents the sensor trees in Site 3, could also be found in (Henderson, 2012).

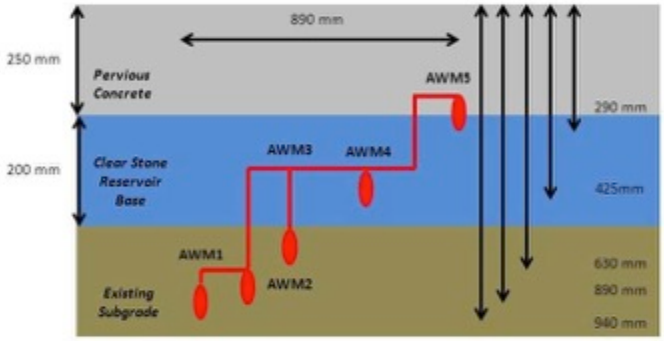


Figure 6-1 Sensor Tree A at Section 3A (Henderson, 2012)

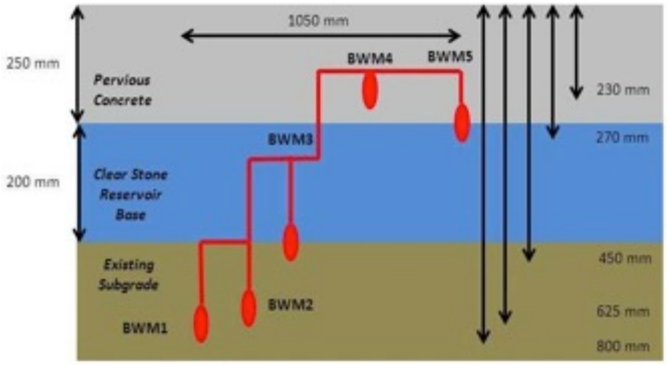


Figure 6-2 Sensor Tree B in section 3A (Henderson, 2012)

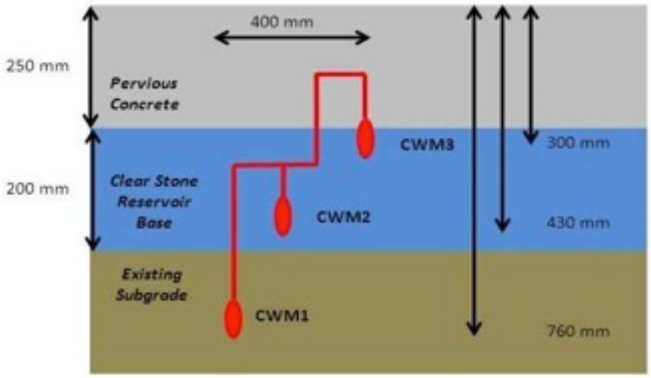


Figure 6-3 Sensor Tree C in section 3B (Henderson, 2012)

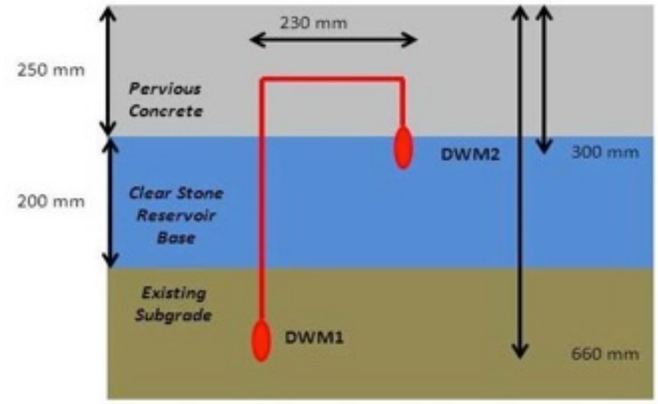


Figure 6-4 Sensor Tree D in section 3B (Henderson, 2012)

A weather station was installed at the site to collect the temperature and precipitation (rain) data. Most of the weather data was collected from the weather station. It was decided that, during the winter, the weather station was brought indoors due to site security and lack of activity at the location and the missing data was collected from the Environment Canada weather station at West Abbey, which is about 15 km away from the site.

6.2.2 Analysis Methodology

The intent of this study was to build on the previous work of Henderson to produce moderate term performance measurements. The analysis methodology is thus consistent with the previous work (Henderson, 2012). To represent the season, the weather data is divided in four groups annually. They are: Winter (December to February), Spring (March to May), Summer (June to August), Fall (September to November). To understand the movement of water in the pavement structure, the soil water potential (SWP) data of the largest rain event of each season is presented in this paper. To evaluate the largest rain event of the season from the daily rain data, continual summation of five days rain was used. Preferably a rain event, which was large in quantity and had minimal rain after and before for several days, is taken into account in this research. It was expected that considering this situation, it would be relatively easy to follow the moisture movement in the structure.

6.2.3 Instrumentation Functioning

The moisture tree in the pervious concrete field sites was designed to evaluate how water moves through the structure. Field permeability can show only the surface percolation rate but with moisture gauges the drainage methodology can be determined by collecting and analyzing the data. Generally SWP in centibar (cb) is collected from the moisture gauges. When the availability of water is higher the SWP is lower and vice versa. For example, SWP data of the moisture gauge AMW5, which is closest to the surface, during a rain event of 100 mm over 7 days is presented in Figure 6-5.

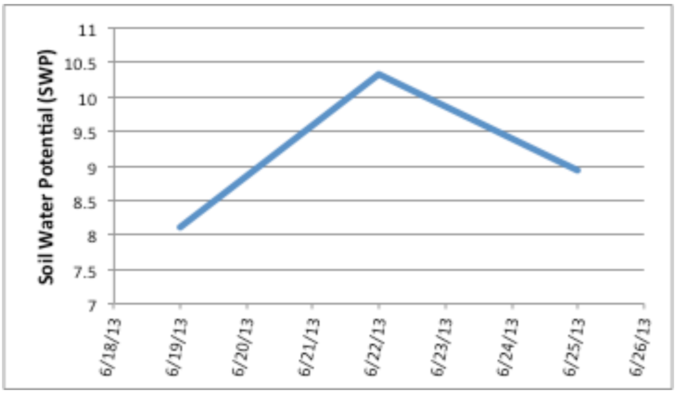


Figure 6-5 Example of SWP data

It shows that from June 19th to 22nd the slope is positive, which means water is draining away from the instrumentation at a higher rate than it is coming into the area. Therefore availability of water is decreasing providing dry soil. After that the slope becomes negative, which indicate the amount of water moving into the instrumented area is higher than that is draining away from it. So, the soil is wet.

6.2.4 Long Term Performance

One of the initial rain events after construction in winter 2009, with a five days total rainfall of 183 mm, is presented in Figure 6-6. From the figure it is clear that the SWP value of the moisture gauge AWM5 is the lowest with the high amount of rainfall. It can be easily understood that as AWM5 is the closest to the surface, water is more available to it after rain and the more the water is available the less the SWP value is. SWP of AWM1 (which is lowest in the subgrade) is the highest as it can be assumed that the amount of water is lower in the subgrade than surface because of absorption, evaporation etc.

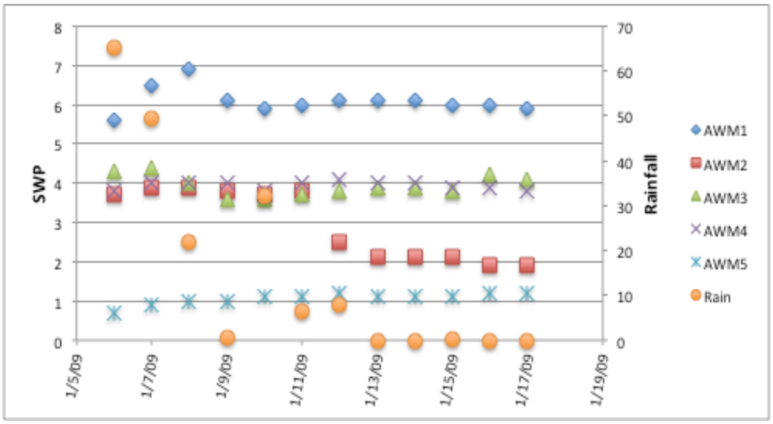


Figure 6-6 SWP value of sensor tree A in Winter 2009

Figure 6-7 represents the SWP value of sensor tree A in winter 2013. At that time the amount of rain was much lower than that of winter 2009. From the Figure 6-7, it can be seen that the SWP values are just opposite of the result of winter 2009. The explanation of this condition is, as less water is available on the surface, SWP of AWM5 is high. But in general subgrade soil can hold some moisture, it remains wetter than the surface, so the SWP of AWM5 is lower.

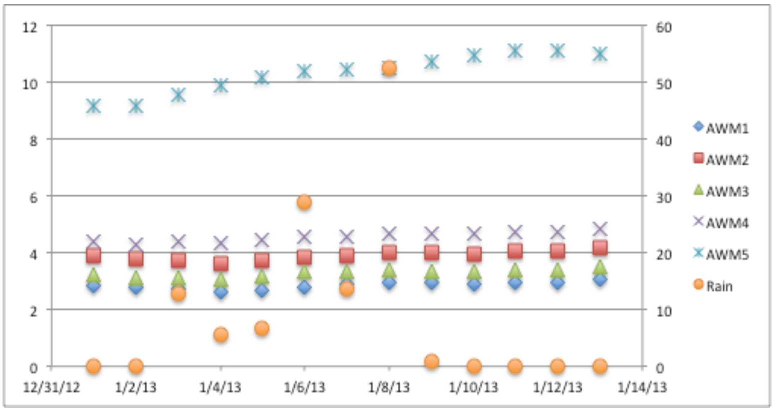


Figure 6-7 SWP of the Sensor Tree A in Winter 2013

Comparing these two figures, the changes is in SWP value with rain is prominent. It can be assumed that the instrumentations were working properly.

6.2.5 Moisture Movement with Rain Event

Table 6-3 shows the moisture movement into the structure from winter 2013 to fall 2013 (data of recent one year). Previous moisture movement data (after construction till winter 2011) was presented in work by Henderson (Henderson 2012). The continuation of that work and long-term instrumentation performance is presented in this section.

To evaluate the movement of moisture through the structure, rain event in each season is collected. As noted earlier, rain over five days was initially considered. But, in some cases, extensive amount of rain would occur over more than five days. When deemed appropriate, these events were also included.

The column “Entering Area” in the Table 6-3 refers to the SWP results showing a negative slope, as shown in Figure 6-5. Therefore more moisture was draining into the instrumented area than out of it and, which render wet soil. The column entitled “Draining Area” refers to the SWP results showing a positive slope, which renders dry soil as shown in Figure 6-5. The day that the rain event started is numbered 0. The values in the “Entering Area” and “Draining Area” represent the day(s) after the initiation of the rain event that the behaviour was noticed in the SWP results. The rain event of the year 2013 is presented in Table 6-4.

Table 6-1 Moisture Movement in the Site

Moisture Gauge Location	***Date***	***Time from Rain Event to Instrumented Area (Days)***	
		Entering Area	Draining Area
Pervious Concrete Layer (230 mm) BWM4	Winter 2013	6,8	0,1-5,7,9
	Spring 2013	0-1,3-5,8,9,13	2,6-7,10-12
	Summer 2013	4-5, 7-8	0,1-3,6, 9-10
	Fall 2013	6	0,1-5, 7-9

Pervious Concrete and Clear Stone Interface (270 mm – 300 mm) AWM5 BWM5 CWM3 DWM2	Moisture Gauge	AWM5	BWM5	CWM3	DWM2	AWM5	BWM5	CWM3	DWM2
	Winter 2013	0,1,2,8	8	3-5,7,8		3-7,9	0,1-7,9	0,1-7,9	
	Spring 2013	0,1,3-6,8,9,11	0,1,3-9,11	0,1-3,7-9,11,13	3,5,7,8	2,7,10,12,13	2,10,12-13	4-6,10,12	0,1,2,4,6,9-13
	Summer 2013	4-10	1,10	1-3,5-9	2-9	1-3	2-9	4,10	0,1,10
	Fall 2013	0,1	3,4,8	0,1,3,6,8	0,1-4,8	2-9	0,1-2,5-7,9	2,4,5,7	5-7,9
Clear Stone (425 mm) AWM4 CWM2	Moisture Gauge	AWM4		CWM2		AWM4		CWM2	
	Winter 2013	0,1,6,8,9		0,1,5,6,8,9		2-5,7		2-4,7,	
	Spring 2013	2-5,8,9,11		0,1-3,7,8,11,13		0,1,6,7,12-13		4-6,9,10	
	Summer 2013	0,1,3-5, 8		0,1-8		2,6-7,9-10		9,10	
	Fall 2013	0,1,3,8,9		3-6,9		2,4-7		0,1-2,7,8	
Clear Stone and Subgrade Interface (450 mm) BWM3	Winter 2013	2,4,6,8,9				0,1,3,5,7			
	Spring 2013	6,10,11				0,1-5,7-9,12,13			
	Summer 2013	1,5,6,7				2-4, 8-10			
	Fall 2013	0,1,5				2-4,6-9			
Subgrade (630 mm - 660 mm) AWM3 BWM2 DWM1	Moisture Gauge	AWM3	BWM2	DWM1		AWM3	BWM2	DWM1	
	Winter 2013	0,1,6,8,9	1,6,8,9	0,2,5,6,8,9		2-5,7	0, 2-5,7	1,3,4,7	
	Spring 2013	2-5,9,11	0,6,10,11	0,2,3,6-9,11,13		0,1,6-8,12-13	1-5,7-9,12-13	1,4-5,10,12	
	Summer 2013	0,1,4-6,	0,1,5-7	0,1,2,5,6		2,7-10	2-4,8-10	3,4,7-10	
	Fall 2013	1-3,8,9	0,1,5	1-3,8,9		0,4-7	2-4, 6-9	0, 4-7	
Subgrade (760 mm – 800 mm) CWM1 BWM1	Moisture Gauge	BWM1		CWM1		BWM1		CWM1	
	Winter 2013	0,1,5,8,9		0,1,8,9		2-4,6,7		2-7	
	Spring 2013	2-5,9,11,13		0,3-6,8-10		0,1,6-8,10,12		1-2,11-13	
	Summer 2013	0,1,5		5-6		2-4,6-10		0,1-4,7-10	
	Fall 2013	0,1-3,8,9		3,8,9		4-7		0,1-2,4-7	
Subgrade (890	Winter 2013	0,1,6,8,9				2-5,7			

mm) AWM2	Spring 2013	2-5,9,11	0,1,6-8,12-13
	Summer 2013	0,1,5,6,8	2-4,7,9-10
	Fall 2013	0-3,8,9	4-7
Subgrade (940 mm) AWM1	Winter 2013	0,1,6,8,9	2-5,7
	Spring 2013	2-5,9-11	0,1,6-8,12-13
	Summer 2013	0,1,5,6,8	2-4,7,9-10
	Fall 2013	0-3,8,9	4-7

Table 6-2 Rain Event of 2013 adapted from Environment Canada Mission West Abbey Climate Data (2014)

Winter			*Spring*			*Summer*			*Fall*		
Date	Day	Rainfall (mm)	Date	Day	Rainfall (mm)	Date	Day	Rainfall (mm)	Date	Day	Rainfa (mm)
1/3/13	0	12.8	3/1/13	0	36.6	6/19/13	0	41.4	11/1/13	0	34.8
1/4/13	1	5.6	3/2/13	1	14.6	6/20/13	1	33	11/2/13	1	0
1/5/13	2	6.6	3/3/13	2	0	6/21/13	2	0	11/3/13	2	0.6
1/6/13	3	28.8	3/4/13	3	0	6/22/13	3	0	11/4/13	3	2.8
1/7/13	4	13.6	3/5/13	4	0	6/23/13	4	10.2	11/5/13	4	20.4
1/8/13	5	52.4	3/6/13	5	9.6	6/24/13	5	3.8	11/6/13	5	31.4
1/9/13	6	1	3/7/13	6	2	6/25/13	6	11.8	11/7/13	6	3.6
1/10/13	7	0	3/8/13	7	0	6/26/13	7	8	11/8/13	7	0
1/11/13	8	0	3/9/13	8	0	6/27/13	8	1.2	11/9/13	8	0
			3/10/13	9	2.6	6/28/13	9	0	11/10/13	9	0
			3/11/13	10	19	6/29/13	10	0			
			3/12/13	11	76.8						
			3/13/13	12	14.6						
			3/14/13	13	18.2						

From the majority of the results from the moisture tree A, it appears that water moves vertically through the structure. For example, in the spring of 2013, on day 0 and 1, there was a 36.6 mm and 14.6 mm of rainfall respectively. It was found that moisture moves through the AWM 5, which is 290 mm below from the surface on day 0 and 1. From day 2 onwards, moisture was found to move the deeper from 425mm to 940mm (from AWM 4 to AWM 1). Moisture moves through all the layers instrumented by sensor tree B on day 0,1 and 2, which indicates that moisture moves from the depth 230 mm to 800mm. Data from sensor tree C also follows the same trend. But, DWM 2 does not show any evidence of movement of moisture before day 3, though DWM 1 (which is in subgrade, at the depth 660mm) shows the presence of water from day 0 and 1.

BWM4 and BWM5 did not show any presence of water before day 6 in the winter 2013. The probable reason could be that, as the amount of rainfall was not heavy until day 4, water could have been absorbed or evaporated before reaching the moisture gauge BWM4 at the depth 230mm. As a heavy rainfall (52.4mm) occurred at day 5, presence of moisture is prominent at day 6 and onward. Although, BWM3, BWM2 and BWM1 show the movement of water from day 0/1.

In some cases, Sensor Tree C and Sensor Tree D act different in comparison to the other sensor trees. Sometimes, CWM3 and CWM2 show continuous increase in moisture though the availability of water from rain was not that high.

6.3 Summary

To verify the functionality the analysis of moisture movement is presented in this chapter. From the above discussion it is obvious that it is difficult to identify the vertical movement of water in the pavement structure. It can be assumed that continuous movement of moisture has not occurred from the surface to the subgrade due to low permeability, loss of water due to evaporation, absorption etc. In many of the movement data, it was found that rain event occurred but water did not enter even the closest instrumented area. The possible reason of this could be water remains on the surface because of clogging or evaporated before it started to drain. However, from the moisture gauge results, it can be assured that moisture is moving and draining through various parts of the structure not through the whole structure.

Therefore it can be anticipated that this pervious concrete is not performing as expected and showing less drainage capabilities.

Chapter 7

PERVIOUS CONCRETE IN LOW VOLUME ROAD APPLICATIONS

7.1 Pervious Concrete and Low volume Road (LVR)

Pervious concrete pavement is a sustainable pavement technology that is an alternative product for low-volume applications. Almost two thirds' of Canada's public roads are either gravel, surface treated, or earth (Government of Alberta, 2013). Other types of surfacing on low volume roads include Thin Bituminous Surfacing (TBS) treatments such as Cold Mixed Cold Laid (CMCL) surfaces and Bituminous Surface Treatments (BST), chemically stabilized surfaces, and some HMA pavements and concrete pavements (Transportation Association Canada, 2013).

As stated earlier, pervious concrete pavement is mostly suitable for low volume traffic roads (Henderson, 2012). To date, most of the data available on pervious concrete are from driveways, sidewalks and parking lots. However, in this chapter only parking lot data has been provided. These data from parking lots can be correlated with low volume roads, as the traffic volume is similar in both cases. However, traffic speed and the driving patterns are often different. It can be assumed that in parking lots, most loads are standing, turning and breaking loads, which can affect the pavement performance. As pervious concrete parking lots are able to withstand this loading, it can be predicted that it would also be durable as low-volume road. In 2011, in Minnesota, several test cells of LVR were constructed with pervious concrete with a design life of 10 years. Road reliability was evaluated with the American Concrete Pavement Association (ACPA) StreetPave Software. All of the LVR test sections passed with a reliability of 90 (Izevbekhai, Akkari, 2011)

7.2 Benefits of Pervious Concrete in Low Volume Road

There are many associated benefits with using pervious concrete pavement compared to the regular low volume roads pavements commonly used.

7.2.1 Dust control

Dust is a very common problem and a safety concern with gravel road. Various kinds of treatments should be adopted to avoid this issue (Transportation Association Canada, 2013). With pervious concrete pavement it can be eliminated easily. Pervious concrete pavement provides a dust free, smooth, and safe surface.

7.2.2 Drainage Control

It is important to control and facilitate proper drainage is important in pavement infrastructure. Often, with improperly maintained not only gravel roads, also other roads, shoulders can be higher than the travelling lane, which causes drainage issues. Roadside drainage and ditches are also important in conventional design (Transportation Association Canada, 2012). Using pervious concrete pavement can eliminate these drainage facilities and reduce the cost of the pavement structure. It also maximizes land uses, as no ditches are required and reduces the likelihood of flooding (Henderson, 2012).

7.2.3 Heat Control

Pervious concrete pavement can minimize the heat island effect and increase reflectivity (Henderson, 2012). The main reason for both of these benefits is attributed to the light grey colour of concrete, whereas the asphalt overlaid low volume road is black in colour. 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 (Henderson, 2012). Another study reported that in hot weather conditions, conventional paving materials can reach of 50°C to 65°C and transmit excess heat to the air above them as well as heat stormwater as it runs across pavements (Rhead, 2012). Porous parking lots have been shown to lower surface temperature and it allows unheated water to infiltrate directly to ground water table minimizing the impact on the aquatic ecosystem (Rhead, 2012). Besides, as the urban heat islands effect on humans are of great concern to communities and cities, reduction of urban heat island effect is a great benefit to the environment. Besides the quality of heat control of pervious pavement it can mitigate the cooling costs of surrounding community.

7.2.4 Lighting Requirements

The light colour of pervious concrete pavement results in greater reflectivity and reduces the amount of lighting infrastructure required to create the desired brightness of parking lots and paths during evening and night use (Henderson, 2012).

7.2.5 Economic

Pervious concrete pavement is a cost effective sustainable pavement technology. With this pavement, the requirement of stormwater retention ponds or infrastructure such as pipe network can be eliminated. It also reduces property space as well as probability of flooding (Rhead, 2012). The infiltrated water through pervious concrete can be transferred to surrounding gardens and lawns to provide natural moisture and thus can be used in the water harvesting system. It limits the expense of watering as well as water demand (Henderson, 2012).

7.3 Parking Lots Site

The six case studies included in this chapter were constructed between 2007 and 2011 with varying levels of monitoring. These sites were located across Canada, with the majority being found in Southern Ontario as presented in Figure 7-1. The first five sites are the sites already discussed in Chapter 6. Figure 7-1 includes the site 6 as well as the five previous sites.

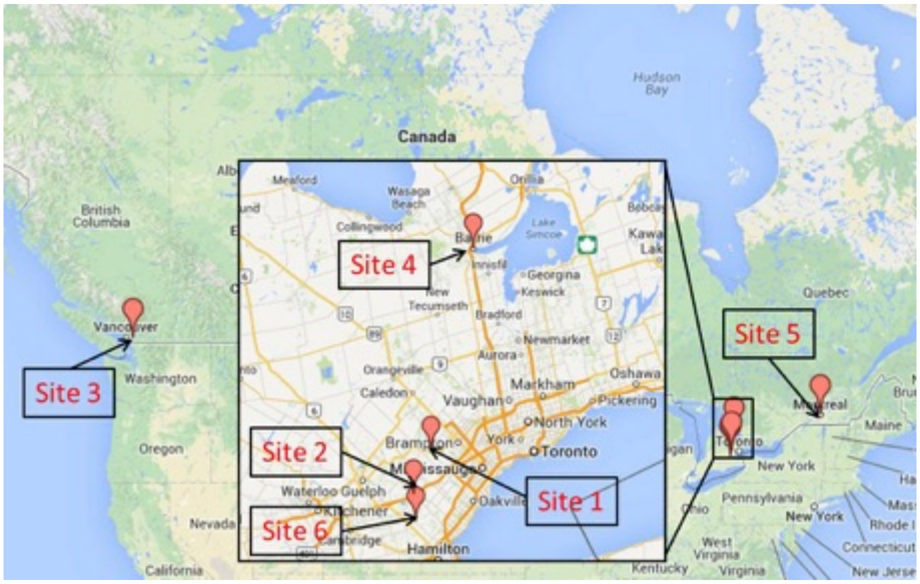


Figure 7-1 Case Study Locations (Google Maps, 2014)

Figure 7-1 shows the locations of the six sites being reviewed with general information of each site outlined in Table 7-1.

Table 7-1 Field Site Location and Structural Design (Henderson V., Tighe S., 2011)

Site	*Location*	*Construction Year*	*Approx. Area (m^2)*	*Structural Design*			
				PC (mm)	CS (mm)	S (mm)	CTB (mm)
1	Georgetown, ON	2007	630	300	600	-	-
2	Campbellville, ON	2007	1800	240	100	200	-
3	Maple Ridge, BC	2008	100	250	200	-	-
4	Barrie, ON	2008	500	200	300	-	-
5	Montreal, QC	2009	108	200	-	-	200
6	Carlisle, ON	2011	4000	150	-	-	150

*PC represents pervious concrete, CS represents clear stone, S represents stone, and CTB represents cement treated base

7.3.1 Performance Evaluation

A variety of tests were performed on samples from the six sites, including evaluating the density, void content, compressive strength, modulus of rupture, and permeability. A summary of the density and void content tests can be found in Table 7-2. Note that Sites 3, 4, and 5 had several different pervious concrete mixtures used in their construction, and these different mixtures are denoted with letters following the site number.

Table 7-2 Density and Void Results from the Field Sites, modified from (Henderson V., Tighe S., 2011; Chai et al., 2011)

Site #	*Avg. Density (CSA A23.2-6C, kg/m^3)*	*Avg. Density (ASTM C1688, kg/m^3)*	*Void Content (using CoreLok*, %)*
1	2011	N/A	18
2	2012	N/A	N/A
3a	1861	N/A	31
3b	N/A	N/A	13
4a	1803	N/A	28
4b	1958	N/A	26
4c	1920	N/A	26
5a	1842	1902	N/A
5b	1996	2025	N/A
5c	1917	1968	N/A
5d	1815	1910	N/A
6-cylinderss	N/A	2249	13
6-cores	N/A	N/A	26

*CoreLok is an equipment that vacuum seals a plastic bag around the pervious concrete sample in the laboratory

Table 7-3 shows the compressive and flexural strength values that were measured from samples from each of the sites. This information further demonstrates that in-practice pervious concrete is a much lower strength material than traditional concrete.

Table 7-3 Compressive and Flexural Strength Results from the Field Sites, modified from (Henderson V., Tighe S., 2011; Chai et al., 2011)

Site #	*28 Day Compressive Strength (MPa)*			*Modulus of Rupture, 28 Days (MPa)*
	Cylinders (CSA A23.2-3C)	Cylinders (Proctor Hammer*)	Cores	
1	21.5	N/A	7.3	1.64
2	22.8/11.8	N/A	7	4.21
3a	31.3	21.3 (10 drops), 30.4 (20 drops)	14.2	N/A
3b	N/A	N/A	N/A	N/A
4a	N/A	8.2 (10 drops)	10	1.5
4b	N/A	9.8 (10 drops)	16	2.0
4c	N/A	8.6 (10 drops)	16.5	1.7
6	28.9	N/A	11.3	5.3

In all cases, the cylinders prepared with the Proctor Hammer involved the pervious concrete being placed in the mould in two lifts. The number of drops applied to each lift is given beside the results in the table.

Surface distress evaluations were also performed on all of the sites in order to visually inspect the structural performance of the pervious concrete. The information from this for all sites is summarized in Table 7-4.

Table 7-4 Surface Condition Evaluation at the Field Sites, modified from (Henderson V., Tighe S., 2011; Rahman S., et al., 2013; Chai et al., 2011; Northmore A., Tighe S., 2012)

Site #	*Age (yr)*	*Distress Types*			
		Ravelling, Joints	Ravelling, Slab	Cracking	Aggregate Fracturing
1	2	M	M	-	-
2	2	S	S	-	-
3a/3b	1	-	M	S	-
4a/4b/4c	1	S	-	-	M
5a	0	-	S	-	-
5b	0	VS	VS	S	-
5c	0	S	S	S	-
5d	0	-	-	-	-
6	1	VS	-	VS	-
6	2	S	-	VS	-
6	3	M	S	S	-

*VS: Very Slight, S: Slight, M: Moderate

7.3.2 Summary

These field sites demonstrate that pervious concrete is an effective option for the structural design and stormwater management of low-volume infrastructure. The minimal surface damage caused over time and the high maintained permeability show that pervious concrete is very applicable to the design of low-volume infrastructure in northern climates.

7.4 Framework Development

The proposed framework for pervious concrete implementation in infrastructure is outlined in Figure 7-2 with descriptions of each step.

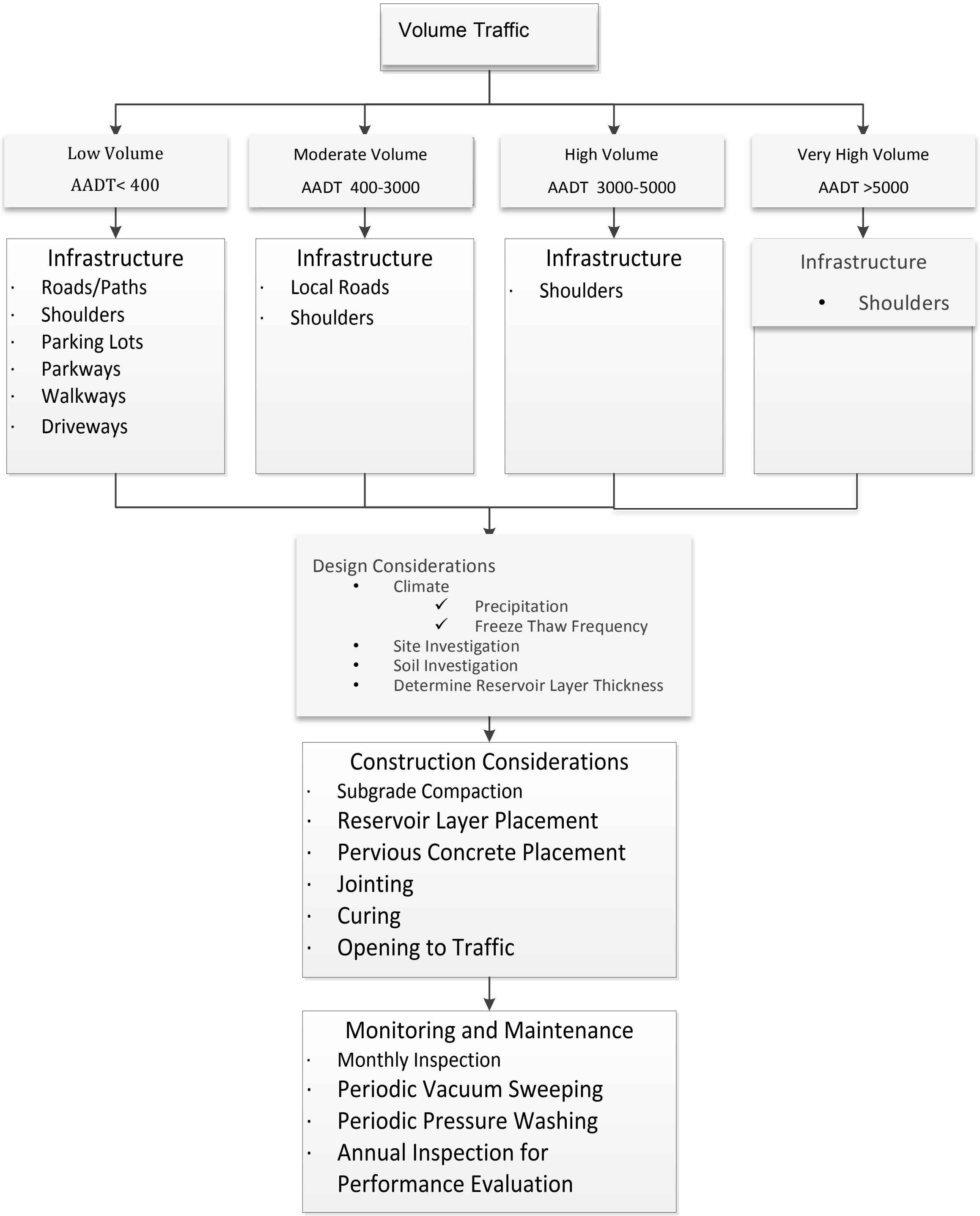


Figure 7-2 Framework for Pervious Concrete Implementation in Low Volume Road Infrastructure

7.4.1 Traffic Determination

Within the framework illustrated in Figure 7-2, there are four levels of traffic considered for the use of pervious concrete pavements.

In traffic determination, the type and level of traffic should be determined according to previous records and recent survey. In general, for low volume road (AADT <400), pervious concrete can successfully perform as paths or roads, parking lots, parkways, walkways, driveways, shoulders etc. For moderate volume road (400≤AADT<3000), pervious concrete can be used in the local roads and shoulders. For high volume road (3000≤AADT≤5000) pervious concrete pavement can only be used on shoulders. For very high volume road (AADT > 5000), pervious concrete could also be considered for shoulder, but it may also not be appropriate given structural performance concern.

7.4.2 Design Considerations

Various important factors for design should be taken into consideration such as climate, site/area, and subgrade condition as each of these can influence the performance, design life and serviceability of the pavement.

7.4.3 Climate

The climate, where pervious concrete will be installed is important. Literature suggests that pervious concrete successfully performs in warm climate (Henderson, 2012) and the case studies presented in this chapter provides valuable information about the satisfactory performance of pervious concrete pavement in cold climates. In cold climate, the number of freeze thaw cycles and precipitation are important factors. Five pervious concrete sites were constructed in different provinces of Canada and monitored for five years and satisfactory performance was observed (Henderson, 2012). Again the laboratory cast samples were undergone through 255 freeze thaw cycles, the equivalent of five years of freeze-thaw exposure in Toronto, Ontario, on average (E. Ho & Gough, 2006), with satisfactory performance During each cycle winter maintenance treatment was applied for the particular scenario: heavy sand; moderate sand; salt solution; or no treatment to determine the appropriate maintenance method for pervious (Henderson, 2012).

7.4.4 Site Investigation

Next, the installation area should be analyzed. Pervious concrete should not be installed in an area with stormwater hotspots such as commercial nurseries, automobile recycling facilities, gas stations and outdoor liquid container storage areas. The runoff from these areas carries high amounts of contaminants, which can pollute the groundwater (American Concrete Pavement Association, 2009). The area, where the availability of sand, fine particles or debris is frequent such as concrete plant, pervious concrete should not be used as clogging could be a major concern there.

7.4.5 Soil Investigation

Soil investigation is the other important step in the design process. Soil strength should be sufficient to provide the pavement the strength to carry the traffic loading. If the California bearing ratio (CBR) of the subgrade soil is less than 4%, then it should be typically compacted to at least 95% of the Standard Proctor Density, which generally rules out their use for infiltration (Virginia Department of Environmental Quality, 2011). Otherwise compaction to 90% of the Standard Proctor Density is enough to provide with a satisfactory drainage capacity (Bush E., et al., 2008). If the CBR value of subgrade is lower or equal to 3; high clay or silt is present in the soil; water table is shallow or subject to flooding then geotextile should be placed over subgrade. In areas where swelling soil is present, precautions should be taken; cement, additives, membranes etc. should be used to stabilize the soil (DCI Engineers, 2010). In Figure 7-3 pervious pavement placed on subbase is presented.

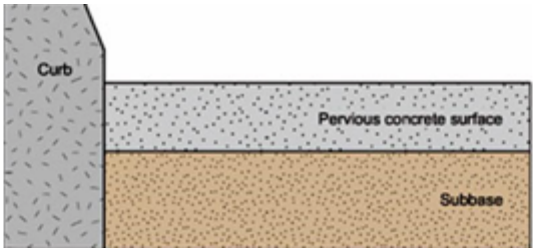


Figure 7-3 Pervious Concrete Layer Direct on the Subgrade (Concrete Answer Series for Architects, Engineers and Developers, 2011)

7.4.6 External Drainage Requirement

The permeability rate of the subgrade soil does not constrain pervious concrete pavement. If a well-drained soil is underneath, no external drainage is required. Native soil that contain silt/clay content less than 40% and clay content less than 20% is considered as well as drained subgrade. Subgrade soil with a minimum permeability rate 12mm (0.5 inch) per hour is also suitable for construction of pervious concrete. Otherwise, if the soil criterion is different or the permeability is lower than the acceptable limit, a reservoir layer or external drainage system is required (Virginia Department of Environmental Quality, 2011). Figure 7-4 represents this type of pervious pavement with draining pipe.

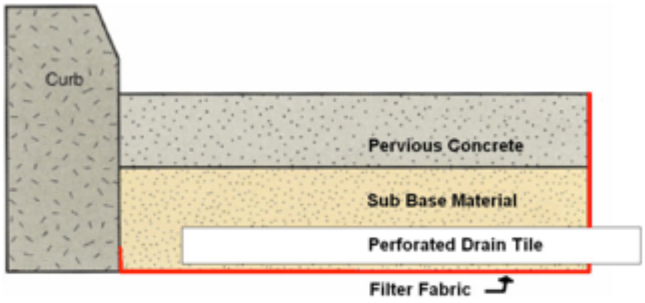


Figure 7-4 Pervious Concrete with External Drainage Pipe (Premium Concrete Service Inc., 2009)

7.4.7 Reservoir Layer Thickness

The main function of the reservoir base layer of the pervious concrete pavement is to work as a detention pond rather than a structural layer. This layer incorporates a storage layer for the percolating water. This layer is generally recommended for pervious concrete in a cold climate with frequent freeze thaw cycles or in the condition when the permeability rate of subgrade soil is low (NRMCA, 2004). It typically consists of open graded aggregate with 20%-30% interconnected voids, which can provide water storage capability (DCI Engineers, 2010). Other literatures suggest that open graded clean stone with 20%-40% void space is required in the base layer of pervious concrete pavement (ACPA, 2009; NRMCA 2010) Maximum drainage time for the reservoir layer should not be less than 24 or more than 48 hours (Virginia Department of Environmental Quality, 2011)

The typical thickness of this layer is 150mm (6"), though a detailed hydrological investigation should be done to find out the proper thickness of the reservoir layer depending upon the subgrade soil condition. The detailed hydrological design procedure can be found in (Virginia Department of Environmental Quality, 2011; Robert R., et al., 2011). Pervious concrete section with reserviour layer is presented in Figure 7-5.

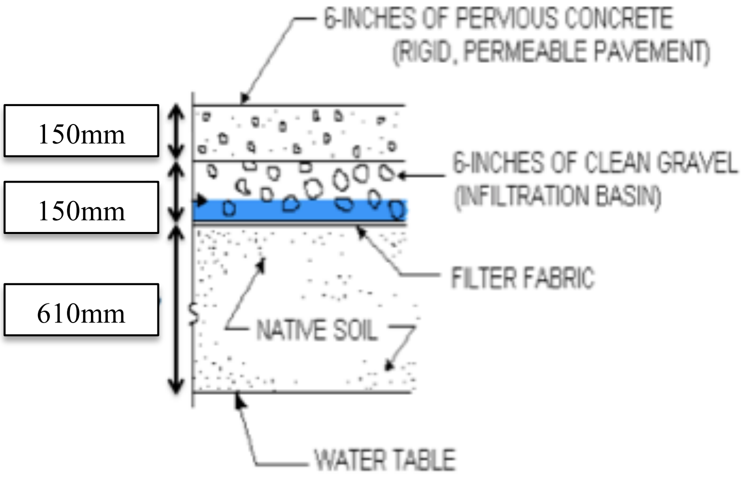


Figure 7-5 Pervious Concrete with Reservoir Layer (Adapted from Concrete Service of NWA, 2013)

7.4.8 Depth to Water Table

A minimum distance of 610mm (2 feet), from the bottom of pervious concrete to the seasonal water table should be maintained (Virginia Department of Environmental Quality, 2011).

7.4.9 Construction Considerations

This section provides the detailed procedure of construction.

7.4.9.1 Pervious concrete Placement

The subgrade soil and the reservoir layer should be prepared as described earlier. After preparing those layers, pervious concrete material is placed directly on the base from the chute. Wood/steel forms with shim on the top are used and these are filled with pervious concrete higher (20 mm-25 mm) than the required final thickness. Then typically a vibratory screed is used on the top of the shim to cross off the pervious concrete and then the shims are removed. Following this, a manual weighted roller or a hydraulic vibratory roller is applied to the forms to compact the pervious concrete and to get a level pervious concrete surface (Kevern et. al., 2008). The level of compaction should be optimized to get the maximum drainage. To get the optimum compaction, methods can be followed from (Culter H. E., et al., 2010)

1. Overfilling the form.
2. Rolling a short 1 m to 3 m section then returning the roller to the initial location.
3. Adding a thin layer of pervious concrete to the previously rolled surface.
4. Rolling the surface again.

7.4.9.2 Jointing

To control cracking, joints are included into pervious concrete pavement in the similar manner as conventional concrete pavement. The typical joint spacing is twice as the thickness of pavement in feet. For example: a six inch pavement would have a joint space of 3.5 m (1.75m X 2 = 3.5m). The maximum joint spacing can be 4.5m (CGP, 2011). Another study recommended joint spacing of 6m up to 13m, which has record of no uncontrolled cracking (Tennis et. al., 2004)

Before paving starts, joint locations must be pre-marked. String line can be used for this type of marking. Generally flanged roller or pizza cutters are used to form joints in pervious concrete pavement (Culter H. E., et al., 2010). All joints should be completed immediately after screed and before curing.

7.4.9.3 Curing

Curing is one of the most important factors for pervious concrete pavement. It is recommended to execute curing as soon as possible behind the screed to ensure hydration occurs (CGP, 2011). Typically, curing is completed by covering the pervious concrete pavement by a 4mm to 6 mm thick plastic sheet. It is recommended to start the curing (cover the pavement with a plastic sheet) within 20 minutes of placement from the truck (Bush E., et al., 2008).

7.4.9.4 Timeline for Opening to Traffic

Guidelines for constructing pervious concrete pavement routinely reference that no vehicle traffic should be allowed on the pavement until seven days after construction [Culter H. E., et al, 2010; Tennis P. D., et al., 2004). The Ministry of Transportation Ontario (MTO) currently requires that pervious concrete not be open to traffic until a core with a compressive strength of 15 MPa is attained from the site. The minimum curing requirement is seven days.

The Ready Mix Concrete Association of Ontario (RMCAO) requires that no truck traffic use a pervious concrete pavement until 14 days after construction (RMCAO, 2009). The Colorado Ready Mixed Concrete Association (CRMCA) requires that pervious concrete pavement not be opened to the traffic until the pavement has reached the equivalent maturity that would have been experienced after 14 days of curing at 21°C at 95% relative humidity (Bush E., et al., 2008). However, a seven day curing period is followed in most cases.

7.4.9.5 Monitoring and Maintenance Considerations

Pervious concrete pavement can perform well with limited maintenance. As the porous structure can easily get clogged with sand, dirt, leaves and other debris, it should be kept clean to confirm the drainage functionality. Routine checking of the pavement porosity and infiltration rate can help to maintain its functionality. In general, clogging is limited to the first 25mm (1”) to 38mm (1.5”) of the pavement thickness. Periodic and routine vacuum cleaning, sweeping or pressure washing can restore the permeability. Sometimes bleach is added to the pressure washing to remove mold and algae (NRMCA, 2008). The literature suggests the following recommendations for maintaining the pavement.

- Monthly inspection to ensure that the pavement is clean of debris, sediments, and dewaters between storms.
- Mow upland and adjacent areas and seed bare areas as necessary.
- Annual inspection to find out the performance and surface distresses.

Ravelling is a common distress in pervious concrete pavement and often related to the mix design and construction. If raveling is observed, the surface should be swept to remove the loose aggregate. If the raveling is a structural deficiency, the surface will completely disintegrate. If it is isolated, the loose aggregate can simply be removed and the remaining surface should not ravel. This process allows the pavement evaluator to assess the depth of the ravelling. After sweeping, the pavement should be monitored. If the distress is structural, then the section can ne replaced or milled and replaced with a pervious concrete overlay (Culter H. E., et. al., 2010).

7.5 Conclusion

The main objective of this chapter is to develop a framework to use pervious concrete in low volume road applications. Overall the state-of-the-art in northern climate pervious concrete field testing has demonstrated that, with diligent design, pervious concrete can be an effective tool available to pavement designers for low-volume applications. All the sites presented here were not under regular maintenance. From the permeability measurement results it is found that permeability reduces with time, as can be expected that without maintenance. With proper maintenance better performance can be obtained. The lower strength and modulus of rupture of the materials do limit the number of heavy vehicles that pervious concrete can withstand, though the slight to moderate surface distresses noted in Table 7-4 show that it withstands low-volume traffic and freeze-thaw cycling very well. Thus pervious concrete can be a potential alternative for sustainable low volume roads and provide a dust free, smooth, cost effective, and safe alternative to traditional pavements.

Chapter 8

Conclusion and Recommendation

The purpose of this research is to provide recommendations for critical material or mix design parameters related to pervious concrete pavement, to establish performance criteria for pervious concrete pavement tested for flexural strength, raveling, abrasion, permeability, scaling resistance, and freeze-thaw resistance and to develop recommendations to form quality assurance acceptance test methods applicable to Ontario conditions. The conclusion from the test results presented in this thesis is summarized in this chapter.

8.1 Summary of Test Methods

This research proposes alternative test methods that could be suitable for pervious concrete pavement. All the test methods described are summarized in the following section.

8.1.1 Compressive Strength Testing

Draft ASTM C09.9 can be used for performing compressive strength testing. But the casting procedure needs to be addressed. The current draft procedure suggests casting samples with 20 drops of Proctor hammer per layer. Generally with 20 drops higher compressive strength is gained which is not common in field and samples prepared in such manner does not replicate field cores. To replicate field sample it is recommended to use 10 to 15 drops of Proctor hammer per layer.

8.1.2 Flexural Strength Testing

ASTM C78 can be successfully used for flexural strength testing for pervious concrete pavement. 150mmX75mmX75mm (6”X3”X3”) beams should be casted in two layers, 20 drops of Proctor hammer per layer. 28 day flexural strength can be determined applying the load with a displacement rate 0.144mm/min.

8.1.3 Lab Permeability Testing

Gilson Permeameter can be used successfully to measure permeability in the laboratory.

Slab/ Different size (100mm/150mm) cylinders or slab samples can be used. In this research 100mm cylinders were used. The samples should be wrapped with latex sleeve to avoid the horizontal movement of water and plumber putty should be used around the rim of the device to seal the device and after that water should be poured to calculate the permeability.

8.1.4 Abrasion Testing

For abrasion testing, between the two tests (ASTM C944 and ASTM C 1747/C 1747M) performed, drilled pressed rotary cutter is recommended to use. The explanation behind this recommendation is with LA abrasion device, following the current procedure, samples are over compacted and does not replicate field samples. Drill pressed rotary cutter at a speed 200 r/min with exerting a normal load of 98±1 N [22±0.2 lbf] is recommended for abrasion testing. The allowable range of weight loss is recommended as 3.5 g to 15g.

8.1.5 Freeze Thaw Resistance Testing

For freeze thaw resistance testing, among the procedure "A" and procedure "B", it would be recommended that procedure "A" is much more applicable. Though procedure "B" replicate field condition much more but as it was done manually in CPATT, much damages happened with manually handling the samples. If any automatic device available that can do the freeze thaw cycle as well as drain the water at the time of freezing automatically, then procedure "B" is recommended. It is recommended to continue freeze thaw cycles until 200 cycles is reach. For determining the transverse resonance frequency the needle of the vibrator should be put on different positions on the beam sample with smooth surface and average should be taken. The Range for transvers frequency is recommended to be in the range 1000 hz to 1900 hz.

8.1.6 Scaling Resistance Testing

Slabs of size 300mmX 300mm should be placed in the freezing environment upto 16 to 18 hrs. Then those should be taken out and submerged in salt water (40g/Liter) for 7-8 hours for thawing. After the thawing period, the samples should be taken out and drained and put back to the freezer. The testing should be continued at least till 25 cycles (50 recommended) and visual examination should be done after each 5 cycles and should be rated. For rating ASTM C 672 is recommended.

8.2 Major Contribution

The major contribution of this thesis is presented in the following section.

8.2.1 Developing the draft test methods

As pervious concrete is structurally different than conventional concrete, it is important to define specific test methods for pervious concrete. The draft test methods are outlined in the previous section.

8.2.2 Compare test results with field samples

In this research, CPATT team not only worked with lab cast samples but also field samples were collected and a comparison was done. The focus was to find out the major reasons of the types of distresses found in the pervious concrete field. The probable explanation and comparison are also presented in this thesis.

8.2.3 Long term drainage performance of pervious pavement

In this thesis a the long term drainage performance, drainage methodology, rain event and movement of moisture in the structure, analysis criteria are also presented.

8.2.4 Developing framework for pervious concrete implementation in low volume infrastructure

A framework is developed to identify how pervious concrete can be integrated into low-volume infrastructure. Various functional and structural design considerations are also outlined which can help the designers to implementing the technology.

8.3 Recommendation and Future Work

Further research to find out optimum mix design and effect of mix design on the performance of pervious concrete is recommended. The performance results from some of the pervious concrete test sites are promising but some of them are challenging. To find out the major catalyst that affects the performance most, future research is recommended.

The developed test methods should be applied in field to find out the acceptability in practical purpose. More investigation is recommended to find out the suitability of the developed test methods.

Further research on durability of pervious concrete is recommended. Raveling is a common problem with pervious concrete pavement. To find out the major reasons behind raveling is important to address the durability of pervious concrete pavement. With freeze thaw cycles the pervious concrete test results are promising. The main reason of raveling could be curing. In the lab samples, as curing is done properly, not much raveling is found. But in the field as curing is not done in a proper way, in most of the cases, this could a reason of drastic raveling. It is important to verify the reason of raveling to implement pervious concrete in Canada successfully.

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