GUIDELINES FOR PERVIOUS CONCRETE SIDEWALKS, PARKING LOTS, AND SHARED-USE PATHS TO IMPROVE DRIVER, BIKER, AND PEDESTRIAN SAFETY

FINAL PROJECT REPORT

By
Somayeh Nassiri
Washington State University

Sponsorship
Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Center

for
Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Transportation Center for Federal Region 10
University of Washington
More Hall 112, Box 352700
Seattle, WA 98195-2700

In cooperation with US Department of Transportation-Research and Innovative Technology Administration (RITA)

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The Pacific Northwest Transportation Consortium, the U.S. Government and matching sponsor assume no liability for the contents or use thereof.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Guidelines for Pervious Concrete Sidewalks, Parking Lots, and Shared-Use Paths to Improve Driver, Biker, and Pedestrian Safety		**5. Report Date** 10/15/2017 **6. Performing Organization Code** 04-148-5301
7. Author(s) Harry Rodin III, MS Student, Washington State University Somayeh Nassiri, Assistant Professor, Washington State University Mina Yekkalar, MS Graduate, Washington State University Othman Alshareedah, PhD student, Washington State University Liv Haselbach, Professor and Chair, Lamar University		**8. Performing Organization Report No.**
9. Performing Organization Name and Address PacTrans Pacific Northwest Transportation Consortium University Transportation Center for Region 10 University of Washington More Hall 112 Seattle, WA 98195-2700		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** UWSC8232
12. Sponsoring Organization Name and Address United States of America Department of Transportation Research and Innovative Technology Administration		**13. Type of Report and Period Covered** **14. Sponsoring Agency Code**
15. Supplementary Notes Report uploaded at www.pacTrans.org		

16. Abstract

The surface frictional properties of pervious concrete (PC) slabs were evaluated by using a British Pendulum Tester (BPT) with two different rubber sliders that represented driver and pedestrian users. The volumetric air content at the finished surface of the slabs was quantified by image analysis to identify any possible correlations between the different surface finishes due to varied porosity and the microtexture of the PC slabs. Frictional evaluation for all the PC slabs was compared with that of traditional portland cement concrete (PCC) slabs under three baseline conditions: dry, wet, and iced. The iced condition was then treated with magnesium and calcium chloride ($MgCl_2$ and $CaCl_2$), used once as anti-icing and again as de-icing agents, and then individually tested by using the BPT. Friction values were recorded as the British Pendulum Number (BPN). Minimal correlation was found in this study between porosity and BPN. The PC slabs showed significantly higher BPN values than the PCC slabs in each of the baseline conditions for the mixture tested in this study. For one icing event, the one-time application of anti- and de-icing agents on PC slabs improved the friction of the PC slabs to the allowable BPN level using both $MgCl_2$ and $CaCl_2$.

17. Key Words		18. Distribution Statement	
Pervious concrete, winter maintenance, friction, deicer, anti-icer		No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages**	**22. Price** NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Table of Contents

List of Figures

List of Tables

Acknowledgments

The authors would like to thank USDOT University Center and Pacific Northwest Transportation Consortium (PacTrans) for funding this project. Thank you to the Washington State University's Facility Services for providing the chemical agents and for their time in consulting regarding the experiments in this study. Dr. Osama Fakron is also acknowledged for providing training with the Image analysis software.

Executive Summary

Pervious concrete pavements provide the traffic load carrying role of pavements while also offering a hydraulic function for runoff control. Pervious concrete (PC) is designed to include air voids at a designated percentage of the volume of the mixture to allow runoff infiltration through the structure of the pavement. The voids on the PC surface result in a different macrotexture than that of traditional concrete and are created by using narrowly graded coarse aggregate and by excluding fine aggregates from the mixture. The use of PC pavements is increasing in cold climates for parking lots, low-traffic volume streets, sidewalks, and driveways. Because of the increased usage of PC, more studies must be completed to understand its skid and slip resistance and the winter maintenance strategies required for permeable pavements. In this study, friction was evaluated by using a British Pendulum Tester (BPT), and the frictional values were recorded as a British Pendulum Number (BPN). Two different rubber sliders were also used to mimic pedestrian skid resistance (PSR) and tire skid resistance (TSR). All BPN values were compared to a minimum threshold of 45 for wet conditions that are laid out by Asi (2005).

For this study, 27 PC slabs and 12 PCC slabs were cast. The PC slabs were placed in three different target porosity groups of 20 (low), 25 (medium), and 35 (high) percent. The porosity for each PC slab was found by using volumetric and image (of surface) analysis. After comparison of the results, the image analysis data were used to accurately represent the surface porosity of each slab. To better understand the frictional properties of PC, three baseline conditions of dry, wet and iced surface conditions were tested. The dry conditions were evaluated after the slabs had been stored under laboratory conditions for 24 hours. For the wet condition, slabs were placed in a water tank for 5 minutes before being tested. For iced

conditions, an environmental chamber at 14°F was used to store the slabs and a tank of water for two hours; the slabs were then placed in the tank for 5 minutes before being removed and left in the chamber for another 30 minutes. At this stage, the slabs formed ice on the surface, and the BPT was used.

The iced conditions were also expanded to include anti-icing and de-icing procedures using both liquid magnesium chloride and calcium chloride pellets ($MgCl_2$ and $CaCl_2$). During the anti-icing procedure, the chemicals were added directly after the slabs had been removed from the water tank to mitigate ice formation; then after 30 minutes the slabs were tested. For the de-icing procedure, the ice was allowed to form for 30 minutes after submersion in water before the chemicals were applied, and then another 30 minutes passed for the chemicals to react before the BPT was used. For all surface conditions, traditional concrete (PCC) slabs were also tested for comparison. Surface images of the PC and PCC under the baseline and chemical conditions used can be seen in fig. A.

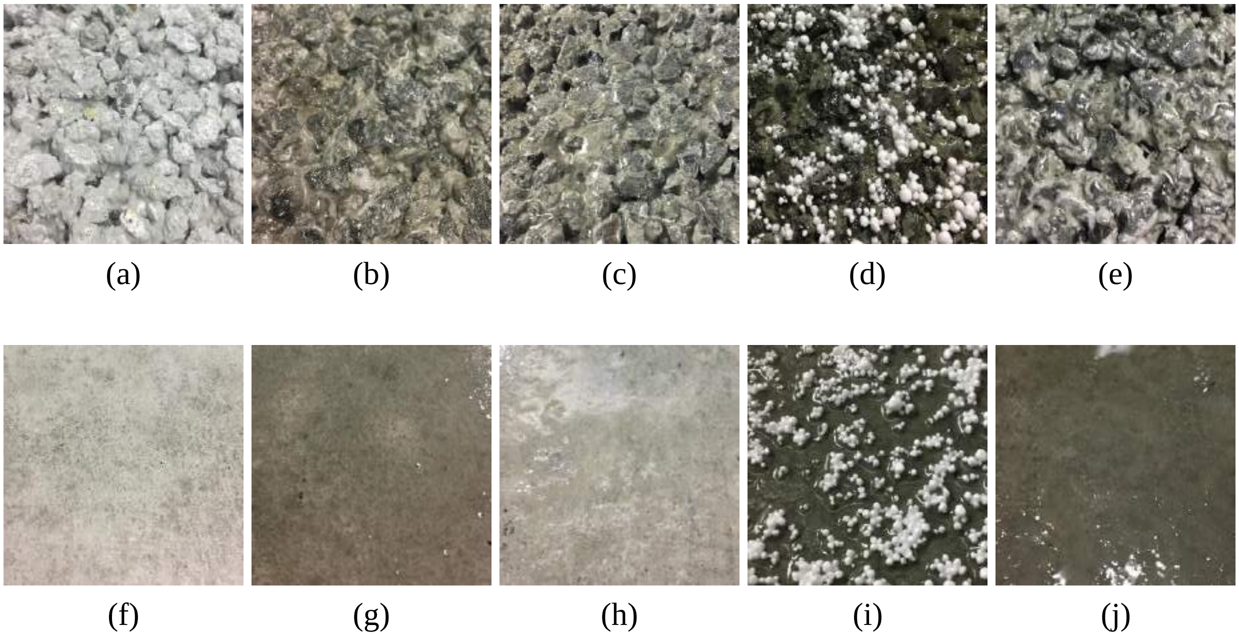


Figure A: PC and PCC slabs under different surface conditions. PC slab conditions: a) dry, b) wet, c) iced, d) calcium chloride, e) magnesium chloride. PCC slab conditions: f) dry, g) wet, h) iced, i) calcium chloride, j) magnesium chloride.

Using statistical analysis, the surface porosities were compared to the BPN values for all the PC slabs. The surface porosities were found to have no statistical impact on the BPN values because of p-values being greater than 0.05. The wet conditions using the TSR did result in a p-value of less than 0.05, but because of an extremely low R^2-value (0.400), the goodness of fit for the data was poor. Throughout the study, the TSR resulted in higher BPN values than the PSR for all tests. This was most likely due to the PSR having a lower hardness and its greater susceptibility to deformation. The PSR's deformation absorbs less energy and therefore does not inhibit the swing of the BPT, resulting in lower BPN values.

During the baseline condition testing, the dry and wet conditions for PC and PCC were all above the threshold value of 45. Iced conditions were around 45 for the PC slabs but well below the threshold value for the PCC slabs. The PC slabs also outperformed the PCC slabs in each of the baseline conditions. In comparing the anti-icing and de-icing treatments, statistical analysis showed significant increases in BPN in comparison to the iced conditions for both PC and PCC slabs, as well as values of over 45. In most scenarios the anti-icing treatment also resulted in higher BPN values than de-icing. In comparing the two chemicals, $MgCl_2$ resulted in higher BPN values than $CaCl_2$ for most test conditions. Both chemicals resulted in significantly higher BPN values than the control, as well as values above 45. For all the altered iced test conditions, the PC outperformed the PCC slabs. This was most likely due to the PC slabs' ability to drain melted ice (water) from the slab surface, leaving less moisture than the PCC slabs.

This thorough evaluation showed that PC slabs had higher BPN values than PCC slabs for both pedestrian and tire users. Anti-icing applications using liquid $MgCl_2$ resulted in the highest BPN values for mitigating ice formation.

Chapter 1 Introduction

Permeable pavements are dual-purpose structures that offer a hydraulic function for runoff control in addition to the primary structural purpose of carrying traffic loads. To meet hydraulic requirements, pervious concrete (PC) contains the same constituents as the traditional concrete, except that PC is made with narrowly graded coarse aggregate and not any or minimal amounts of fine aggregate. This mixture design yields an interconnected void system that composes around 15 to 30 percent of the total volume. The void system allows runoff to infiltrate through the PC media and to drain into the sub-drainage system or naturally percolate into the subgrade soil (Tennis et al. 2004) (see fig. 1.1).

Figure 1.1: Pervious concrete allows infiltration of runoff through the pavement surface.

The use of PC pavements is increasing for applications such as parking lots, low-traffic volume streets, sidewalks, and driveways across the United States, including those regions with a cold climate; therefore, there is a critical need for timely development of effective winter maintenance policies to employ appropriate ice/snow control practices for PC pavements. Plowing, sanding, anti-icing, and de-icing are the most common maintenance strategies in response to winter pavement conditions. However, alterations to these conventional practices may be required to accommodate the porous nature of permeable pavements and to maintain their serviceability over their service lives (Huber 2000).

Chapter 2 Literature Review and Scope of Work

2.1 Winter Maintenance of Permeable Pavements

The application of abrasives such as sand is a common winter maintenance strategy for traditional pavements. However, permeable pavements that have been sanded have experienced significant reductions in hydraulic conductivity over the course of a single winter season in some cases (Isenring et al. 1990, Noort 1996, Brattebo and Booth 2003, James and Gerrits 2003, Boving et al. 2008, Van Duin et al. 2008, Gulliver 2015). In one of the studies, a 96 percent decrease was reported in hydraulic conductivity of the pavements treated with sand (Gulliver 2015). On the other hand, another study showed that PC clogged with sand might be readily remediated (Haselbach et al. 2006).

Varied winter maintenance practices other than sanding have been suggested in the literature as well. One agency recommended mechanical ice/snow removal and/or the application of liquid/solid deicer agents as a preferred strategy over sanding for permeable pavements (UDFCD 2010). Snow plowing and blowing may also be performed on PC; however, front end or skid loaders should not be used, and only a polyurethane cutting edge should be equipped on the plow truck (NRMCA). In one study, immediate and continued applications of anti-icing agents onto permeable pavements was deemed necessary to maintain sufficient anti-icing chemicals on the surface (Litzka 2002). As a result, this anti-icing was found costly for permeable pavements because of a roughly 30 percent higher demand for chemicals to achieve the same level of service as traditional pavements treated with the same method (Giuliani 2002).

In comparison to anti-icing, salt and chemical agents were applied during and after ice/snow events on open-graded pavements as de-icing agents; however, the effectiveness of de-icing practices on permeable pavements is unclear in the literature. In contradiction to the previous studies, based on measurements of ice/snow cover and pavement skid resistance (SR), the need for salting was found to be 75 percent less for permeable pavements than for conventional pavements to maintain an equivalent or better surface condition (Houle 2008, Cahill et al. 2003). Noort (1996) also reported that despite a loss of dissolved salt in the pores of porous asphalt (PA), the salt solution in the voids was transported back to the surface by air pumping under sufficient traffic (Noort 1996). Other studies have offered conservative guidelines for de-icing practices for permeable pavements: European road administrations suggest a higher salting frequency (every 60 to 90 minutes) and a (30 to 50 percent) larger quantity of de-icer chemicals for permeable pavements to compensate for the de-icers infiltrating into the pavement structure and leaving minimal residual de-icer materials on the surface (Poulikakos et al. 2006, Bendtsen 2011, Danish Road Directorate 2012). Similarly, Dooley et al. (2009) reported an up to 100 percent increase in consumed salts on pervious asphalt (PA) pavements.

2.2 Skid Resistance of Permeable Pavements

Surface macro- and megatexture are governed by the finishing of the concrete pavement surface and also depend on the aggregate connectivity pattern at the surface. Macrotexture has an impact on the pavement SR at low speeds on wet surfaces as the macrotexture provides channels for water escape at the tire-pavement interface (AASHTO 1976, Mahone 1975, TRB 1998). The most common procedures for evaluating frictional properties are surrogate tests by small-scale devices such as the British Pendulum Tester (BPT). The contributions of the pavement surface macrotexture to rolling and skid resistance has been established for traditional pavements; however, the frictional properties of permeable pavements with varied surface micro- and macrotexture has scarcely been investigated (Noyce et al. 2005, Pattanaik et al. 2017). In addition to the pavement composition and condition of the pavement surface, comparisons of the SR in winter pavement conditions to reference non-winter conditions can shed light on the varied safety levels of PC pavements for driver and pedestrian users. The presence of moisture, mud, snow, ice, oils, and other substances that can alter the surface texture of the pavement and may impact SR by changing the tire-pavement interaction (Wallman and Aström 2001).

In a study by Houle (2008), the frictional properties of two active parking lots paved with PA and PC were studied by using a BPT under several forms of pavement surface covers: dry, wet, snow, slush, compacted-snow, and ice. In the study, friction was measured five times within each condition and averaged to characterize the variability in friction between each type of pavement cover. The average British Pendulum Number (BPN) values were then multiplied by their respective surface cover type percentages (evaluated from the field conditions) for the purpose of developing a weighted friction value for each test. In this procedure, a single number was assigned to each condition to describe the pavement safety level in comparison to the standard dry condition. Using these metrics, the authors concluded that permeable pavements provide better functionality than impermeable pavements under cold climate conditions (Houle 2008).

Yu et al. (2015) also studied a PA pavement section located on a highway in China for five years to collect its performance data and compare them to two control sections with stone mastic asphalt and dense graded asphalt. Skid resistance tests were conducted with the BPT to evaluate the surface friction in the wheel paths. Test data were corrected for the effects of pavement temperature during different measurements to an equivalent BPN value at 20 degrees Celsius. The skid resistance of the three pavement sections were considered acceptable because the data had low variability and all BPN values were greater than 42, as required in Chinese asphalt pavement specifications (Yu et al. 2015).

2.3. Scope of Work

The limited research conducted to date to objectively evaluate the winter safety of permeable pavements calls for further investigation of the related properties of this class of pavements, given the rapid increase of their application in cold climate regions. To address this need, the scope of this study entailed establishing the frictional properties of three PC surface finishes, imposed by varying the level of the volumetric air void content (porosity). The evaluation was repeated for the two main users of PC pavements: pedestrians for sidewalk applications and drivers for parking lots and streets. Included in this investigation were also three different baseline conditions of dry, wet, and, iced. The friction of the iced condition was then further evaluated using separate anti- and de-icing treatments. The test conditions and the chemical agent types were selected on the basis of discussions with the maintenance facilities at Washington State University in Pullman, Washington. The tests were designed to represent current common practice in eastern Washington for PC pavements. Sanding and salting were avoided because of their potential to clog permeable pavements, as reported in the literature.

The following objectives were targeted to evaluate the frictional properties of PC under these conditions:

- Establish the baseline BPN for dry, wet, and iced conditions for pervious concrete slabs in comparison to traditional concrete slabs by using two BPT rubber sliders to represent pedestrians and drivers.
- Evaluate the significance of different surface macrotextures from variable porosity levels ranging from 12 to 40 percent for one coarse aggregate type.

- Investigate the effectiveness of anti-icing versus deicing methods on friction by using two commonly used chemical agents, magnesium and calcium chloride ($MgCl_2$ and $CaCl_2$).

Chapter 4 Study Site/Data

3.1 Mixtures and Slab Specimen Preparation

A total of 27 PC slabs with approximate dimensions of 25.4 (10) by 25.4 (10) by 8.89 (3.5) centimeters (inches) were cast in three groups with a 20 percent (L-low), 25 percent (M-medium), and 35 percent (H-high) targeted porosity (Φ). Nine slabs were cast in each Φ group. Twelve conventional portland cement concrete (PCC) slabs were also cast for comparison purposes. The mixture designs for both the PC and PCC mixtures are provided in table 3.1. The PCC was ready-mixed concrete provided by Atlas Sand & Rock and was made with a 3/4-inch maximum coarse aggregate (CA) size and Type I/II portland cement. On the other hand, the PC mixture was batched in the laboratory, and the mixture consisted of crushed basalt CA with a 3/8-inch nominal maximum size. Type I/II portland cement from Ashgrove Cement Company was used. The PC mixture design had a 0.27 water-to-cement ratio (w/c).

Table 4.1: PC and PCC mixture constituents and proportioning.

Mixture	Weight (lb/yd^3)							Admixtures
	3/4" Crushed CA	3/4" Round CA	3/8" Crushed Basalt CA	Sand	Type I/II Cement	Class F Fly Ash	Water	
Pervious Concrete	-	-	2,319	-	697	-	189	39 oz/yd^3 of VMAR and 38 oz/yd^3 of Recover
Portland cement concrete	1,340	460	-	1,551	423	47	258	BASF MasterPozzilith 322 per manufacturer's recommendation

During PC mixing, the fresh density (D) of each batch was recorded to determine the mass of the fresh material to be placed in the slab molds. The medium target porosity was the same as the design porosity of the mixture; therefore, when the slabs were cast at the medium target porosity, D was used to determine the mass of material needed in the specific volume of the mold. For the other porosity ranges, the masses were scaled to achieve the two different target porosities. The scaling factors were created by evenly scaling the mixture design so that design porosity matched the high or low targeted porosity. That same scale factor was then applied to D to achieve the targeted porosity values. Each slab was cast in two lifts, and uniform compaction was achieved by rodding the edges and corners, as well as by drops of a standard Proctor hammer, as needed. The slabs were also hit with a rubber mallet on the sides during compaction. The slab surfaces were then finished by using a float and a rod to roll over the surface (see fig. 3.1-a).

The PCC slabs were cast so that the material filled the mold evenly in two lifts. They were compacted with a shake table and mallet strikes. The PCC slab surfaces were finished by using a float and trowel (see fig. 3.1-b).


(a)


(b)

Figure 4.1: a) Cast PC slabs and b) cast PCC slabs and final finishing.

3.2 Description of the Experimental Plan

3.2.1 Volumetric Porosity Characterization

On the basis of visual observation, the voided structure of PC creates a rougher macrotexture than that of traditional PCC, and it is therefore expected that PC pavements provide a higher SR than traditional concrete pavements. As opposed to PCC, PC pavement is not finished with a trowel and is typically struck off and compacted to the desired slab depth, which leaves a less smooth finish and rougher macrotexture. At higher porosities, the slabs require even less compaction to fit in the molds; therefore, the slabs require less finishing, leaving a rougher surface. In addition, higher porosities have more interconnected voids, allowing more water drainage, which may result in higher SR in wet and winter conditions. As described before, to evaluate the effects of air void content on the macrotexture of the slabs, the slabs were compacted in three different groups of target porosities.

Upon casting, the slabs were air cured for seven days and covered by plastic wrap before demolding. Hardened volumetric porosity was then determined at the seven-day age by first taking the dry mass (M_d) of each slab, followed by submersion in water to determine the underwater mass (M_w). The volume (V) of each slab was determined by using the average of three caliper measurements for each dimension. The density of water (ρ_w) was also used as shown in Eq. 1.1 to compute the total permeable porosity of each slab, as per ASTM C1754 (2012). See figure 3.2 for a photo of the test set-up.

$$\varphi = \left[1 - \left(\frac{M_d * M_w}{\rho_w * V}\right)\right] \qquad (1.1)$$

Figure 4.2: Water bath for submerging specimens for porosity testing.

3.2.2 Surface Air Void Characterization Using Image Analysis

In an attempt to obtain surface porosity, rather than the interconnected volumetric porosity provided by the ASTM C1754 (2012) method described in the previous section, an image analysis of the surfaces of all the slabs was performed. The top and bottom full faces of each slab were photographed with a cell phone camera, and the photographs were converted into binary images. After that, image segmentation was performed by using the ImageJ software (Ferreira and Rasband 2012), which applies a specific threshold to isolate the air voids from the solid particles, as in the image as seen in figure 3.3. Using image segmentation, an optimum threshold value is selected, and the image histogram is divided into two portions: the foreground and the background. When a pixel value is higher than the threshold value, it is counted as the foreground and vice versa. The threshold point can be used to separate the air voids (low pixel values) from the solid particles (high pixel values) (Manahiloh et al., 2012; Wirjadi 2007). ImageJ utilizes the modified IsoData algorithm as the default thresholding technique (Ferreira and Rasband 2012). Matlab image analysis toolbox was also used, which successfully validated the ImageJ results for the surface porosity of the slabs.

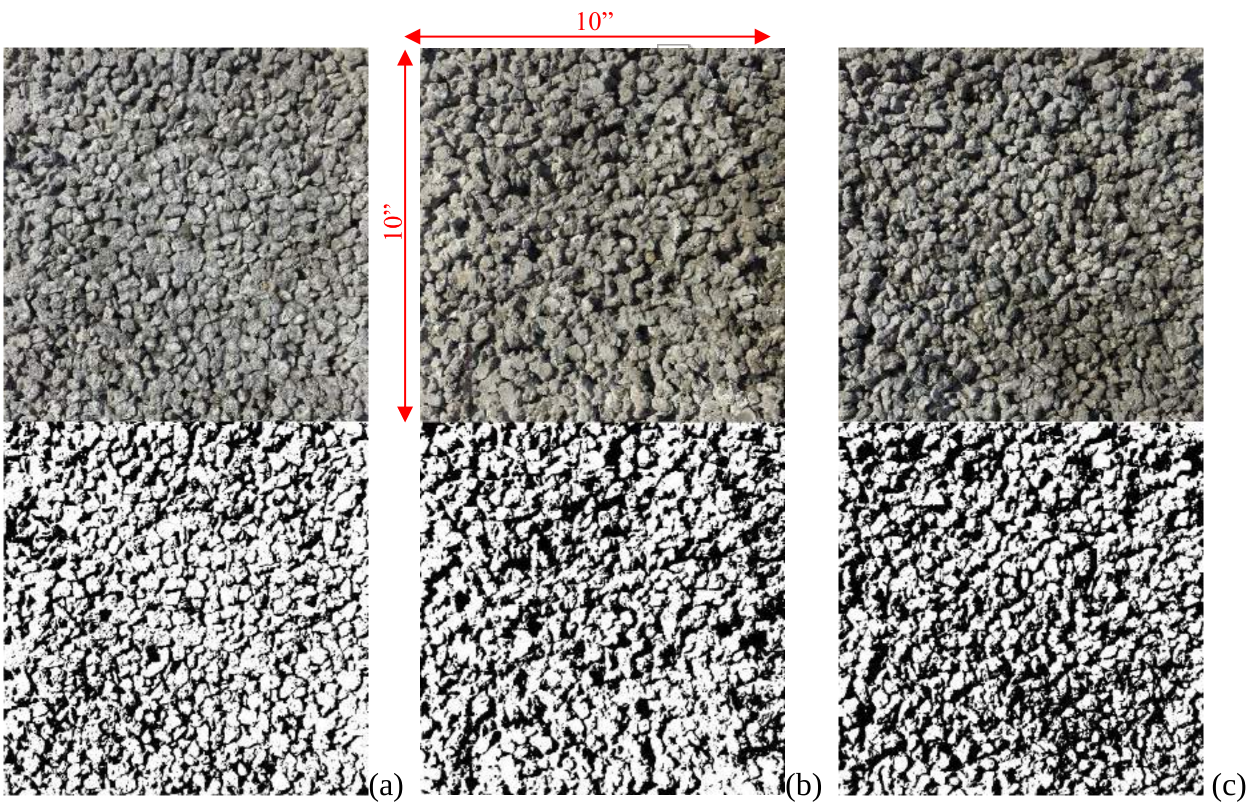


Figure 4.3: Image segmentation using the ImageJ software for a) low, b) medium and c) high surface porosity specimens. For each image, the top is the original surface image while the bottom is the binary image.

3.2.3 Porosity Evaluation

The results of the two methods are summarized in table 3.2. The porosity based on the submerging methods resulted in marginal standard deviations among the slabs within each porosity group, as seen in table 3.2. The standard deviations among the slabs was larger than the surface porosity based on ImageJ analysis. The larger standard deviations may have been due to slightly different camera angles causing different shadows to be cast on the slab voids. Any aggregate that had a dark spot on the surface also could have caused the image analysis to locate a void where none existed. Despite the standard deviation differences, the mean values between the two methods agreed well; therefore, because of the direct relationship of surface porosity to the SR testing, the results of the ImageJ method were used in the study.

Table 4.2: Comparison of porosity calculations based on the volumetric and ImageJ methods.

Porosity (Φ)	**Interconnected porosity based on submerging method (ASTM C1754)**		**Surface porosity based on ImageJ Analysis**	
	Mean Φ	**Std. Dev. Φ**	**Mean Φ**	**Std. Dev. Φ**
Low	0.16	0.010	0.18	0.027
Med	0.24	0.009	0.27	0.021
High	0.36	0.004	0.37	0.030

3.2.4 Friction Evaluations

The frictional properties of the slabs were established by using the BPT from James Cox & Sons in accordance with ASTM E303 (2013). The BPT is used to evaluate surface friction by swinging a rubber slider across the surface of the slab. The pendulum arm of the BPT swings down over the specimen surface and barely makes contact with the slab surface. The slab surface with a higher frictional property dampens the swing of the arm more than a surface with a lower frictional property, which results in larger BPN values (fig. 3.4). The contact surface between the rubber slider and the slab surface is approximately 5 inches. Skid resistance values are recorded in BPN values, which can be converted into coefficients of friction (COF) (Cooper Technology, 2006). In the present study, BPN values were not converted to COF because any BPN value of 82 or greater would result in a COF of 1.0, which would limit comparability at higher BPN values.

To ensure the validity of the test results, all of the reported test values for each slab in each cover condition were an average of four pendulum swings. For this experiment, two different rubber sliders were used: a Pedestrian Slip Rubber (PSR) (CS-PEND-855/1070) and a Tire Slip Rubber (TSR) (CS-PEND-855/1060). The PSR represents shoe sole rubber, which is applicable for testing sidewalks and walking paths. The TSR is used to mimic the tire rubber that comes in contact with the road surfaces and parking lots for vehicles, bicycles, and any other modes of transportation involving wheel-to-road contact.

(a)

(b)

Figure 4.4: Running the BPT on a PC slab, a) setting up the pendulum arm and b) reading the BPN value after the pendulum swing.

According to ASTM E303, each test had to include four swings of the BPT. The four repeats were performed as close to the center of each slab as possible. In some cases, the testing location was moved because of random aggregate pop-out at the surface. In all cases, the exact test locations were marked so that the tests were performed in the same location using both rubber sliders and in the various cover conditions. Although only one location on each slab was tested, nine slabs were incorporated in each test to account for variability.

Chapter 5 Methodology

4.1 Baseline Conditions

The BPT was used on all the slabs under three different baseline conditions: wet, dry, and iced using both rubber types. The overall experimental procedure can be seen in the flow chart shown in figure 4.1. Dry tests were performed after the slabs had been stored in dry conditions at room temperature for a minimum of 24 hours. Wet conditions were tested after each slab had been submerged in water for 5 minutes. Iced slabs were stored in a walk-in environmental chamber at 14°F for 2 hours concurrently with a tank of water that was large enough to maintain a temperature just above freezing, allowing for faster ice formation on the slab surfaces after submersion. Upon removal from the water, the slabs were kept in the chamber for an additional 30 minutes to allow for ice to form before the BPT was used. The iced condition experiments were followed by additional series of experiments to include the evaluation of the effectiveness of anti-icer and de-icer applications.

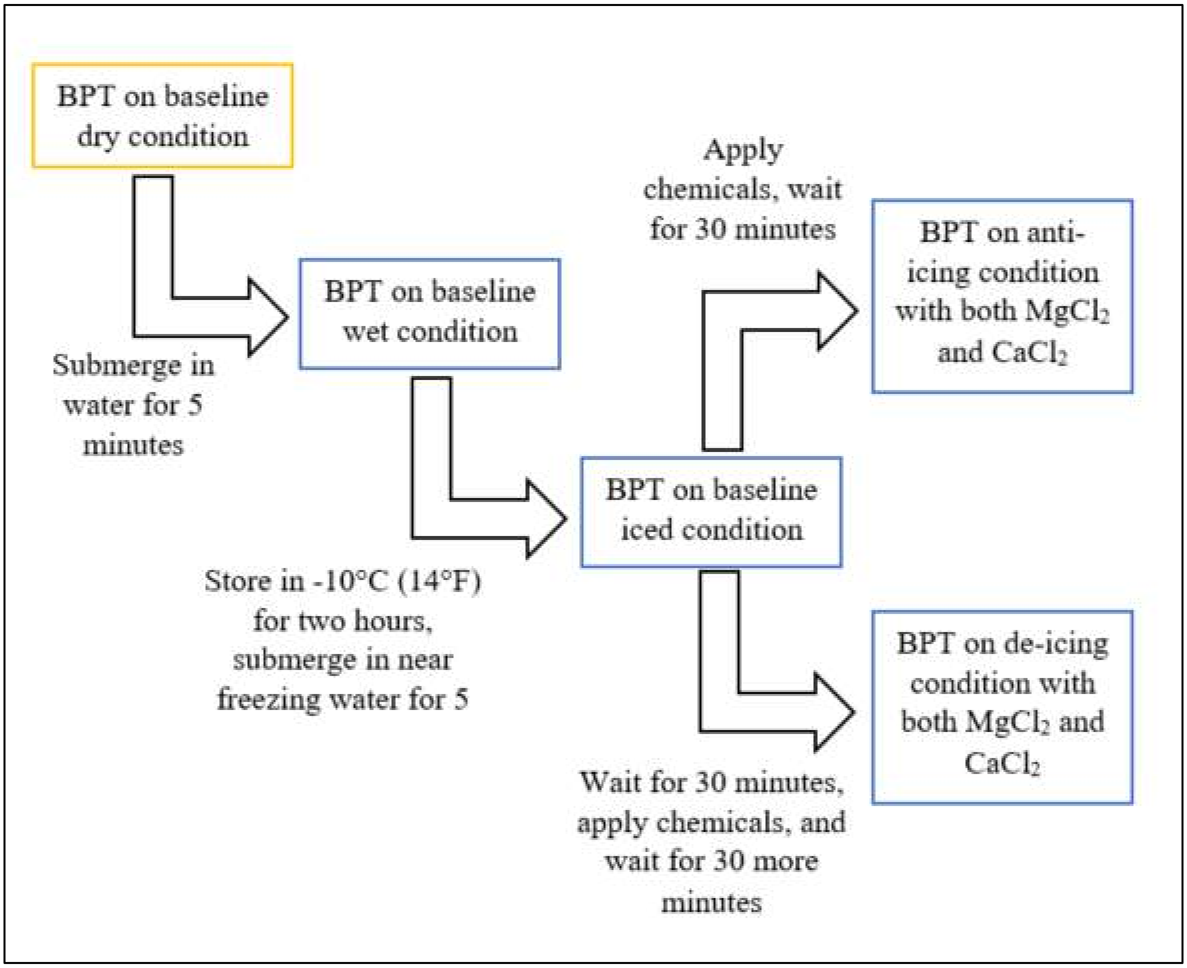


Figure 5.1: Flow chart of the overall experimental procedure.

4.2 De-icing and Anti-icing Conditions

The process for the anti-icing conditions was similar to that of the iced conditions; however, the anti-icing agents were applied after submersion in the water to delay the ice particles from forming on the surface. The test procedure for de-icing conditions was also similar to that of the iced condition, except that after submersion in water, the slabs were left in the chamber for 30 minutes for ice to form before the anti-icing agents were applied, after which another 30 minutes were allowed for the agents to take effect on the slab surface before the friction tests were performed. Both anti-icing and de-icing experiments were repeated using two chemical agents, liquid $MgCl_2$ and $CaCl_2$ pellets. Commonly used dosages of $MgCl_2$ and $CaCl_2$ were applied evenly over the surface at 17.4 milliliters (0.59 fluid ounces) and 40 grams (1.41 ounces), respectively, per slab surface in one application. If scaled for a typical 3.7 meter (12-foot) wide highway lane, $MgCl_2$ was applied at 993 liter/kilometer (422 gallons/mile) and $CaCl_2$ was applied at 2268 kilograms/kilometer (8046 pounds/mile). The $MgCl_2$ was FreezGard CI Plus produced by Compass Minerals, and the $CaCl_2$ was produced by Peladow. Table 4.1 shows the experimental layout, which shows how the slabs were designated to the different tests.

Table 5.1: Experimental matrix with all slabs and corresponding tests performed.

Specimen	Surface Porosity based on ImageJ	Baseline Conditions			Modified Iced Conditions			
		Dry	Wet	Ice	Anti-icing	De-icing	Magnesium Chloride	Calcium Chloride
L1	0.21	X	X	X				
L2	0.12	X	X	X				
L3	0.19	X	X	X				
L4	0.19	X	X		X	X	X	
L5	0.17	X	X		X	X	X	
L6	0.18	X	X		X	X	X	
L7	0.19	X	X		X	X		X
L8	0.22	X	X		X	X		X
L9	0.19	X	X		X	X		X
M1	0.26	X	X	X				
M2	0.28	X	X	X				
M3	0.30	X	X	X				
M4	0.27	X	X		X	X	X	
M5	0.29	X	X		X	X	X	
M6	0.23	X	X		X	X	X	
M7	0.28	X	X		X	X		X
M8	0.24	X	X		X	X		X
M9	0.28	X	X		X	X		X
H1	0.29	X	X	X				
H2	0.38	X	X	X				

Specimen	Surface Porosity based on ImageJ	Baseline Conditions			Modified Iced Conditions			
		Dry	Wet	Ice	Anti-icing	De-icing	Magnesium Chloride	Calcium Chloride
H3	0.38	X	X	X				
H4	0.37	X	X		X	X	X	
H5	0.38	X	X		X	X	X	
H6	0.37	X	X		X	X	X	
H7	0.39	X	X		X	X		X
H8	0.39	X	X		X	X		X
H9	0.37	X	X		X	X		X
PCC1	n/a	X	X	X	X	X	X	
PCC2	n/a	X	X	X	X	X	X	
PCC3	n/a	X	X	X	X	X	X	
PCC4	n/a	X	X	X	X	X	X	
PCC5	n/a	X	X	X	X	X	X	
PCC6	n/a	X	X	X	X	X	X	
PCC7	n/a	X	X	X	X	X		X
PCC8	n/a	X	X	X	X	X		X
PCC9	n/a	X	X	X	X	X		X
PCC10	n/a	X	X	X	X	X		X
PCC11	n/a	X	X	X	X	X		X
PCC12	n/a	X	X	X	X	X		X

All tests listed in this table were performed with both rubber sliders.

Chapter 7 Results

5.1 Effect of Porosity on BPN

The comparisons of BPN for different surface porosities for the wet and dry conditions indicated that more porous slabs yielded higher BPN values, in both dry and wet conditions; however, the effect of Φ on BPN was not significant for most tested cases (table 5.1). The P-values were greater than 0.05, which showed an insignificant Φ–BPN correlation for all comparisons at the 95 percent confidence interval, except for the wet condition with TSR. Although the P-value for this scenario was less than 0.001, a coefficient of determination (R^2) value of 0.400 showed that the goodness of the fit was relatively poor. Because the correlation between BPN and Φ was shown to be relatively weak, the average of all porosities was used for all other comparisons for the rest of the study.

Table 7.1: Statistical analysis of the relationship between porosity and BPN values for PC.

Slider Type	Porosity (Φ)	Mean Φ	Std. Dev. Φ	Mean BPN		Std. Dev. BPN		P-value (R^2-value)	
				Dry	Wet	Dry	Wet	Dry	Wet
PSR	Low	0.18	0.027	87	77	5	5	0.068 (0.128)	0.124 (0.092)
	Med	0.27	0.021	90	79	3	3		
	High	0.37	0.030	91	80	4	4		
TSR	Low	0.18	0.027	102	88	7	8	0.182 (0.070)	<0.001 (0.400)
	Med	0.27	0.021	103	92	10	9		
	High	0.37	0.030	106	104	9	9		

5.2 Baseline Conditions: Dry, Wet and Iced

As expected, the porous and rough surfaces of the PC slabs resulted in higher baseline BPN values than those of the PCC slabs in all three baseline conditions (fig. 5.1). Paired t-test statistical analysis showed that the differences between the BPN values of PC and PCC for all three baseline conditions were significant (p-values of less than 0.05) (table 5.2). Table 4.1 describes which slab surface frictions were averaged for the data in each graph. The error bars represent the standard deviation of each data group. The minimum threshold value of 42 mentioned previously was not used for this project because it is an asphalt specification; therefore, the study used a minimum threshold of acceptance for PC of 45 under wet conditions (marked by a red line on the graphs), per specifications by Asi (2005). This value pertains to low traffic roadways in low speed zones, which is applicable to PC used for parking lots, driveways, and collector streets. Both the PC and PCC were well above the minimum threshold for wet conditions using PSR (fig. 5.1-a) and TSR rubber types (fig. 5.1-b). PC in iced conditions performed near the minimum threshold, while PCC performed well below the threshold value at 22 BPN. Asi (2005) also stated that the minimum BPN value for difficult sites, including roundabouts, low radius corners, steep gradients, and “approaches to traffic lights on unrestricted roads” should be 65 in wet conditions, which was also surpassed by the PC under both wet and dry conditions. The dry, wet, and iced condition slab surfaces for both PC and PCC can be seen in figure 5.2.

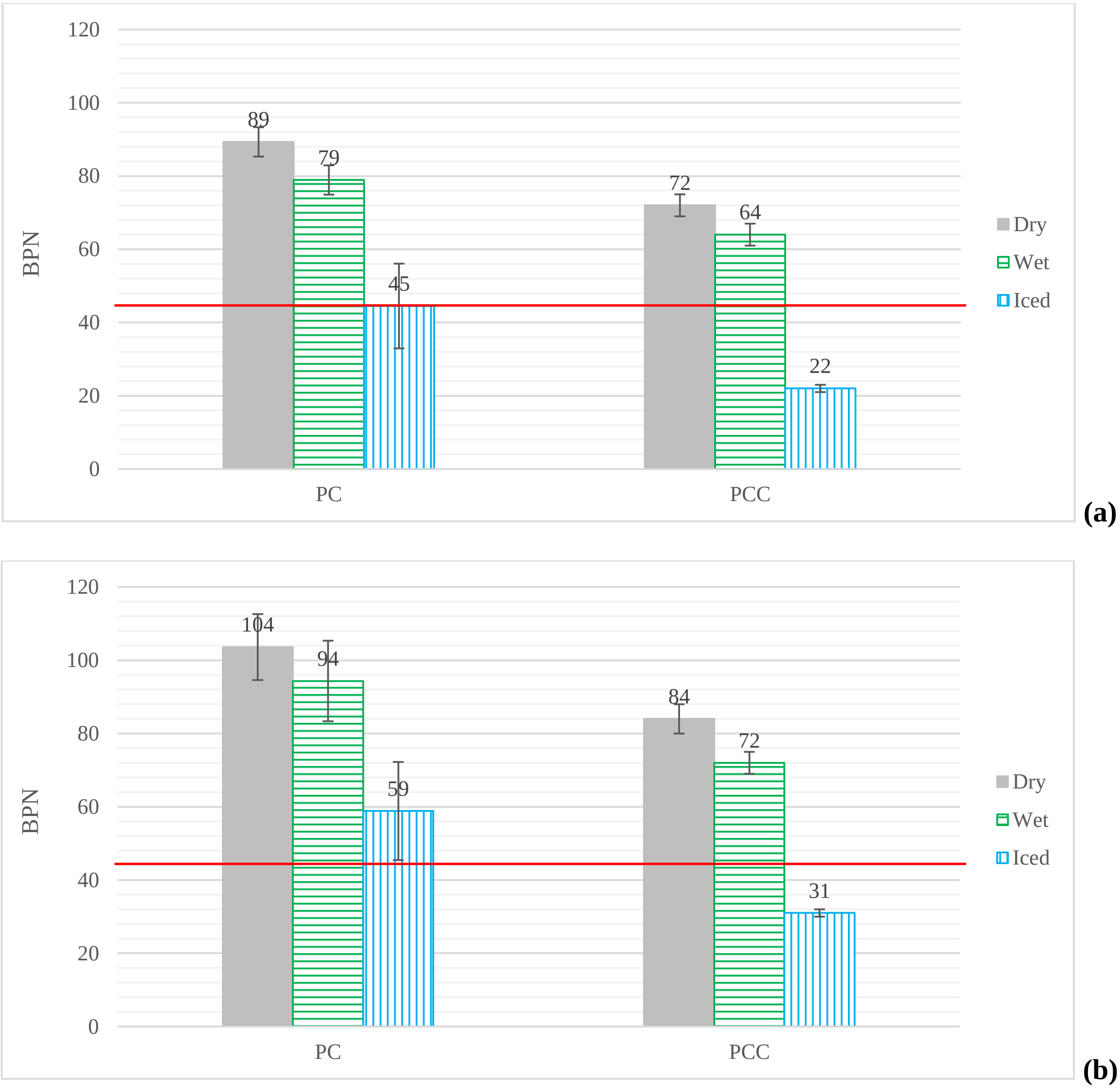


Figure 7.1: Baseline test condition comparisons between PC and PCC using a) PSR and b) TSR. The red line marks the minimum value of 45 allowed for wet conditions for concrete pavements (Asi 2005).

Table 7.2: P-value from statistical evaluation of PC versus PCC for each of the baseline test conditions.

Baseline Test Condition	P-value comparing PC to PCC	
	Rubber type: PSR	**Rubber type: TSR**
Dry	0.000	0.000
Wet	0.000	0.000
Iced	0.000	0.000

Liu et al. (2003) reported BPN values for PCC of 67 in dry conditions and 32 in wet conditions. Lee et al. (2005) reported values of 75 in dry conditions, when testing traditional concrete. Houle (2008) tested all three baseline conditions for PCC and recorded values of 97, 74, and 29 for dry, wet, and iced conditions, respectively. Comparing these results to those obtained in this study and shown in figure 5.1, it can be concluded that PC outperformed PCC in the wet and iced conditions tested in this study as well as those reported in the literature, which are critical for evaluating SR in winter. Iced testing conditions were associated with the largest difference between PC and PCC, which was most likely due to the PC's ability to drain water through the voided system and leave less free-standing water to form ice crystals. In iced conditions, the BPN of the PC increased by 23 for PSR and 28 for TSR over those values for the PCC.

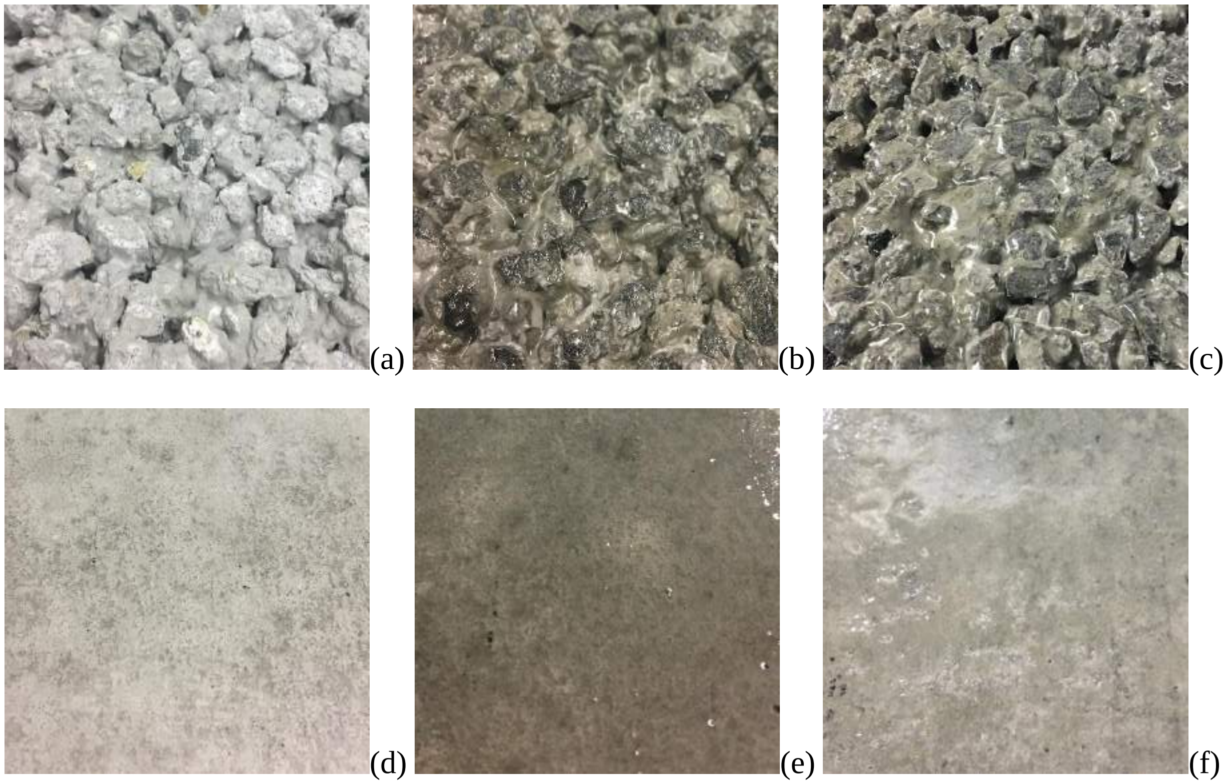


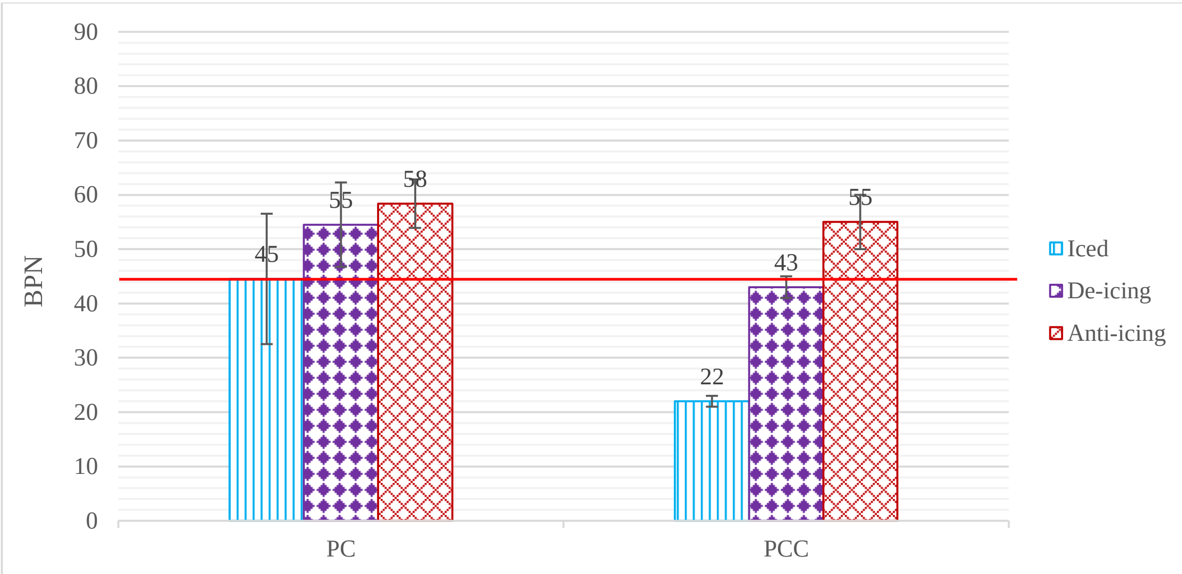
Figure 7.2: PC and PCC slabs under different baseline conditions. PC slab conditions: a) dry, b) wet, c) iced. PCC slab conditions: d) dry, e) wet, f) iced.

As expected, the TSR showed higher BPN values than the PSR in each of the baseline conditions, which reflects that tire rubber has better SR than that of shoe rubber on concrete pavements. This is because the PSR is harder than the tire slip rubber. With more hardness and thereby a larger elastic range, the rubber contributes less to friction through hysteresis loss (Salimi et al. 2015).

5.3 Anti-icing vs. De-icing

Two methods of ice control, de-icing and anti-icing, were used in the experiment. Anti-icing methods are used to prevent ice from forming on the surface, whereas de-icing methods are used to melt ice after its development. The BPN values after both of these treatments in comparison to the baseline iced condition are presented in figure 5.3 for both PC and conventional concrete.

De-icing and anti-icing treatments resulted in higher frictional properties than iced conditions. In comparing the two methods, the BPN after anti-icing on PC was 3 higher for PSR (fig. 5.3-a) and 5 higher for TSR (fig. 5.3-b) than de-icing on PC. Statistically comparing iced conditions to both de-icing and anti-icing showed that both methods resulted in significantly higher BPN values than the baseline iced condition (table 5.3). In addition, comparing de-icing and anti-icing of both the PC and PCC showed that the difference between the two methods was statistically significant for all scenarios except one. That is, testing PC with the PSR showed no statistical significance between the two methods. The anti-icing methods did not allow ice to form, which left the surface wet rather than iced. Anti-icing of both PC and PCC left no ice, leading to higher BPN values than those of the plain ice cover. De-icing methods worked in a similar way, even though de-icing had different impacts on PC and traditional concrete. For both scenarios, the ice melted, but water drained into the voids of the PC whereas for PCC the water remained on the surface. The water was able to drain through the PC for both the de-icing and anti-icing procedures, which may be why their BPN values are similar for the PC slabs. The TSR resulted in higher BPN values than the PSR for each of the chemicals tested, confirming that tire rubber, which is from a stiffer rubber material, has greater SR than shoe soles.



(a)

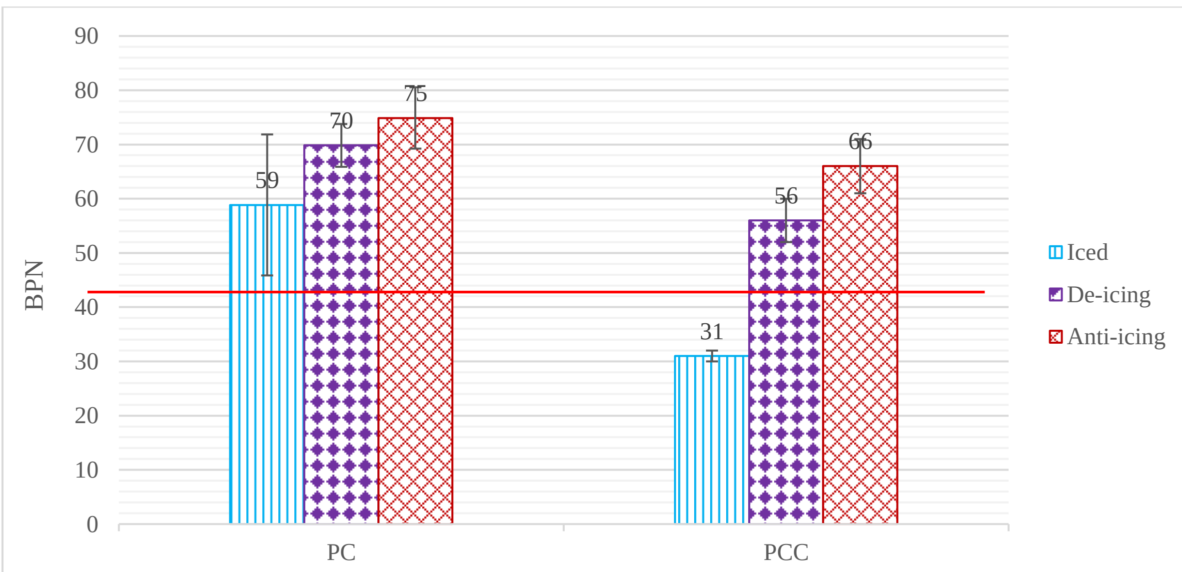


Figure 7.3: Winter maintenance methods using a) PSR and b) TSR. Both magnesium and calcium chloride were used. The red line marks the minimum value of 45 allowed for wet conditions of concrete pavements (Asi 2005).

Table 7.3: P-values from statistical analysis comparing iced conditions to de-icing and anti-icing methods for both PC and PCC slabs.

Slab Type	Statistical Comparison	P-value	
		Rubber type: PSR	Rubber type: TSR
PC	Iced vs De-icing	0.044	0.001
	Iced vs Anti-icing	0.001	0.000
	De-icing vs Anti-icing	0.091	0.005
PCC	Iced vs De-icing	0.000	0.000
	Iced vs Anti-icing	0.000	0.000
	De-icing vs Anti-icing	0.000	0.000

5.4 The Effect of Chemical Agent Type

Both $MgCl_2$ (liquid) and $CaCl_2$ (pellets) effectively increased BPN in comparison to the baseline iced condition on the slab surfaces, as seen in figure 5.4, to above the minimum threshold of 45. The values used in figure 5.4 were an average of the de-icing and anti-icing results for each agent. Magnesium chloride was more effective at mitigating ice than the calcium chloride for all testing scenarios except for PSR (fig. 5.4-a) testing on pervious concrete, which only had a BPN value difference of 1.0 between the two chemical agents. Statistical analysis showed that the use of $CaCl_2$ and $MgCl_2$ resulted in significant increases of the BPN value in compareison to the baseline iced condition (table 5.4). The difference between the two chemicals was also statistically significant for all scenarios except PC using the pedestrian slip rubber.

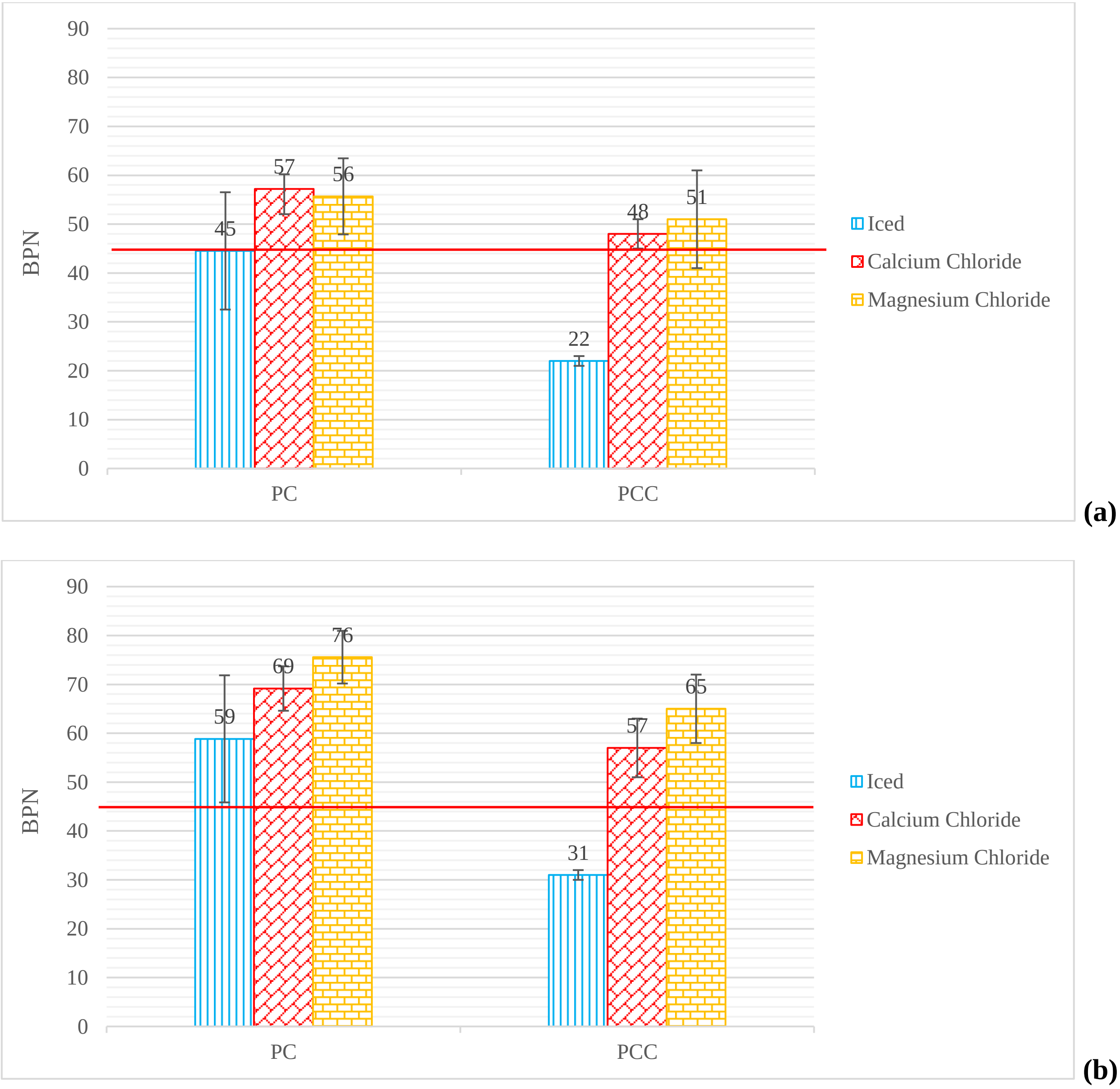


Figure 7.4: Winter maintenance chemicals comparison using a) PSR and b) TSR. The red line marks the minimum value of 45 allowed for wet conditions of concrete pavements (Asi 2005).

Table 7.4: P-value from statistical analysis comparisons of iced conditions to liquid magnesium chloride and calcium chloride pellets for both PC and PCC slabs.

Slab Type	Statistical Comparison	P-value	
		Rubber Type: PSR	Rubber Type: TSR
PC	Iced vs $CaCl_2$	0.003	0.001
	Iced vs $MgCl_2$	0.015	0.000
	$CaCl_2$ vs $MgCl_2$	0.550	0.007
PCC	Iced vs $CaCl_2$	0.000	0.000
	Iced vs $MgCl_2$	0.000	0.000
	$CaCl_2$ vs $MgCl_2$	0.000	0.000

The $CaCl_2$ created a slick surface when coated with moisture, which explains the lower values of friction in comparison to $MgCl_2$. In the one scenario in which the $CaCl_2$ showed higher BPN than the $MgCl_2$, it is likely that as the pellets decreased in size they settled into the voids of the PC and were no longer on the surface to affect the skid resistance. Figure 5.5 shows the slab surface of PC and PCC slabs after the chemical agents have been applied. For PC, the use of both chemicals had BPN values that were greater than the standard laid out by Asi (2005). The PC's ability to drain water from the surface helped prevent ice formation and the mitigation of ice using chemicals. The advantage of water drainage produced higher SR in the tested conditions for the PC pavements. As seen in the previous sections, the TSR (fig. 5.4-b) resulted in higher BPN values than those of the PSR across all categories of conditions and implemented chemicals.

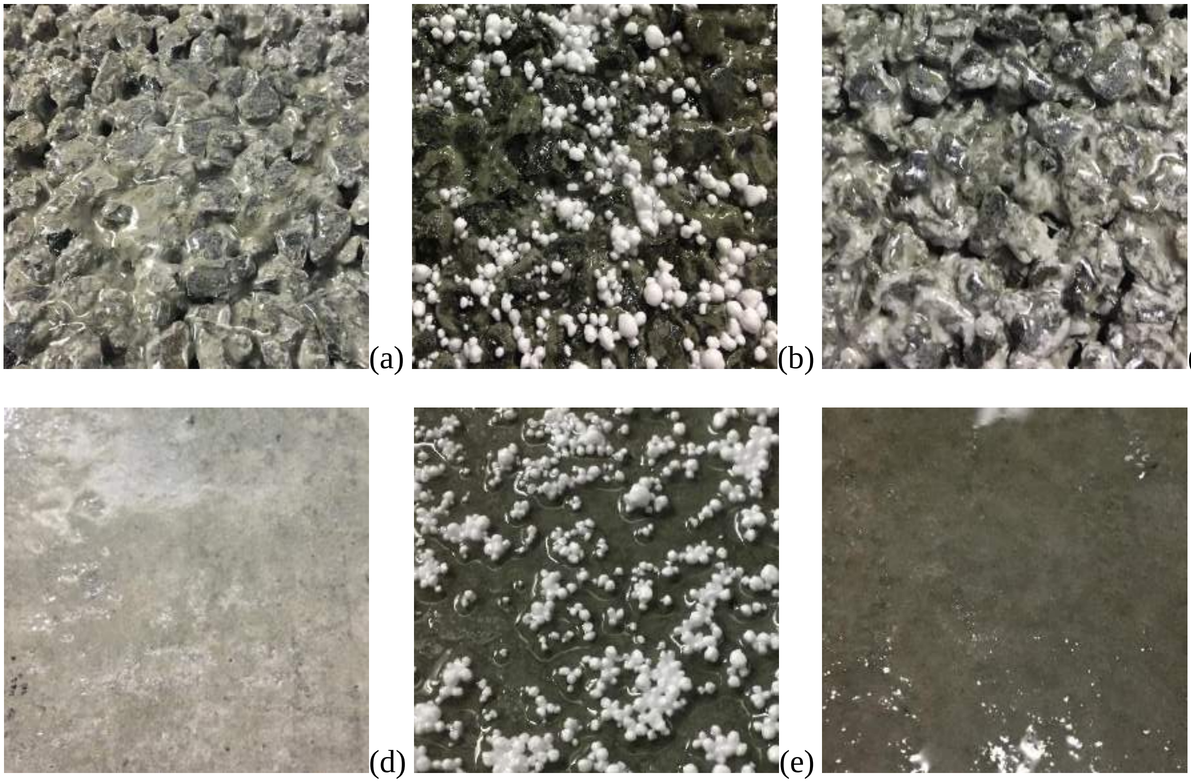


Figure 7.5: PC and PCC slabs under different iced conditions. PC slab conditions: a) iced, b) calcium chloride, c) magnesium chloride. PCC slab conditions: d) iced, e) calcium chloride, f) magnesium chloride.

Chapter 8 Conclusions and Recommendations

The objective of this study was to evaluate the winter surface conditions of pervious concrete (PC) by using the skid resistance (SR) measures. Skid resistance was recorded in values of the British Pendulum Number (BPN) by using the British Pendulum Tester (BPT). Pervious concrete slabs were compared to traditional portland cement concrete slabs (PCC) in dry, wet, iced, anti-icing, and de-icing conditions. Calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) agents were used to reduce ice formation. On the basis of the results of this study, the following conclusions can be drawn:

- Three groups of low, medium and high porosity PC slabs were cast, finished and tested using a BPT. However, porosity showed insignificant correlations with the BPN values. The goodness of the fit for all data was low, and the correlation p-values were large except for one scenario. The goodness of the fit for this scenario was poor, which indicates that although there may be some statistical significance, the data were scattered.
- Two rubber sliders were used to compare pedestrian and vehicle users. The tire slip rubber (TSR) showed higher friction than the pedestrian slip rubber (PSR) because of their difference in hardness. The PSR had a higher hardness, and its more elastic behavior resulted in less energy absorption and hysteresis loss.
- Pervious concrete outperformed PCC in all of the baseline test conditions: dry, wet, and iced in terms of the BPN values. The differences between PC and PCC for each of the baseline conditions were statistically significant. The PC also outperformed BPN values for PCC that were found in the literature, showing that the tested PC had higher friction under the evaluated test conditions than other PCC mixture designs.

- All PC and PCC slabs tested in this study in dry and wet conditions surpassed the minimum 45 BPN threshold in wet pavement conditions as established by Asi (2005). However, in the iced conditions, the BPN values for PC were around 45, while the PCC values were well below the threshold, results most likely due to drainage of melted ice (water) through the PC slab.
- Both anti-icing and de-icing treatments were found statistically significant for improving the frictional properties of iced PC and PCC slabs. The positive effects were similar throughout all the experiments; however, the anti-icing treatment outperformed the de-icing method. The differences between de-icing and anti-icing were statistically significant for every scenario, except PC surfaces tested with the PSR.
- Both liquid $MgCl_2$ and $CaCl_2$ pellets were successful at significantly improving the SR of PC and PCC slabs. Magnesium chloride resulted in higher BPN values than the $CaCl_2$ for all test conditions except one; this condition was the PC tested with the PSR, which was the only scenario that did not produce statistically significant differences. The $CaCl_2$ pellets resulted in slick surfaces when surrounded by moisture, which was likely the cause of their lower BPN values. The $MgCl_2$ left the surfaces in a condition similar to wet slab surfaces.

Given the results of this study and the observations above, the tested PC mixture in this study with an angular crushed basalt coarse aggregate had an overall better BPN performance than traditional PCC and maintained acceptable levels of SR under wet conditions and marginally acceptable SR in iced conditions. One-time application of liquid anti-icing agents on PC streets and sidewalks was successful in bringing the BPN values to the required level of BPN—higher than 45—for both sidewalks and streets in one icing event. Future testing should include multiple icing cycles to establish proper application rates over time. Under the tested conditions and for the tested mixture, anti-icing with liquid $MgCl_2$ rather than pelleted $CaCl_2$ provided the optimum solution to mitigating ice formation and improving the SR of PC in iced conditions on sidewalks. One aggregate type was used in the experiment. It is suggested that other aggregate shapes and types also be investigated in the future.

References

American Association of State Highway and Transportation Officials (AASHTO) Task Force for Pavement Design of the AASHTO Operating Subcommittee on Design (AASHTO). 1976. "Guidelines for Skid Resistant Pavement Design." , Washington, D.C.

Asi, I. M. 2005. "Evaluating skid resistance of different asphalt concrete mixes." *Building and Environment*, 42: 325-329.

ASTM. 2012. "Standard Test Method for Density and Void Content of Hardened Pervious Concrete." ASTM C1754-2012, West Conshohocken, PA.

ASTM. 2013. "Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester." ASTM E303-2013, West Conshohocken, PA.

Bendtsen, H. 2011. "European Experience – Winter Service of Porous Asphalt". *Technical note 123-2012,* Vejdirektoratet, Denmark.

Boving, T., Stolt, M., Augenstern, J., and Brosnan, B. 2008. "Potential for Localized Groundwater Contamination in a Porous Pavement Parking Lot Setting in Rhode Island." *Environ. Geol,* 55(3): 571–582.

Brattebo, B. O. and Booth, D. B. 2003. "Long-Term Stormwater Quantity and Quality Performance of Permeable Pavement Systems." *Water Research,* 37(18): 4369–4376.

Cahill, T., Adams, M., and Marm, C. 2003. "Porous Asphalt: The Right Choice for Porous Pavements." *Hot Mix Asphalt Technology,* 26–40.

Cooper Technology. 2006. "CRT-Pendulum User Manual". Issue 2. 25.03.14.

Danish Road Directorate. 2012. "Winter Service of Porous Asphalt." *European Experience, Technical Note,* 123–2012, 34.

Dooley, T. P., Jackson, M. P. A., and Hudec, M. R. 2009. "Inflation and Deflation of Deeply Buried Salt Stocks during Lateral Shortening." *Journal of Structural Geology,* 31: 582–600.

Ferreira, T., Rasband, W. 2012. ImageJ User Guide (IJ 1.46r). ImageJ.

Giuliani, F. 2002. "Winter Maintenance of Porous Asphalt Pavements." *XIth International Winter Road Conference, World Road Association (PIARC),* Sapporo, Japan, Accession Number: 00925136.

Gulliver, J. S. 2015. "Permeable Pavements in Cold Climates: State of the Art and Cold Climate Case Studies." *Department of Civil, Environmental, and Geo- Engineering,* University of Minnesota.

Haselbach, L., Valavala, S., Montes, F. 2006. "Permeability Predictions for Sand Clogged Portland Cement Pervious Concrete Pavement Systems." *Journal of Environmental Management,* 81(1): 42-49.

Houle, K. M. 2008. "Winter Performance Assessment of Permeable Pavements: A Comparative Study of Porous Asphalt, Pervious Concrete, and Conventional Asphalt in a Northern Climate." Worcester Polytechnic Institute.

Huber, G. 2000. "Performance Survey on Open-Graded Friction Course Mixes". *National Cooperative Highway Research Program. National Academy Press, Synthesis of Highway Practice,* 284(50).

Isenring, T., Koster, H., and Scazziga, I. 1990. "Experiences with Porous Asphalt in Switzerland." *Transportation Research Record 1265,* Transportation Research Board, Washington, D.C.: 41–53.

James, W. and Gerrits, C. 2003. "Maintenance of Infiltration in Modular Interlocking Concrete Pavers with External Drainage Cells." *Practical modeling of Urban Water Systems,* CHI Publishers, Guelph: 417–435.

Lee, Y. P. K., Fwa, T. F., Choo, Y. S. 2005. "Effect of Pavement Surface Texture on British Pendulum Test." *Journal of Eastern Asia Society for Transportation Studies,* 6: 1247-1257.

Litzka, J. 2002. "Austrian Experiences with Winter Maintenance on Porous Asphalt". *Ninth International Conference on Asphalt Pavements,* Copenhagen, Denmark.

Liu, Y., Fwa, T. F., Choo, Y. S. 2003. "Finite-Element Modeling of Skid Resistance Test." *Journal of Transportation Engineering,* 10.1061/(ASCE)0733(2003)129:3(316).

Mahone, D. C. 1975. "An Evaluation of the Effects of Tread Depth, Pavement Texture, and Water Film Thickness on Skid Number-speed Gradients." *Virginia Highway and Transportation Research Council,* Charlottesville, VA.

Manahiloh, K. N., Muhunthan, B., Kayhanian, M., and Gebremariam, S. Y. 2012. "X-ray computed tomography and nondestructive evaluation of clogging in porous concrete field samples." *Journal of Materials in Civil Engineering,* 10.1061/(ASCE)MT.1943-5533.0000484.

Noort, M. 1996. "Winter Maintenance on Porous Asphalt." *4th International Symposium on Snow Removal and Ice Control Technology,* Preprints Vol. I. Transportation Research Board. Reno, NV.

Noyce, D. A., Bahia, H. U., Yambó, J. M., and Kim, G. 2005. "Incorporating Road Safety into Pavement Management: Maximizing Asphalt Pavement Surface Friction for Road Safety Improvements." *Midwest Regional University Transportation Center,* Traffic Operations and Safety (TOPS) Laboratory.

NRMCA. "Pervious Concrete Pavement Maintenance and Operation Guide."

Pattanaik, M. L., Choudhary, R., and Kumar B. 2017. "Evaluation of Frictional Pavement Resistance as a Function of Aggregate Physical Properties." *J. Transp. Eng., Part B: Pavements,* 10.1061/JPEODX.0000005, 04017003.

Poulikakos, L. D., Pittet, M., Arnaud, L., Junod, A., Gubler, R., Simond, E., Partl, M., and Dumont, A. G. 2006. “Mechanical Properties of Porous Asphalt, Recommendations for Standardization.” *Swiss Federal Laboratory for Materials Testing and Research,* LAVOC-REPORT-2008-020, 110.

Salimi, S., Nassiri, S., Bayat, A., & Halliday, D. 2015. “Lateral coefficient of friction for characterizing winter road conditions.” *Canadian Journal of Civil Engineering*, 43(1): 73-83.

Scholz, M. and Grabowiecki, P. 2007. “Review of Permeable Pavement System”. *Building and environment,* 42: 3830–3836.

Stenmark, C. 1995. “An Alternative Road Construction for Stormwater Management in Cold Climates.” *Wa. Sci. Tech.*, 32: 79–84.

Tennis, P. D., Leming, M. L., and Akers, D. J. 2004. “Pervious Concrete Pavements.” *Portland Cement Association,* Skokie, IL, and *National Ready Mixed Concrete Association,* Silver Spring, Maryland.

(TRB) Transportation Research Board. 1998. “Improved Surface Drainage of Pavements: Final Report.” Washington, DC: The National Academies Press.

UDFCD (Urban Drainage and Flood Control District). 2010. “Urban Storm Drainage Criteria Manual, version 3.” Denver, CO.

Van Duin, B., Brown, C., Chu, A., Marsalek, J., and Valeo1, C. 2008. “Characterization of Long-Term Solids Removal and Clogging Processes in Two Types of Permeable Pavement under Cold Climate Conditions”. *11th International Conference on Urban Drainage,* Scotland, UK.

Wallman, C. G., Astrom, H. 2001. “Friction measurement methods and the correlation between road friction and traffic safety. A literature review.” *Swedish National Road and Transport Research Institute.*

Wirjadi, O. 2007. “Survey of 3d image segmentation methods.” (Vol. 35). ITWM.

Yu, B., Liya, J., Ni, F., and Yang, J. 2015. “Long-Term Field Performance of Porous Asphalt Pavement in China.” *Road Materials and Pavement Design,* 16(1): 214–226.