Strength and Permeability Characteristics of Porous Concrete Pavements

George N. McCain, Graduate Research Assistant
Mandar M. Dewoolkar, Assistant Professor

School of Engineering
The University of Vermont
301 Votey Hall, 33 Colchester Ave.
Burlington, VT 05405, U.S.A.
Tel: (802) 656 1942
Fax: (802) 656 8446
E-mails: gmccain@uvm.edu, mandar@cems.uvm.edu

Words: 5,319
Tables: 3 x 250 = 750
Figures: 2 x 250 = 500
Total Words: 6,568

ABSTRACT

A laboratory study evaluating strength and permeability characteristics of a porous concrete mix is presented. The experiments included compressive strength tests and falling head permeability tests on clean specimens. Falling head permeability tests were repeated after introducing some sand-salt mixture on the top surface of the specimens as a simulation of winter surface applications. The experiments were performed on specimens of three sizes: 7.62 cm (3"), 10.16 cm (4"), and 15.24 cm (6") in diameter to examine if the test results were influenced by the size of the specimens. Multiple specimens were tested for a particular size. For the particular mix examined, the compressive strength ranged between about 4.5 MPa (650 psi) and 7.6 MPa (1,100 psi) with an average of about 6.2 MPa (900 psi). Permeability test results yielded hydraulic conductivity ranging between 0.68 cm/s and 0.98 cm/s (971 in/hr and 1,387 in/hr) with an average of about 0.87 cm/s (1,233 in/hr). All of the above values were within the expected range found in the literature. The reduction in the hydraulic conductivity was about 15% with the surface application of the sand-salt mixture. The observed variations in the properties were also similar to those reported in the literature. Any effects arising from the size of the specimen on the test results could not be distinguished from those arising from normal variations among specimens.

Key Words: Porous concrete, Compressive strength, Hydraulic conductivity, Winter surface applications, Specimen size effects

INTRODUCTION

There has been a strong sentiment to increase the regulation of stormwater runoff within the United States in recent years. The Clean Water Act and other EPA regulations (e.g. EPA Stormwater Phase II Final Rule) were introduced, in part, to create more stringent standards for stormwater runoff control. Estimates of the impact that stormwater has on water resources in the United States indicate that up to 13% of impaired rivers, 18% of impaired lakes, and 32% of impaired estuaries are affected by stormwater runoff in urban or suburban areas (EPA, 2005). In an attempt to cease the further degradation of these water resources viable alternatives to current construction and other development practices need to be considered.

A pervious pavement system is an environmentally conscious alternative to a traditional asphalt and concrete pavement system (Ferguson, 2005). An impervious pavement system, particularly parking lots, collect oil, anti-freeze, and other pollutants which can then be washed into water bodies during a storm event creating a point source for pollution. On the other hand, a properly designed and implemented porous pavement system allows for the polluted water to pass through the pavement into an infiltration bed, store the water temporarily if necessary in the gravel sub-base, and then allows the water to infiltrate into the natural sub-base or discharge after treatment (Ferguson, 2005). In addition to these environmental benefits, porous pavements have numerous structural and economic advantages when compared to traditional asphalt and concrete pavements. It creates a drier surface during a storm event making these systems safer for drivers, produces less noise than traditional systems, and a pervious pavement could negate the need for other forms of stormwater treatment, such as retention ponds that can be both costly and impractical in many situations (Ferguson, 2005). Northern states have been slow to adopt this kind of technology, largely because there is little data on the effects of wet freezing climate along with a lack of experience base in implementing porous pavements.

In order to properly utilize these kinds of systems in Northern climates the efficacy of current porous pavement techniques and characteristics when they are applied to a cold climate with wet freezing characteristics need to be evaluated. Sand and salt applications in winter can also affect the infiltration rate of porous pavements. Studies have been performed that suggest porous pavements can be effective in a cold climate (Schaefer, et al., 2005; Murata, et al., 2005), but each region has its own unique properties and utilizes local materials in its concrete mix designs. The evaluation of local concrete constituents such as coarse aggregate will aid in the determination of what components are needed to produce durable, high quality porous pavement systems.

The objectives of the study presented here were to determine the compressive strength and permeability properties of a particular porous concrete mix design. Winter maintenance was simulated by applying sand and salt mixture to the top surfaces of specimens. Each type of test was performed on samples with diameters of 7.62 cm (3”), 10.16 cm (4”), and 15.24 cm (6”) to determine what role, if any, the sample size has on reported results. For a given sample size, each test was conducted on at least three different “identical” specimens.

BACKGROUND

Literature related to the strength and permeability of porous concrete is reviewed in this section. No studies were found that investigated effects of laboratory specimen size on measured compressive strength and hydraulic conductivity of porous concrete.

Strength

The disadvantages of a porous pavement are perceived to be lower strength and durability that can sometimes occur in these systems, which may lead to a service life that is shorter than that of the designed life (Schaefer, et al., 2006; EPA, 1999). However, several studies have shown that adequate strength can be achieved for a variety of applications in which porous pavements would be useful, specifically low-volume traffic areas such as parking lots (e.g., Ghafoori and Dutta, 1995; Schaefer, et al., 2005). In these areas the benefits of porous pavement systems can outweigh the perceived limitations, as low-volume areas have a smaller strength demand and act as point sources for stormwater pollution.

Laboratory studies have shown a wide range of values for 28-day compressive strengths of porous concrete. Some studies have reported that strengths of about 21 MPa (3,000 psi) or more are readily attainable with the proper water-cement ratio and densification process (Ghafoori and Dutta, 1995). Other studies have found compressive strengths that range from about 4 MPa to 25 MPa (600 psi to 3,600 psi) (Chopra and Wanielista, 2007; Schaefer, et al., 2006). Several factors have attributed to this wide range of reported strengths. The first of which is the effect of compaction or densification on the sample. It has been shown that in general, as the compaction energy or densification effort on the sample increases, there is a corresponding increase in the compressive strength of the sample (Chopra and Wanielista, 2007; Schaefer, et al., 2006). The issue that arises when applying too much compaction or densification on a porous concrete is that these efforts may reduce the air voids of the sample significantly and as such may reduce its permeability significantly. As achieving adequate permeability for stormwater control is generally the main goal of a porous pavement system, compacting concrete until it reaches adequate strength is not always an option, and a balance must be achieved between strength and void ratio (Ferguson, 2005).

The water-cement ratio (W/C), aggregate-cement ratio (A/C), unit weight of the mix and their effects on the overall strength of porous concrete have also been studied. The W/C ratio alone does not affect the overall strength, but may cause cement to settle on the bottom of the sample thereby reducing permeability (Chopra and Wanielista, 2007). The A/C ratio does have a direct effect on the compressive strength of the system, and as this ratio increases the strength of the concrete decreases (Chopra and Wanielista, 2007). The unit weight of the mix also has a direct effect on the compressive strength of porous concrete, and as the unit weight increases the strength also increases (Chopra and Wanielista, 2007; Schaefer, et al., 2006).

Studies have also been performed to evaluate the properties of porous pavement systems in the field. Several parking lots in Florida with various traffic loads were monitored and inspected visually for any kind of damage due to normal, everyday use (Chopra and Wanielista, 2007). These parking lots were designed for anywhere from 3,000 lb vehicle loads to 80,000 lb loads, and constructed between 8 and 20 years before the study was performed. In general damage was limited to the areas within the lots that received the most traffic, such as entryways and exits. The damage that was exhibited included raveling (damage due to wear and tear over time) and cracking. Much of the failure in other areas of the lots designed for passenger vehicles was attributed to garbage trucks, as damage was centralized around dumpsters and the trucks exerted large stresses on the porous concrete pavements when emptying them. There was also some documented algae growth at one of the sites, which had no effects on the strength of the system although had some effect on its permeability (Chopra and Wanielista, 2007).

A potential concern for porous pavements in cold climates is the durability of the pavements subjected to freeze-thaw (f-t) cycles. Standard concrete designed for f-t resistance will generally have somewhere between 4% and 8% air entrainment in microscopic pores, at a pore spacing of less than about 0.25 cm (0.01") (NRMCA, 2004). These parameters provide air voids for water expansion during the freezing process, reducing the internal stresses of the concrete. However, the structure of porous concrete is very different. Porous concrete is generally designed for anywhere between 15% and 35% air voids, and the voids are both interconnected and large enough so that they readily allow water to pass through. When these pores are critically saturated, there is no open void space for the water to expand into which produces internal tensile forces on the concrete. The thin cement layer that bonds the aggregate together is not always strong enough to withstand these tensile forces and spalling or cracking occurs (NRMCA, 2004). Porous concrete pavements can be susceptible to critical saturation if clogging of the pore structure occurs, the underlying subbase materials remain frozen for extended periods of time, or if the groundwater table rises within 3 ft of the porous concrete surface. To protect against critical saturation, specifications for cold weather regions include suggestions for aggregate base depth, drainage pipes, and addition of an air entraining agent in the mix design to protect the cement paste (NRMCA, 2004).

Some laboratory studies have investigated the f-t resistance of porous concrete systems. An issue that arises with this kind of testing is that the standard test for f-t resistance of concrete samples is ASTM C666, procedure A; *The Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*. This method tests the samples under completely saturated conditions for up to 300 cycles of freezing and thawing. However, this standardized test was designed to be performed on normal concrete samples, and is a particularly severe test. The results may be misleading as far as porous concrete is concerned, because it does not accurately represent conditions that would be found in the field. Also, measurements for the evaluation of f-t durability, such as change in length and relative dynamic frequency, were shown to be ineffective for porous concrete samples (NRMCA, 2004). Therefore percentage of mass lost during the f-t cycling is commonly used as a standard for durability (Ghafoori and Dutta, 1995; Schaefer, et al., 2006).

Ghafoori and Dutta (1995) performed f-t tests using ASTM C666, procedure A and reported mass loss results that ranged from less than 1% to 6% after 300 f-t cycles. They found that compaction energy played an important role in the f-t resistance, and as compaction energy was increased the f-t resistance of the concrete improved. They also found that using an air-entraining agent in the mix design improved the f-t resistance of the porous concrete. Schaefer, et al. (2006) reported a wide range of mass loss values for several different mix designs tested according to ASTM C666, procedure A. The study included several mixes that failed before 300 f-t cycles were completed (greater than 15% mass loss), as well as others that showed as low as 2% mass loss after 300 f-t cycles. They found that including small amounts of sand and/or latex in the mix design provided improved f-t resistance compared to those mixes that had neither. Compaction energy played an important role in the f-t durability of porous concrete (Schaefer, et al., 2006).

Permeability

The primary goal of any porous concrete system is to achieve adequate porosity so that water can readily pass through the system and into the subbase. The creation of air voids is achieved by limiting or completely eliminating fine aggregates (FA) such as sand from the mix design, and using a well-sorted coarse aggregate (CA). With no fines in the mix, the CA is bound together only by a thin layer of cement creating air voids. The use of a uniform CA ensures that smaller pieces do not settle in the pore spaces decreasing the porosity of concrete (Ferguson, 2005).

Several methods for determining the permeability of porous concrete systems have been proposed. Most studies utilize a falling-head apparatus adapted from soils testing, although other methods have been used to measure permeability both in the laboratory and in-situ. In their laboratory study, Schaefer, et al. (2006) utilized a falling-head permeameter in testing 7.62 cm (3”) diameter porous concrete specimens prepared using several mix designs and different compaction energies. The measured hydraulic conductivity ranged between about 0.01 cm/s and 1.5 cm/s (14.4 in/hr to 2,000 in/hr). Their results also indicated that permeability increased exponentially with increasing void ratio and that an increase in compaction energy corresponds to a decrease in permeability.

Montes and Haselbach (2006) also utilized a falling-head apparatus in determining the hydraulic conductivity of porous concrete specimens in the laboratory, which ranged between 0.014 cm/s (about 20 in/hr) and 1.19 cm/s (about 1,700 in/hr). The results showed that the hydraulic conductivity of a porous concrete sample increased exponentially with increasing porosity, and that porous concrete with porosity of less than 15% had limited to no permeability.

Ghafoori and Dutta (1995) utilized a constant head permeameter in measuring the hydraulic conductivity of porous concrete samples in the laboratory. The study focused on the effects that compaction energy and the aggregate to cement ratio had on the hydraulic conductivity of porous concrete. Both of these factors were found to play a role in the overall hydraulic conductivity of the concrete, with an increasing compaction energy corresponding to a lower hydraulic conductivity and a larger A/C also yielding a lower hydraulic conductivity.

Crouch et al. (2006) evaluated the hydraulic conductivity of porous concrete specimens prepared at various compaction energies in the laboratory as well as similar specimens retrieved from the field. With the use of a constant head permeameter the results showed that the hydraulic conductivity was dependent on the effective air void content and the effective void size. Hydraulic conductivity increased with either increasing effective void size or increasing air void content. Drain down also occurred in some samples when there was too much cement paste in the mix design for a given compactive effort, and resulted in the paste filling the air voids at the base of the sample, making it nearly impermeable.

To measure the hydraulic conductivity of porous concrete in-situ without having to obtain cores from the field, other tests have been adapted from soil mechanics. Bean, et al. (2007) measured the hydraulic conductivity of several porous concrete systems based on ASTM D3385, *Standard Test Method for Infiltration Rate in Field Soils Using Double-Ring Infiltrometer*. Areas that had been susceptible to clogging by fine soil particles were located based on visual inspection, and compared to areas that were free of any fines. The infiltrations were significantly lower in those areas that had been susceptible to fines. In areas free of fines, the median infiltration rate was about 1.5 cm/s (2,000 in/hr), whereas in areas that had been affected by fines the median rate was only about 0.005 cm/s (6.4 in/hr).

In order to adequately determine the effectiveness of porous pavement systems in Northern regions, the effects of winter surface applications must be evaluated. Through winter maintenance activities, it is possible for these systems to be exposed to sand and salt, which can clog the pores and significantly reduce permeability. Methods for reclaiming the pore space have been recommended, and include pressure washing or vacuuming (Ferguson 2005).

Murata et al. (2005) found porous concrete pavements to be effective in more than just low-volume traffic areas. Porous concrete pavements were utilized on three separate road sections in Fukui, Japan, with the objectives of determining their behavior in cold climate. Follow-up surveys were done during a three year study beginning from the initial construction. Although the field surveys found that the sites were nearly impermeable after the first year, permeability was able to be reclaimed through pressure washing techniques. Using a water pressure of 5 MPa, 40% of the original permeability was restored. Reduction in permeability was attributed to agricultural trucks that deposited fines on the road as they traveled rather than changes in the pore structure of the porous concrete pavement. The results also showed that plows and winter tires had little effect on the properties of the porous concrete pavement.

RESEARCH METHODS

Mix Design

The particular porous concrete mix design adopted for this study was based on the constituents that are readily available in the central Vermont region and local experience. The mix consisted of a 10 cm (3/8”) crushed stone aggregate and Lafarge type I-II cement. Admixtures were used including a viscosity modifying admixture (VMA), an air entraining agent, and a high-range water reducer (HRWR). These admixtures were used in an effort to improve the bond between the cement and the coarse aggregate, and to improve workability. A retarder was also used, due to the fact that the low water content of porous concrete pavement mixes causes them to dry quickly. The actual mix proportions for a batch volume of 1.75 cu. ft. are summarized in Table 1.

Table 1: Porous Concrete Mix Design

ITEM	Volume (10^{-6} m^3)	Mass (kg/m^3)
Cement	-	374
Coarse Aggregate	-	1660
Air-Entraining Agent	78.4	-
HRWR	941	-
Stabilizer	1180	-
Viscosity Modifying Admixture	1180	-
Water	-	94.1

Sample Preparation

The mix was prepared using a 2 ft^3 machine mixer. In order to protect against any loss of material, an initial butter batch was prepared in the mixer with the same proportions as the desired mix. The mixing procedure proposed by Schaefer, et al. (2006) was used. As per the procedure, the coarse aggregate was added to the mixer with about 5% (by mass) cement. This was mixed for 1 minute, or until the aggregate was fully coated by a thin layer of dry cement. After this initial mixing, the remaining cement along with all water and admixtures were added to the mixer. This was then mixed for 3 minutes, rested for 3 minutes, and then mixed again for 2 minutes.

All samples were prepared as cylindrical specimens. In order to evaluate the size effects of porous concrete samples, three mold sizes were used. The diameters of these samples were 7.62 cm (3”), 10.16 cm (4”), and 15.24 cm (6”). The specimens were compacted in the molds based on ASTM C192; *Practice for Making and Curing Concrete Test Specimens in the Laboratory*. Concrete was placed in molds in either 2 or 3 lifts (depending on sample size) according to Table 1 of ASTM C192. To provide uniform compaction in all cylinders, each lift was rodded 25 times with an appropriately sized tamping rod according to Table 2 of ASTM C192.

For strength testing, samples with a height to diameter ratio of 2:1 were used. For permeability testing, cylinders with same diameters as those used for strength testing were used, but the height of all cylinders was fixed at 10.16 cm (4”). A photograph of representative samples is presented as Figure 1. This particular height was used because most porous concrete pavements are of that thickness. Once the sample preparation was complete, the cylinders were capped to prevent water contact and placed in a fog room. All samples were de-molded after approximately 24 hrs, and then placed back in the fog room. Specimens used for strength testing were allowed to cure for a period of 28 days, up until the time of compression testing. Specimens allotted for permeability testing were cured in the fog room for at least 14 days, and then stored in open air at approximately 70°F until the time of testing.

Figure 1: Porous concrete specimens used for permeability testing

Test Procedures

Compressive Strength

Compressive strength testing was performed in general accordance with ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. Samples were capped with appropriately sized caps before being placed in the loading frame. Failure was considered to be the ultimate load applied to the sample before it could no longer support further load.

Permeability

Permeability tests were performed using three separate falling head permeameters, specifically designed to accommodate specimens of three different diameters. However, all three permeameters had similar design. As an example, Figure 2 shows a photograph of the permeameter used for testing 7.62 cm (3”) diameter specimens.

Figure 2: Falling head permeameter used for 7.62 cm (3”) diameter porous concrete specimens

The specimens were enclosed in a mold that was lined with a thin rubber sheet, and tightened with hose clamps to minimize any flow along the sides of the mold that would affect the measurement of hydraulic conductivity. The sample was then connected to a vertical PVC pipe on both the upstream and downstream sides. The apparatus was filled with water from the downstream end, to expel any air voids that may have been present in the porous concrete sample. Once water had reached the top of the specimen, the apparatus was then filled from the upstream side. The system was allowed to reach equilibrium, at which time the water level was recorded, representing the head level on the downstream side. Maintaining the constant downstream head at a higher elevation than the top of the porous concrete sample provided full saturation of the sample throughout the test. The upstream water level was then increased to a height of 30 cm (about 12”) and allowed to fall to a height of 10 cm (about 4”), during which the time it took to fall was recorded. These values were chosen to represent values that could possibly occur for a porous concrete pavement system during a storm event. This head difference was expected to maintain laminar flow for the range of anticipated hydraulic conductivity (Montes and Haselbach 2006).

Winter Surface Applications

The application of winter maintenance materials was done as an attempt to evaluate how the fines on the surface may affect the permeability of the concrete. In Vermont, typically a 2:1 sand to salt ratio is used for winter maintenance activities to protect against ice buildup and provide traction for vehicles. In order to model these activities, a similar mixture of sand and salt was created using materials that were representative of those found in central Vermont. The porous concrete samples were air-dried, at which time the sand/salt mixture was applied to its surface. Visual inspection of the concrete surface showed that a representative amount of sand-salt to use on the surface of the concrete specimens was about 0.12 g/cm^2. This amount of winter maintenance material was enough to coat the surface of the specimen and visually clog a significant amount of the pore space. This amount was set constant so that each size sample would have an equivalent amount of the winter maintenance materials applied. At this point it is not clear if this amount of winter surface application is representative of that in the field. Local data on that are presently being collected. After the application of these materials, the samples were placed in the falling head permeameter, and generally the same procedure (explained above) was followed to determine their hydraulic conductivities.

RESULTS

Strength

The results of the 28-day compressive strength tests are summarized in Table 2. The tests yielded a range of values from about 4.4 MPa to 7.5 MPa (about 650 psi to 1,100 psi), with an average strength of 6.22 MPa (about 900 psi). These values fall within the expected range of strengths for a porous concrete pavement as reported in the literature. For a given sample diameter, there was some variation of compressive strength up to about 3 MPa. Based on the results, size effects of compressive strength testing could not be distinguished from material variation, even though the same procedure was used for preparation of all porous concrete samples. Typically, the failure in the specimens was primarily between the aggregate-cement interfaces.

Table 2: Results of Compressive Strength Tests

Specimen Diameter (cm)	Specimen Number	Compressive Strength	
		(MPa)	(psi)
7.62 (3")	1	4.99	724
	2	6.76	980
	3	6.53	946
10.16 (4")	1	6.61	959
	2	6.27	909
	3	7.59	1101
	4	7.17	1040
15.24 (6")	1	4.46	647
	2	6.27	909
	3	5.51	799
	4	6.27	909

Hydraulic Conductivity

Table 3 summarizes the results of the falling head tests. The densities are also reported in Table 3, which are within a reasonably narrow range. The tests showed a range of hydraulic conductivities between 0.68 cm/s and 0.98 cm/s, (971 in/hr and 1,387 in/hr) with an average value of 0.87 cm/s (1,233 in/hr). These values fall within the expected range for porous concrete pavement as reported in the literature, providing adequate permeability to effectively reduce stormwater runoff. The size of the sample used for permeability testing does not appear to have any effect on the results that are distinguishable from the effects arising from variability in the samples. The most likely reason for differences in hydraulic conductivity would come from the difference in the pore structure among the specimens themselves. This same kind of variation would also occur in any porous concrete pavement system, so it is reasonable to take the average value of 0.87 cm/s to be the hydraulic conductivity of the mix design.

Winter Surface Applications

Table 3 also summarizes the results of falling head permeability tests after the application of winter maintenance materials. These materials show a marked impact on the permeability of porous concrete pavement. The reduction in hydraulic conductivity ranges from 11% to 21%, with an average reduction of 15.6%. While this is a significant reduction from the virgin hydraulic conductivity, the smallest value is still 0.54 cm/s (767 in/hr), which is considered adequate to allow water to pass through the system. It would be beneficial to conduct similar testing on specimens retrieved from the field after winter maintenance applications for field verification. Current research is underway to determine what amount of winter maintenance material would be representative of an entire winter's worth of maintenance activities to better characterize the effects of winter surface applications over an extended period of time.

Table 3: Falling Head Test Results

Diameter (cm)	Sample	Dry Density (g/cm^3)	Hydraulic Conductivity		Hydraulic Conductivity After Winter Surface Application		Reduction in Hydraulic Conductivity (%)
			(cm/s)	(in/hr)	(cm/s)	(in/hr)	
7.62 (3")	1	2.02	0.76	1074	0.64	900	16.20
	2	2.04	0.91	1294	0.75	1066	17.65
	3	2.00	0.86	1220	0.77	1086	11.00
	4	2.02	0.92	1301	0.75	1059	18.61
10.16 (4")	1	1.85	0.98	1387	0.82	1163	16.15
	2	1.94	0.95	1353	0.84	1184	12.49
	3	2.04	0.83	1181	0.73	1030	12.74
	4	1.95	0.96	1367	0.83	1179	13.77
15.24 (6")	1	1.76	0.95	1350	0.81	1154	14.52
	2	1.81	0.78	1100	0.65	923	16.11
	3	1.99	0.68	971	0.54	767	20.99
	4	1.92	0.86	1212	0.71	1003	17.28

Size Effects

No significant effects arising from specimen sizes were observed in the strength and permeability measurements. All variations in the reported values for strength and permeability can also be attributed to material variations in the samples themselves. Using the same procedure during the sample preparation process was in an effort to reduce these effects, but some variability is inevitable. No trends were found relating the sample sizes to increases or decreases in strength or permeability. Further research is underway to test a larger set of samples in order to obtain statistically relevant results that confirm these findings.

CONCLUSIONS

Compressive strength and hydraulic conductivity of laboratory porous concrete specimens prepared using a particular mix design were measured. The experiments included compressive strength tests and falling head permeability tests on clean specimens. Falling head permeability tests were repeated after introducing some sand-salt mixture on the top surface of the specimens as a simulation of winter surface applications. The experiments were performed on specimens of three sizes: 7.62 cm (3”), 10.16 cm (4”), and 15.24 cm (6”) in diameter to examine if the test results were influenced by the size of the specimens. Multiple specimens were tested for a particular size. The following conclusions are drawn for the particular mix examined:

1) The compressive strength ranged between about 4.5 MPa (650 psi) and 7.6 MPa (1,100 psi) with an average of about 6.2 MPa (900 psi), which was within the range of strength reported in the literature.

2) The hydraulic conductivity ranged between 0.68 cm/s and 0.98 cm/s (971 in/hr and 1,387 in/hr) with an average of about 0.87 cm/s (1,233 in/hr). These values were within the expected range found in the literature.

3) The reduction in the hydraulic conductivity was about 15% with the surface application of the sand-salt mixture.

4) Characteristics such as compressive strength and hydraulic conductivity did not show clear dependence on the size of the specimens.

ACKNOWLEDGMENTS

This work was funded by the United States Department of Transportation through the University of Vermont Transportation Research Center along with the Vermont Agency of Transportation (VTrans). The authors are grateful to Jim Wild, Curtis Morrill and T. J. Davison for their assistance in sample preparation.

REFERENCES

ASTM C39 (2003). "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." *Annual Book of ASTM Standards* 4.02. West Conshohocken, PA: ASTM International.

ASTM C192 (2003). "Standard Practice for Making and Curing Concrete Test Specimens." *Annual Book of ASTM Standards* 4.02. West Conshohocken, PA: ASTM International.

ASTM C666 (2003). "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing." *Annual Book of ASTM Standards* 4.02. West Conshohocken, PA: ASTM International.

ASTM D3385 (2003). "Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer." *Annual Book of ASTM Standards* 4.08. West Conshohocken, PA: ASTM International.

Bean, E. Z., Hunt, W. F., and Bidelspach, D. A. (2007). "Field Survey of Permeable Pavement Surface Infiltration Rates." *J. of Irrigation and Drainage Engineering*: 133(3), 249-255.

Chopra, M. and Wanielista, M. (2007). "Performance Assessment of Portland Cement Pervious Pavement." Stormwater Management Academy, University of Central Florida.

Crouch, L. K., Smith, N., Walker, A. C., Dunn, T. R., and Sparkman A. (2006) "Determining Pervious PCC Permeability with a Simple Triaxial Flexible-Wall Constant Head Permeameter" *TRB 2006 Annual Meeting CD-ROM.*

Environmental Protection Agency (2000. "Stormwater Phase II, Final Rule" (Revised December 2005), Office of Water (4203).

Ferguson, Bruce K. (2005), *Porous Pavements*, Boca Raton, FL: CRC Press.

Ghafoori, N., and Dutta, S. (1995). "Laboratory Investigation of Compacted No-Fines Concrete for Paving Materials." *Journal of Materials in Civil Engineering*: 7(3), 183-191

Murata, Y., Nishizawa, T., and Kokubu, K. (2005). "Evaluation of Porous Concrete Pavements in Japan." *8th In. Conf. on Concrete Pavements*, Colorado Springs, CO, 462-473.

Montes, F. and Haselbach, L. (2006). "Measuring Hydraulic Conductivity in Pervious Concrete." *Environmental Engineering Science*: 23(6), 960-969

NRMCA (National Ready Mixed Concrete Association) (2004). "Freeze-Thaw Resistance of Pervious Concrete." Silver Spring, MD.

Schaefer, V., Wang, K., Suleimman, M. and Kevern, J. (2006). "Mix Design Development for Pervious Concrete in Cold Weather Climates." *Final Report, Civil Engineering*, Iowa State University.