An Investigation into Porous Concrete Pavements for Northern Communities

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16. Abstract

A study evaluating the mechanical and hydraulic properties of several porous concrete pavement mix designs is presented. The objectives of the study were to: (1) quantify mechanical and hydraulic properties of select porous concrete pavement mix designs; (2) determine the effects of sample size on measured parameters; (3) evaluate the effects of winter surface applications (i.e. salt and sand) on hydraulic conductivity; (4) compare laboratory results with those obtained from the field; (5) measure surface infiltration capacity of porous concrete pavement installations; and, (6) determine the effects of plowing on surface infiltration capacity.

Compressive strength results for the various mix designs ranged from about 6.2 MPa (910 psi) to 26.7 MPa (3,880 psi). Hydraulic conductivity test results yielded average values ranging from 0.18 cm/s (255 in/hr) to 1.22 cm/s (1,729 in/hr). Both compressive strength and hydraulic conductivity results were within the range of values reported in the literature. Compressive strength and hydraulic conductivity also showed a clear linear dependence with specimen density. Reduction in hydraulic conductivity of laboratory specimens after one winter surface application was found to be approximately 15%. Reduction in hydraulic conductivity after maximum clogging of laboratory specimens was found to be approximately 35%. Specimens that were vacuumed to reclaim hydraulic conductivity after clogging were on average restored to within 10% of the initial hydraulic conductivity.

Preliminary surface infiltration capacity results showed that the porous concrete pavement facility recently built in Burlington, VT had adequate capacity for design storms in the region. Preliminary results from plowing simulation laboratory tests showed that plowing with no winter surface applications appeared to have an effect on the surface infiltration capacity of porous concrete specimens, reducing it somewhere between 6% and 15%. Using salt as a winter surface application appeared to yield similar results, reducing the surface infiltration capacity by 10%. Using a 2:1 sand to salt mixture had a more marked effect on surface infiltration capacity, leading to reductions of 96%.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement and Research Objectives

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 using 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 pavement designs. The evaluation of local constituents such as coarse aggregate will aid in the determination of what components are needed to produce durable, high quality porous pavement systems.

This research focused on porous concrete pavements. The specific objectives of the study presented here were to:

- quantify the mechanical and hydraulic properties of select porous concrete mix designs;
- evaluate the effects of winter surface applications (e.g., salt and sand) on hydraulic conductivity of porous concrete;
- determine the effects of sample size on measured parameters;
- compare laboratory results with field measurements;
- investigate the effects of water-cement ratio, high-range water reducer (HRWR) and air-entraining agent (AEA) on measured parameters;
- perform preliminary investigation on the use of a field permeameter to measure changes in in-situ surface infiltration capacity over time, and the effects of winter maintenance activities (e.g., plowing) on the engineering properties of porous concrete; and
- develop recommendations for an optimal mix design for Vermont and the surrounding region.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

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

2.2 Porous Concrete Pavements

Porous concrete pavements differ from traditional concrete pavement systems due to the fact that the concrete has a large amount of pore space, generally somewhere between 15-30% (Ferguson, 2005). In order to achieve this pore space, fine aggregates such as sand are either removed from the mix design completely or used sparingly. A typical mix design would include only coarse aggregate, cement, water, and admixtures such as high-range water reducers, air entraining agents, or viscosity modifying admixtures.

2.3 Stormwater Management

The main use of porous concrete pavements, primarily designed as parking lots, has been as a stormwater management technique. These types of systems have been identified as a best management practice (BMP) for stormwater pollution prevention (EPA, 1999). There are several advantages to choosing porous pavements over more traditional methods of stormwater prevention. Porous pavements are ideal for sites that have existing structural components, when systems such as retention ponds are not a viable solution due to area restrictions. A porous pavement system could easily be retrofitted to the site, as it could replace existing parking areas and serve a dual purpose as both a stormwater BMP and parking lot (Leming, et al., 2007).

Porous pavement systems are effective stormwater management tools for multiple reasons. One of the main benefits is that these systems are able to capture the "first flush" from a storm event, or approximately the first inch of rainfall that occurs (Tennis, et al., 2004). This "first flush" is generally the most polluted stormwater that is produced during a storm event, and being able to capture and treat this stormwater significantly reduces the amounts of pollutants that make their way into streams and other water bodies. Porous pavement systems are also able to create short-term detention of rainfall, resulting in a reduced amount of surface runoff, recharging of the groundwater table, and reducing the sediment load that makes its way into water bodies via stormwater (Leming, et. al, 2007). Porous pavements have been shown to be effective in pollutant removal, capable of eliminating up to 95% of the total suspended solids (TSS), 65% of the total phosphorous (TP), 85% of the total nitrogen (TN), and 99% of the metals from stormwater runoff (Schueler, 1987).

2.4 Design

Porous concrete pavements are generally designed as retention structures, much like other more traditional stormwater BMP's such as retention ponds. There are two possible categories porous pavement systems fall into, either a passive system or an active system. A passive system is designed to only replace impervious surface with pervious surface, and is not intended to store or treat stormwater runoff from other areas within the selected site. Alternatively, an active system is designed to accommodate stormwater resulting from more than just its own "footprint" (Leming, et al., 2007). An active system is ideal for areas where remediation is a priority, as they can be designed to store and treat stormwater from nearby impervious surfaces.

Two main components control the design of porous concrete pavement systems. The first component is the hydraulic considerations, both of the materials used and the site. Material properties that play an important role in the design include permeability of the porous concrete pavement, although this is generally not a limiting factor as permeability rates are commonly much greater than rainfall intensity (Tennis, et al., 2004). The permeability of the subbase material has been found to play a much more important role in design of porous concrete systems. Porosity of the subbase material is also important in design, as the storage capacity of the system is vital in determining the required depth of the system (Tennis, et. al, 2004). The hydraulic properties of the site itself are also important in the design process. Selecting the design storm is a critical aspect in order to have an effective system. Although design storms for various geographic locations vary according to local guidelines, the 2-yr, 24-hr storm is generally utilized as the service load for a porous pavement system, although the 10-yr, 24-hr storm is often used if flood control is an issue (Leming, et al., 2007). The properties of the subgrade soil at the site are also utilized in the design process. The infiltration capacity of the soil is used in calculating the storage capacity of the system, as well as the drawdown time (time for 100% of the storage capacity to be recovered). Soils with a percolation rate of at least 12 mm/hr (0.5 in/hr) have been found to be suitable for porous pavement systems, although there are design alternatives that can make porous pavement systems effective even when percolation rates are considerably lower (Tennis, et al., 2004).

Structural design of porous concrete pavements should be designed according to ACI 330R if the system is being designed as a parking lot, or ACI 325.12R if the system is being designed for streets or roads (ACI 522R-06, 2006). Structural design thicknesses should fall somewhere between 125 and 250 mm (5” to 10”), determined using either the AASHTO or PCA method (Tennis et. al., 2004). It is also common to increase the calculated structural thickness by 25% due to the lower strength that can occur in porous concrete pavements (Schaefer, et al., 2006). The subbase and subgrade materials must also be examined, to determine their support values and effectiveness in a structural pavement system.

In general, the larger of the two thicknesses from the hydraulic and mechanical designs will control. However, there are other design considerations that must be taken into account for special situations. In cold weather climates, it is suggested that the depth of the subgrade material extend anywhere from half the frost depth to below the frost line, as frozen soils are nearly impermeable (CWP, 1997; IDEQ, 2005). It is also recommended that there be at least 3 ft between the bottom of the subbase material and the bedrock layer, as well as 2 to 4 ft between the bottom of the subbase material and the seasonally high water table (TDEC, 2002).

2.5 Temperature Behavior

One of the secondary benefits of a porous concrete pavement system is that they are generally considered to have less of a heat island effect than traditional asphalt pavement systems (PCA 2003). The heat island effect occurs as urban development features such as pavements and rooftops absorb heat from the sun due to their dark color. These surfaces can reach temperatures of up to 50°C (90°F) greater than the surrounding air (EPA, 2009a). These systems store the excess heat that it gains during the day, and re-emits the heat at night when the air cools. Warmer pavement temperatures can also lead to increased temperature of stormwater runoff, leading to the warming of streams and other water bodies (EPA, 2009b). Porous pavements have traditionally been attributed to reducing the heat island effect, as the open pore structure (and lighter color in the case of porous concrete pavements) stores less heat (PCA, 2003).

Kevern et al. (2008) studied the temperature behavior of a porous concrete system installed at Iowa State University. Sensors were installed in the porous concrete pavement as well as the subbase material, and data was recorded over both warm and cold weather periods. The study found that air in the gravel subbase underneath the pavement surface acted as an insulator, and could potentially delay or completely eliminate any heaving due to frost formation. The study did find that porous concrete pavements have a much more rapid heating and cooling rate as compared to traditional systems, which could act to reduce the heat island effect. However, Kevern et. al. (2008) also found that even with the open pore structure and lighter color, the porous concrete pavement was significantly warmer than the surrounding air, potentially negating some of the proposed benefits of using porous concrete pavement to combat heat island effects. This higher temperature was mainly attributed to porous concrete having a lower albedo than traditional concrete pavements, and reflecting less sunlight. However, even with a higher surface temperature, studies have shown that the rate of heat transfer for porous concrete pavements is only 59% of the heat transfer rate for a traditional concrete pavement (Haselbach, 2008). This suggests that although porous concrete pavements are observed to have higher surface temperatures, they can still be used as a tool to mitigate the urban heat island effects associated with urban development.

2.6 Strength and Durability

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, 2007a; 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, 2007a; 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 highest 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, 2007a). 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, 2007a). 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, 2007a; 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, 2007a). 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, 2007a).

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 mm (0.01”) (NRMCA, 2004). These parameters provide air voids for water expansion during the freezing process, reducing the internal stresses of 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 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 (NRMCA, 2004). 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. 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. This however poses an issue with porous concrete pavements, as the test was designed to be performed on standard concrete samples, and is particularly severe. As such, 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 (greater than 15% mass loss) before 300 f-t cycles were completed, 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).

2.7 Hydraulic Conductivity

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 hydraulic conductivity 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 hydraulic conductivity 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.

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.

2.8 Field Verification

Several studies have investigated both the performance of porous concrete pavement systems in the field and the performance of similar mix designs in the laboratory. Many of the tests that are performed in the laboratory are not feasible or cannot be performed to determine in-situ properties. To work around these obstacles, several methods of determining the engineering properties of porous concrete pavement systems have been proposed.

To measure the surface infiltration capacity of porous concrete in-situ without having to obtain cores from the field, some tests have been adapted from soil mechanics. Bean, et al. (2007) measured the surface infiltration capacity 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).

Delatte et al. (2008) developed a surface drainage test for use at porous concrete facilities. The apparatus consisted of a plastic concrete cylinder mold 10 cm in diameter and 20 cm tall (4” by 8”). A 2.2 cm (0.875”) hole was drilled in the bottom of the mold to allow water to flow through the cylinder, and the bottom of the mold was lined with foam rubber in an attempt to seal the cylinder against the pavement. The mold was then filled with water, and the time it took for the water to drain through the mold and into the pavement was then measured. Two dozen sites were evaluated in 4 States, and mean values of surface drainage varied from 21 seconds to 136 seconds.

Henderson et al. (2008) used similar methods to assess the in-situ hydraulic conductivity at 16 sites for three porous concrete facilities in Ontario, Canada. The apparatus used was a Gilson Asphalt Permeameter, commonly used for on-site evaluation of asphalt pavement systems to insure that adequate compaction has been achieved. The permeameter was sealed to the porous pavement surface using a plumber’s putty, and time measurements were recorded for water to drop a specified distance. Surface infiltration capacity values were then obtained utilizing Darcy’s law. Averages for surface infiltration capacity at the three sites ranged from 0.1 cm/s to 0.6 cm/s (140 to 850 in/hr). Henderson et al. (2008) also investigated the performance of the systems after a winter of sanding/salting had been performed and rehabilitation of the system had been attempted. Using a wet-dry vacuum, several sites that been chosen for surface infiltration capacity testing were vacuumed, and the tests were performed again. This led to increases in hydraulic conductivity from the clogged values, and the values ranged from as low as 1.3% to as high as 287%. No ponding was observed at the sites.

Chopra and Wanielista (2007b) developed a method to determine the infiltration rates of the entire porous concrete system, including the gravel subbase and natural subsoil. A concrete coring drill was used to drill a core with a diameter of approximately 30 cm (12") from 10 porous concrete pavement systems that had been in service from 6-20 years. The core was then left in place, and a steel tube was inserted around the core and embedded into the natural subsoil, much like a single-ring infiltrometer test that is generally performed on soils. This apparatus encouraged one-dimensional flow through the system, and therefore, could be considered more representative of in-situ hydraulic conductivity than other methods that allow for lateral flow within the pavement layer and underlying materials. The test also allowed for determination of whether the infiltration rate was controlled by the subsoil or the pavement surface. The results of the tests showed an average infiltration capacity ranging from 2.8 x 10^{-4} cm/s to 0.16 cm/s (0.4 to 227 in/hr), with a porous concrete as the limiting factor for six sites and the subsoil as the limiting factor for four sites.

Visual observation has also been used to effectively characterize the performance of porous concrete pavement systems in the field. These observations include damages such as clogging/ponding, raveling, cracking, scaling, and joint separations (Delatte et al., 2008; Henderson et al., 2008). These visual observations can be a valuable tool in the regular maintenance and upkeep of porous concrete pavements, especially as they can be particularly susceptible to clogging due to winter maintenance activities or improper installation practices and cracking or raveling as a result of heavy vehicle traffic. Numerous incidents have been documented with a wide variety of potential causes;

another reason regular inspection can benefit the performance of porous concrete systems.

2.9 Construction

Porous concrete pavement installations require expertise and special requirements during construction. Excavation usually must take place in order to install a gravel subbase and filter material or geotextiles. During this excavation, care must be taken to not over-compact the natural soil and reduce its infiltration capacity. Any reduction in infiltration capacity could affect the performance of the entire system and cause various kinds of failure. Any gravel layer(s) is then laid in the excavation, and pavement construction commences. Traditionally, porous concrete pavements are laid by hand and are a labor-intensive process. Concrete is discharged from the truck, and several construction workers shovel the material into place, as the workability of porous concrete pavement is generally lower than that of traditional concrete. The pavement is then compacted generally using some combination of a roller screed, steel roller, and/or vibratory screed. Typically the density is not monitored. The quality control is typically through visual inspection and preliminary test patches. Although porous concrete pavements generally experience less shrinkage than conventional concrete pavements, construction joints are often installed using a joint roller, to improve cracking resistance and prevent random cracks. The porous concrete pavement is also covered with clear plastic for a minimum of 7 days to prevent excessive drying or water infiltration to ensure that adequate strength is achieved (Tennis et al., 2004). Figures 2.1-2.5 show the construction sequence at the Park-and-Ride Facility located in Randolph, VT.

Figure 2.1: Gravel Subbase with Wooden Forms Placed

Figure 2.2: Placing Porous Concrete Material

Figure 2.3: Finishing with Roller Screed and Steel Roller

Figure 2.4: Control Joint being Rolled In

Figure 2.5: Covering with Plastic Sheeting

CHAPTER 3

POROUS CONCRETE PAVEMENTS: MECHANICAL AND HYDRAULIC PROPERTIES

(Submitted for publication in TRB 2010 – invited for presentation and recommended for TRR)

3.1 ABSTRACT

A study evaluating the mechanical and hydraulic properties of several porous concrete pavement mix designs is presented. The objectives of the study were to: (1) examine various mix designs with constituents available in Vermont; (2) evaluate compressive strength and hydraulic conductivity of laboratory and field cured specimens; (3) compare the results to those found in the literature, and; (4) characterize the effects of specimen size on measured parameters. To evaluate the role of sample size on these testing procedures, the experiments were performed on specimens of three diameters: 7.62 cm (3”), 10.16 cm (4”), and 15.24 cm (6”). Multiple specimens were tested for a particular size. A specimen size of 10.16 cm (4”) was found to be optimal for the experiments performed and is therefore recommended. The measured compressive strength and hydraulic conductivity for the various mix designs showed a clear linear dependence on sample density. Also, the measured values fall within the expected range obtained from a review of the literature. Parametric studies included effects of water-cement ratio and admixtures. In general, increased water content yielded a higher density, higher

compressive strength, and reduced hydraulic conductivity. Admixtures such as a high-range water reducer and viscosity modifying admixture had insignificant effects on the compressive strength, hydraulic conductivity, and workability of the porous concrete mixes examined. Field cores displayed a much greater variability in hydraulic conductivity as compared to laboratory prepared specimens, largely because of the differences in compaction effort that are inherent to porous concrete placement in the field.

3.2 INTRODUCTION

A porous pavement system is an environmentally conscious alternative to a traditional asphalt or 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 using porous pavements.

This paper focuses on porous concrete pavement. Porous concrete is constructed in a similar fashion to traditional concrete, by mixing cement, water, and aggregates. 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). Effects of freeze-thaw, winter surface applications, and other engineering aspects of porous concrete that influence factors such as durability are currently being studied and the results will be published separately.

The objectives of this study were to: (1) examine various mix designs with constituents available in Vermont; (2) evaluate compressive strength and hydraulic conductivity of laboratory and field cured specimens; (3) compare the results to those found in the literature, and; (4) characterize the effects of specimen size on measured parameters.

3.3 BACKGROUND

Literature related to the design and engineering properties of porous concrete pavements, such as strength and permeability, is reviewed in this section. No studies that investigated effects of specimen size on compressive strength and hydraulic conductivity properties of porous concrete were found.

3.3.1 Strength

The disadvantages of a porous concrete pavement are perceived to be the 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, 2000). 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., 2006). 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 (EPA, 2000).

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 hydraulic conductivity significantly. As achieving adequate permeability for stormwater control is generally the main goal of a porous pavement system, compacting concrete until it reaches its highest strength is not always an option, and a balance must be achieved between strength and void ratio (Ferguson, 2005).

3.3.2 Hydraulic Conductivity

Porous concrete pavements are primarily a tool for stormwater management. Several methods for determining the hydraulic conductivity 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 hydraulic conductivity 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 hydraulic conductivity increased exponentially with increasing void ratio and that an increase in compaction energy corresponds to a decrease in hydraulic conductivity.

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 (20 in/hr) and 1.19 cm/s (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% generally had limited hydraulic conductivity, and in some cases zero hydraulic conductivity.

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 aggregate to cement ratio (A/C) 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 (voids through which water could infiltrate from the surface) 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 the cement paste was too fluid, and resulted in the paste filling the air voids at the base of the sample, making it nearly impermeable (Crouch et al., 2006).

3.4 RESEARCH METHODS

This section reviews the methods that were developed to test the engineering properties of several porous concrete mix designs.

3.4.1 Field Site

A motivating factor for this research was the construction of a porous concrete Park-and-Ride facility in Randolph, the first of its kind in the State of Vermont. The porous portion of the facility is comprised of a parking area constructed using porous concrete pavement, approximately 49 m by 64 m (160’ by 210’). A typical cross section of the porous concrete pavement system consists of a 15.2 cm (6”) thick layer of porous concrete, a 5.1 cm (2”) thick layer of AASHTO No. 57 stone (4.75 to 25.0 mm), followed by at least an 86.4 cm (34”) thick layer of AASHTO No. 2 stone (37.5 to 63 mm).

Underneath this stone layer is a non-woven geotextile, resting on top of the natural subgrade. The mix design employed at this site is summarized in Table 3.1.

3.4.2 Mix Design and Sample Preparation

The porous concrete mix designs adopted for this study were based on constituents that are readily available in the central Vermont region and local experience. The mixes consisted of a 10 mm (3/8”) crushed stone aggregate and Lafarge type I-II cement. Admixtures that were used included a viscosity modifying admixture (VMA), an air entraining admixture (AEA), a high-range water reducer (HRWR), and a stabilizer. These admixtures were used in an effort to improve the bond between the cement and the coarse aggregate, and to improve workability. The study included examination of multiple mix designs, to characterize the effects of water-cement ratio and certain admixtures on both compressive strength and hydraulic conductivity. The actual proportions used in each lab mix design are summarized in Table 3.1, along with the mix design used in the field.

Table 3.1: Porous Concrete Mix Designs

Mix Number	Cement (kg/m^3)	Aggregate (kg/m^3)	Water (kg/m^3)	AEA (mL/m^3)	HRWR (mL/m^3)	VMA (mL/m^3)	Stabilizer (mL/m^3)	Water-Cement Ratio
LAB-1	374	1,660	94	77.4	488	1,180	1,180	0.25
LAB-2	374	1,660	109	77.4	488	1,180	1,180	0.29
LAB-3	374	1,660	124	77.4	488	1,180	1,180	0.33
LAB-4	374	1,660	124	77.4	-	1,180	1,180	0.33
LAB-5	374	1,660	124	-	488	1,180	1,180	0.33
FIELD*	374	1,660	109	77.4	488	1,180	1,180	0.29

*as reported by project documents at Randolph Park-and-Ride

Mixes were prepared in general accordance with the mixing procedure proposed by Schaefer, et al (2006). 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. This method was chosen to provide the greatest repeatability when preparing specimens in the laboratory.

Cylinders were cast using this same process during construction of the Park-and-Ride facility, to examine the actual mix used in the field (“FIELD” mix from Table 3.1). Lab Mix 2 had the same proportions as the mix design that was utilized in the construction of the field facility, in an attempt to examine differences between the two (laboratory and field) mixing methods.

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 15.2 cm (6”). This particular height was used because it is representative of typical porous concrete pavement systems, as well as the design thickness used at the Park-and-Ride facility in Randolph, VT. Cores obtained from the Randolph site after construction were also obtained to determine hydraulic conductivity of the actual porous concrete system itself.

3.4.3 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 loading.

3.4.4 Hydraulic Conductivity

Permeability tests were performed using three separate falling head permeameters, specifically designed to accommodate specimens of three different diameters. However, all three permeameters had a similar design. As an example, Figure

3.1 shows a photograph and schematic of the permeameter used for testing 10.2 cm (4”) diameter specimens.

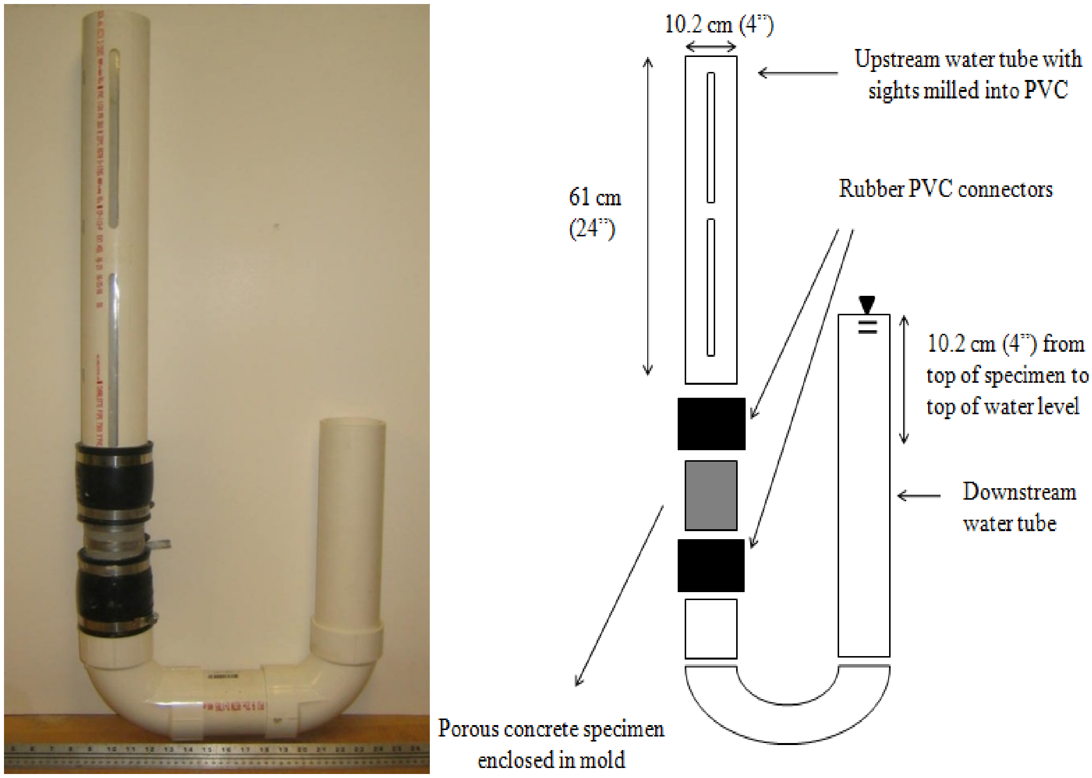

Figure 3.1: Falling head permeameter used for 10.2 cm (4”) diameter specimens. Photo (left), Schematic (right)

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 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 for the water level to fall was recorded. This head difference was expected to maintain laminar flow for the range of anticipated hydraulic conductivity (Montes and Haselbach 2006).

3.5 RESULTS

This section summarizes the results of the tests performed on the concrete specimens. These results include the size effects on the engineering properties of the porous concrete samples, as well as the compressive strength and hydraulic conductivity of the various mix designs.

3.5.1 Size Effects

The effects of sample size were evaluated for Lab Mix 2 and are shown in Figure 3.2. Both hydraulic conductivity and compressive strength are plotted against density. This was done to determine differences between specimen sizes that have equivalent density, allowing a direct comparison.

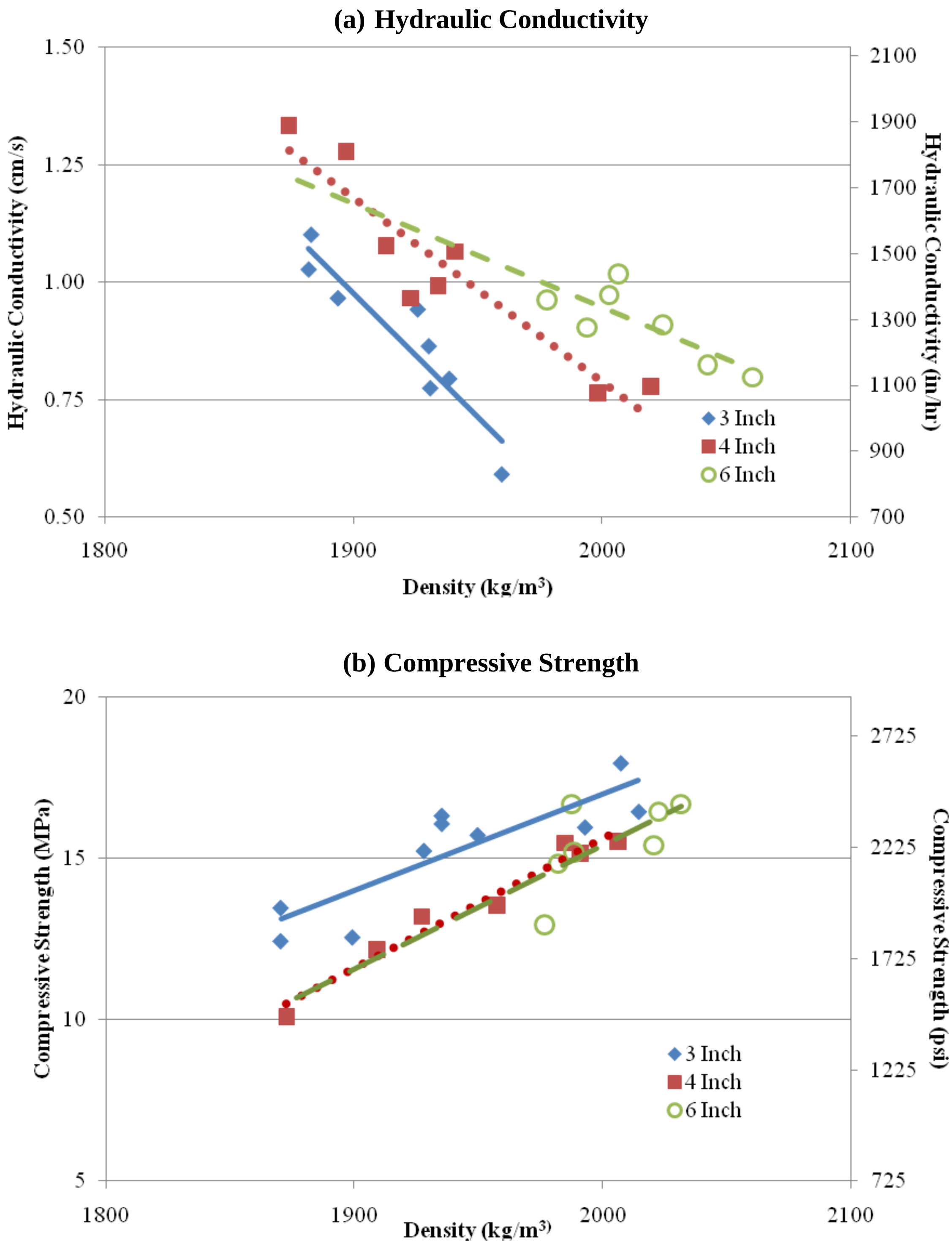

Figure 3.2: Specimen Size Effects (Data from Lab Mix 2)

3.5.2 Strength

The results of the 28-day compressive strength tests for all mix designs are summarized in Table 3.2 and Figure 3.3. Between 4 and 8 specimens were prepared for each mix design. Although they were intended to have the same density there were some variations, as shown in Figure 3.3. Table 3.2 provides average quantities for density and compressive strength. The tests yielded a range of values from about 4.4 MPa to 24.3 MPa (about 650 psi to 3,500 psi). For a given sample diameter, there was some variation of compressive strength up to about 5 MPa. For all mixes except Lab Mix 1, the failure in the specimens was primarily through the aggregate and could be characterized as cone failure or cone and shear failure according to ASTM C39. In Lab Mix 1, failure was predominantly observed between the cement-aggregate interfaces, resulting in the lower average compressive strength. Failure in this mix design was generally due to crumbling and spalling on the exterior of the concrete specimen.

Table 3.2: 28-Day Compressive Strength

Mix	Ave. Dry Density	Ave. Compressive Strength		Standard Deviation	
	(kg/m^3)	(MPa)	(psi)	(MPa)	(psi)
Lab Mix 1	1,820	6.2	910	0.95	138
Lab Mix 2	1,970	13.5	1,960	1.88	272
Lab Mix 3	2,152	22.6	3,270	1.17	170
Lab Mix 4	2,105	18.9	2,740	1.15	167
Lab Mix 5	2,138	26.7	3,880	1.99	288
Field Mix	2,073	18.7	2,710	0.14	20

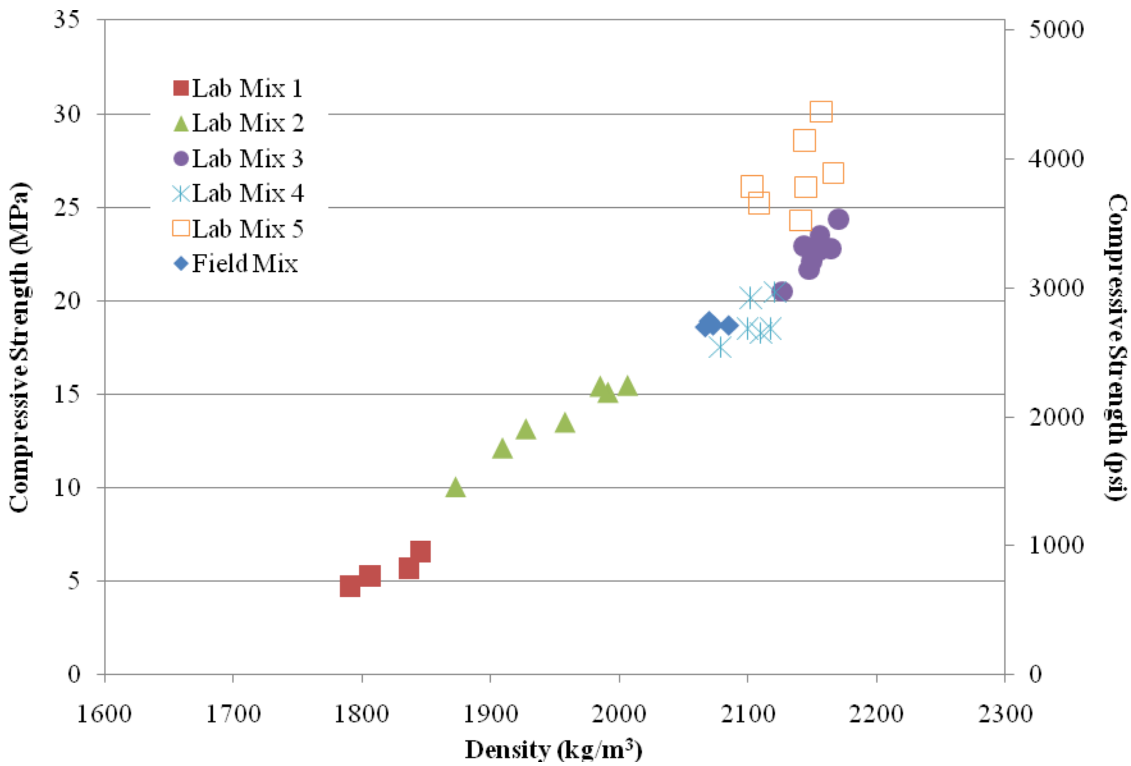

Figure 3.3: 28-Day Compressive Strength Results

3.5.3 Hydraulic Conductivity

Table 3.3 summarizes the average values of density and hydraulic conductivity for the 5 lab mixes as well as for the Field Mix and the field cores. The tests showed a range of hydraulic conductivities between 0.18 cm/s and 1.22 cm/s, (255 in/hr and 1,729 in/hr). All values obtained for the lab mixes and the Field Mix are presented in Figure 3.4. Figure 3.5 presents hydraulic conductivity data from Lab Mix 2, the Field Mix, and the field cores. Recall that all three have the same mix design.

Table 3.3: Falling Head Test Results

Mix	Ave. Dry Density (kg/m^3)	Ave. Hydraulic Conductivity (cm/s)	Ave. Hydraulic Conductivity (in/hr)
Lab Mix 1	1,866	1.22	1,729
Lab Mix 2	1,938	1.03	1,460
Lab Mix 3	2,053	0.32	454
Lab Mix 4	2,082	0.36	510
Lab Mix 5	2,110	0.18	255
Field Mix	1,938	0.93	1,318
Field Cores	1,910	0.44	624

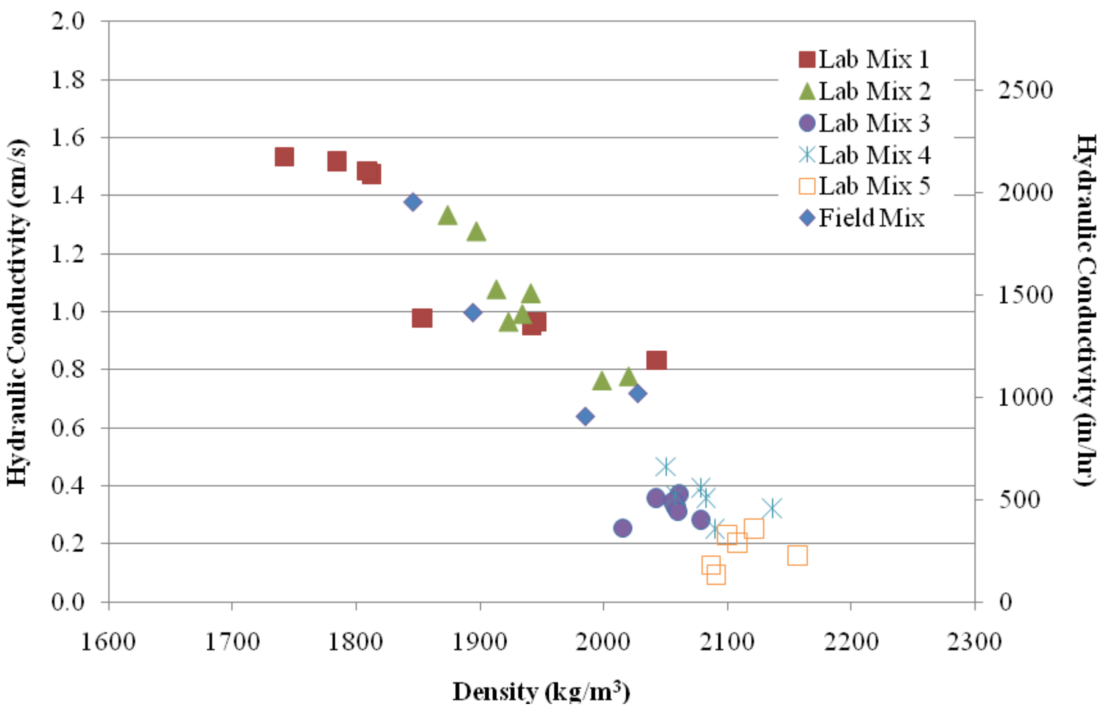

Figure 3.4: Hydraulic Conductivity for Laboratory Specimens

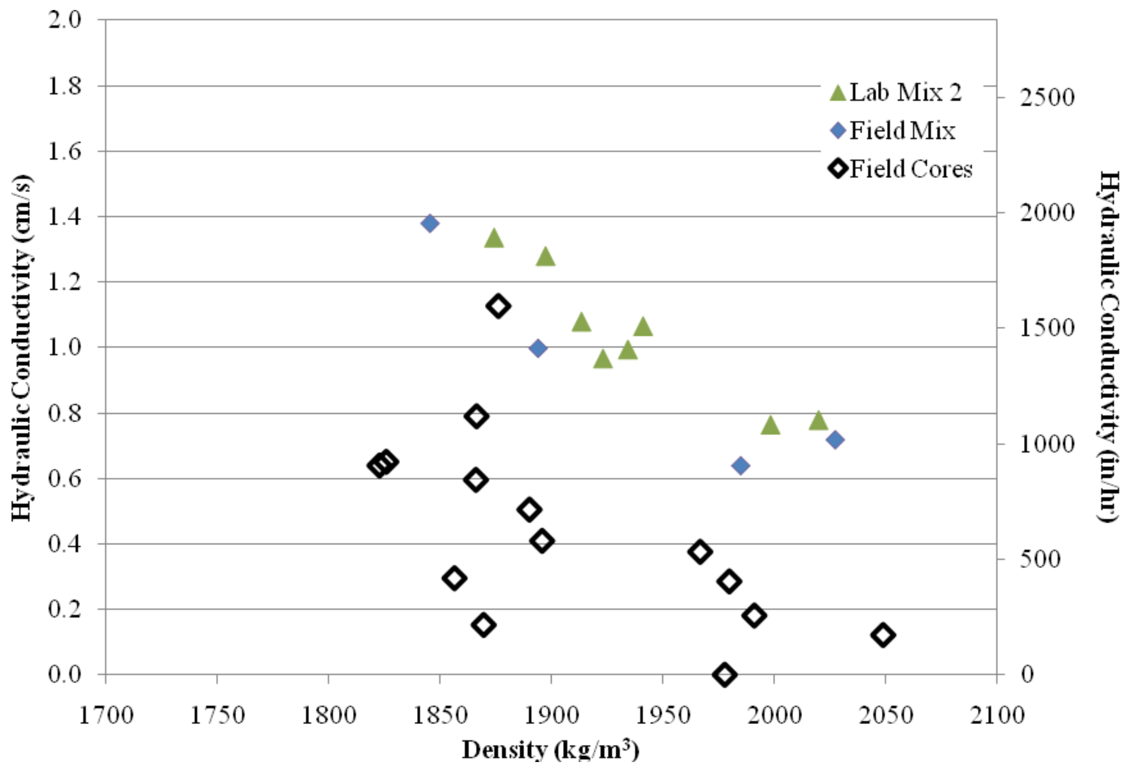

Figure 3.5: Hydraulic Conductivity Laboratory and Field Comparison

3.6 DISCUSSION

3.6.1 Size Effects

In examining Figure 3.2, it does appear that the specimen size plays a role in the reported values of both hydraulic conductivity and compressive strength. Although some variation between samples may be attributed to material variations in the samples themselves, it became evident that the 7.6 cm (3”) samples yielded a lower estimate of hydraulic conductivity when compared to larger samples, especially in the higher density ranges. The 7.6 cm (3”) samples also gave an inflated value for compressive strength when compared to both the 10.2 cm (4”) and 15.2 cm (6”) samples. Values for the 7.6 cm (3”) samples were consistently about 2 MPa (300 psi) higher than the values obtained for 10.2 cm (4”) or 15.2 cm (6”) specimens at the same density. The strength and hydraulic conductivity of both 10.2 cm (4”) and 15.2 cm (6”) specimens gave similar results. The differences observed were most likely due to the compaction energy imparted on the specimens while preparing them in the laboratory. ASTM C192 calls for the same size tamping rod to be used for compaction of both 7.6 cm (3”) and 10.2 cm (4”) specimens, and both specimens are prepared with the same number of lifts. Therefore, the 7.6 cm (3”) mold could undergo more densification of the pervious material, leading to greater compressive strength and lower hydraulic conductivity that was observed. Since the engineering properties of porous concrete pavements are greatly influenced by compaction energy, this could have led to the differences that were observed. Based on these size effect results, 10.2 cm (4”) specimens were chosen for laboratory testing. 15.2 cm (6”) specimens could also have been utilized, however 10.2 cm (4”) specimens were less cumbersome for the research methods described and used significantly less resources during specimen preparation. Additionally, cores obtained from the field also had a diameter of 10.2 cm (4”) allowing tests developed for use in the laboratory to be utilized on field cores, and their results directly comparable.

The authors (McCain and Dewoolkar, 2009) reported preliminary results based on limited data indicating there might not have been significant size effects. However, values for the compressive strength and hydraulic conductivity were distinctly different for 7.6 cm (3”) specimens when looking at a larger dataset. Therefore, 10.2 cm (4”) diameter specimens are recommended for laboratory testing for similar mix designs including 10 mm (3/8") coarse aggregate.

3.6.2 Effects of Density

Figures 3.3 and 3.4 show that density played a role in both the compressive strength and hydraulic conductivity of the porous concrete specimens. These changes can be mainly attributed to the increase in workability of the mix designs as the water-cement ratio is adjusted. Traditional methods of measuring the workability of a concrete mix are not effective for porous concrete mixes, as they generally have negligible slump even when the water-cement ratio is above the optimal level. With increased workability, greater densification occurs even when the same compaction energy is applied during the casting process. This greater densification led to both the increase in compressive strength and decrease in hydraulic conductivity that were observed for the various mix designs. This suggests that proper placement in the field is one of the most important parameters for a successful porous concrete pavement system.

3.6.3 Effects of Water-Cement Ratio

The water-cement ratio and its effects on porous concrete mixes were evaluated in Lab Mixes 1-3, which had water-cement ratios of 0.25, 0.29, and 0.33, respectively.

Figure 3.3 shows the linear relationship between compressive strength and density, supporting the conclusion that greater workability leads to a denser specimen with higher strength. Lab Mix 1 had the lowest compressive strength, and failure was predominantly crumbling of the cement bonds between coarse aggregate. This failure can be attributed to a water-cement ratio that was too low, as there may have been inadequate water available for full hydration of the cement paste. The low workability of the mix indicates that the cement paste may have been stiff, and therefore may not have readily coated the coarse aggregate in the mix. This would also have contributed to the lower compressive strength. With Lab Mixes 2 and 3 this crumbling failure was not observed, as failure was primarily through the aggregate. The higher water-cement ratio would have contributed to an increased workability as well as made more water available for hydration of the cement paste, resulting in a stronger concrete specimen. Figure 3.4 shows that Lab Mix 1 also had the highest hydraulic conductivity of these three mix designs, supporting the conclusion that the low water-cement ratio would have led to decreased workability and a lower density. This lower density resulted in a greater amount of pore space available for water to pass through.

3.6.4 Effects of Admixtures

Lab Mixes 3-5 investigated the role of two admixtures, HRWR and AEA. Figures 3.3 and 3.4 show that although removal of these admixtures did have some effect on the engineering properties of the porous concrete mix, they had a much smaller effect on compressive strength and hydraulic conductivity as compared to the effects from changes in the water-cement ratio.

3.6.5 Field Comparisons

Comparison of Lab Mix 2, the Field Mix, and the field cores shown in Figure 3.5 suggest the hydraulic conductivity is affected by the mixing and casting method. Recall that Field Mix specimens were cast during construction of the field site, in the same manner as the lab mixes, whereas the field cores were obtained following field placement of the porous concrete. Figure 3.3 shows that the Field Mix had higher values for compressive strength than Lab Mix 2, which could be attributed to several factors. The Field Mix could have potentially had a slightly different water-cement ratio due to small changes that could have been made to achieve proper consistency in the field. The mixing method utilized in the field could also have more readily coated the coarse aggregate due to the greater volume of constituents, leading to an increase in bond strength between the aggregate. Figure 3.5 also shows that the hydraulic conductivity of the Field Mix compared well with the values obtained for Lab Mix 2, suggesting that curing and mixing method may not have a significant effect on the hydraulic conductivity characteristics of porous concrete mixes.

Cores obtained from the site were evaluated to characterize any differences between laboratory casting methods and those utilized in the field. The results presented in Figure 3.5 show the variability of the field cores was much greater than that observed using the laboratory methods described in ASTM C192, and the average value for hydraulic conductivity of the cores are about 50% of either the Field Mix or Lab Mix 2. These results suggest that there are differences between the two compaction methods, and the laboratory methods may not impose the same compaction energy as the field methods. The higher variability found in the field cores could also be attributed to the compaction method procedures used in the field. Other investigations have also observed similar variations in the field (e.g., Henderson et al., 2009; Crouch et al., 2006). In general this is to be expected, as higher variability could be the result of slightly uneven gravel subbase layer, uneven compaction effort applied when shoveling the concrete into the proper place, uneven compaction at curbs or joints, along with several other factors inherent in the construction processes.

3.6.6 Comparison to Literature

Figures 3.6 and 3.7 present results obtained from this study as well as data obtained from other research during the literature review. This was done to see how well the results of this study compared with other research, as well as to assimilate data from the literature into one place, providing general trends for future designs. Data from this study are plotted as average values, with bars representing upper and lower bounds of variation within each mix design. Data from other studies were also plotted as average values, and were calculated if not provided in the literature. Although not all compaction methods, sample sizes, and mix designs were consistent, there is a clear trend that as density increases, there is a corresponding increase in compressive strength and decrease in hydraulic conductivity. Figure 3.7 compares hydraulic conductivity and compressive strength to determine the relationship between these two parameters and verify the results of this study were within the range reported in the literature.

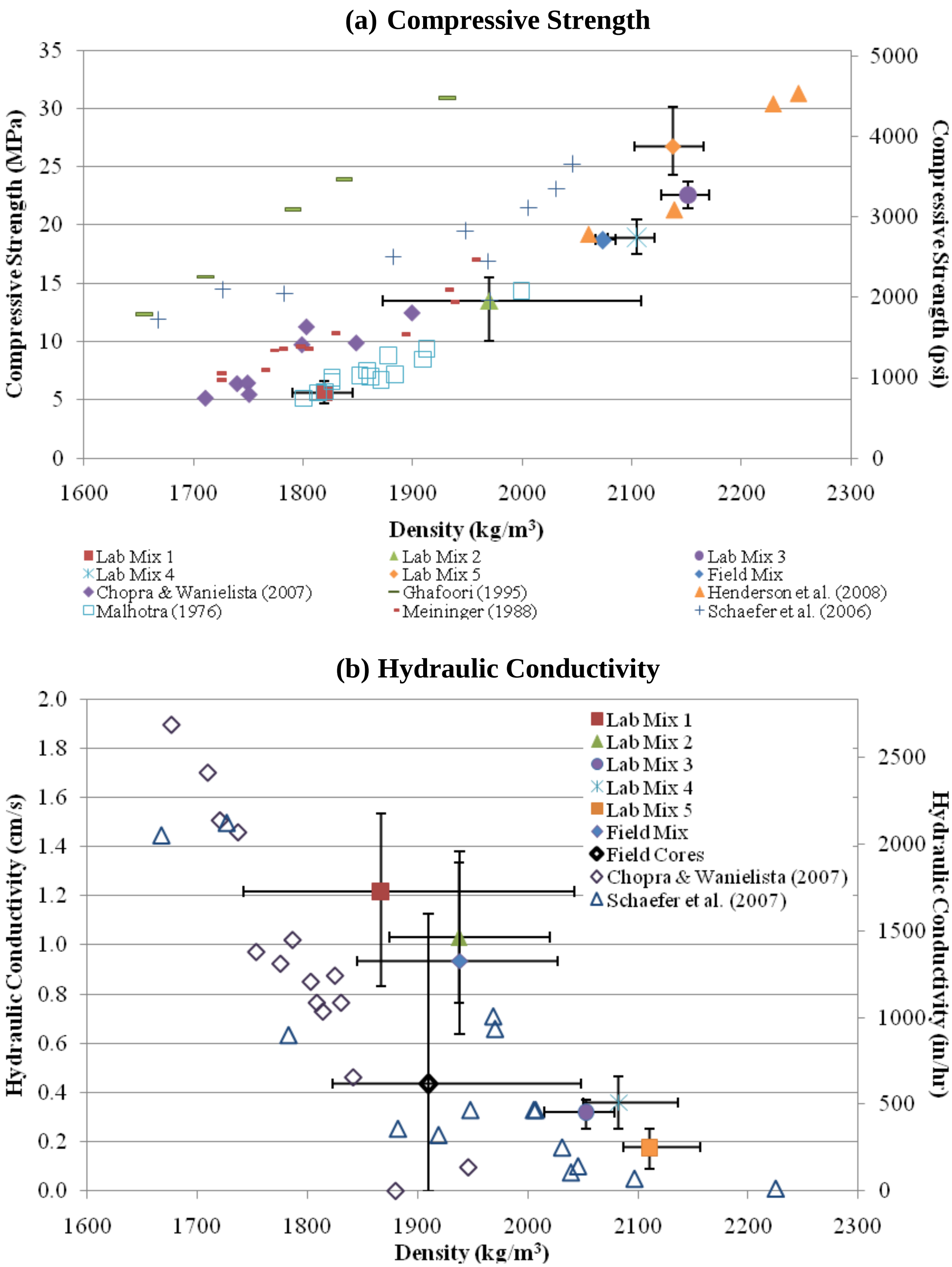

Figure 3.6: Comparison with Reported Values

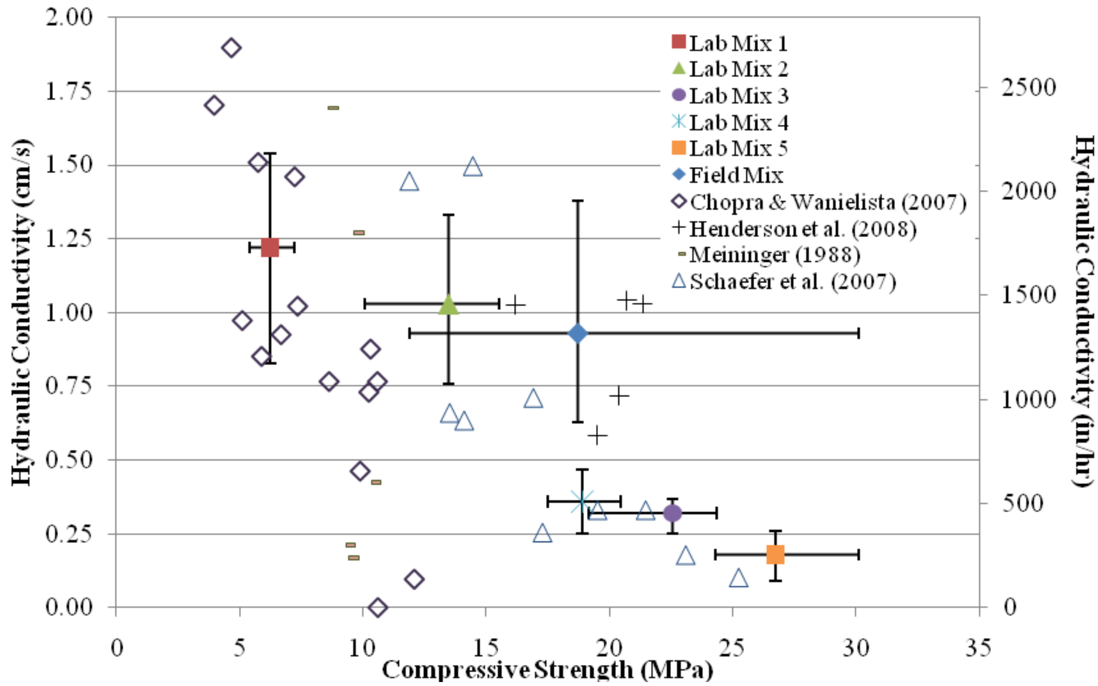

Figure 3.7: Relationship between Hydraulic Conductivity and Compressive Strength

3.7 SUMMARY

This study examined the strength and hydraulic conductivity of porous concrete mix designs for pavements. The experiments included compressive strength tests and falling head permeability tests on porous concrete specimens, using constituents readily available in Vermont. Effects of water-cement ratio and admixtures were examined. In addition, a subset of experiments included tests on specimens of three sizes: 7.6 cm (3”), 10.2 cm (4”), and 15.2 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 mixes studied:

1) The average values for compressive strength ranged between about 6.2 MPa (910 psi) and 26.7 MPa (3,380 psi) depending on the mix design, which was within the range of strength reported in the literature.

2) The average values for hydraulic conductivity ranged between 0.18 cm/s and 1.22 cm/s (250 in/hr and 1,730 in/hr) depending on the mix design. These values were within the expected range found in the literature.

3) Both compressive strength and hydraulic conductivity showed a clear linear dependence on sample density.

4) Characteristics such as compressive strength and hydraulic conductivity showed clear dependence on the size of the specimens. Specimens of 10.2 cm (4") or 15.2 cm (6") diameter showed very similar results, but they differed significantly from the measurements made on 7.6 cm (3") specimens. Therefore, specimens of at least 10.2 cm (4") diameter are recommended for laboratory testing procedures. 10.2 cm (4") samples were considerably easier to utilize in laboratory procedures as compared to 15.2 cm (6") specimens, and also allowed for direct comparison of the field cores obtained from the site.

5) Water-cement ratio played a strong role in both the compressive strength and hydraulic conductivity of porous concrete pavement. In general, increased water content corresponded to an increase in density, increase in compressive strength, and decrease in hydraulic conductivity.

6) Admixtures such as HRWR and AEA had little effect on the compressive strength, hydraulic conductivity and workability of laboratory specimens. However, AEA is expected to provide increased freeze-thaw resistance to the cement paste during winter conditions.

7) Field cores showed a significantly higher variation in hydraulic conductivity than laboratory prepared specimens. This is primarily due to differences in the compaction methods used for laboratory cast specimens and field sites.

3.8 ACKNOWLEDGEMENTS

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CHAPTER 4

A LABORATORY STUDY ON THE EFFECTS OF WINTER SURFACE APPLICATIONS ON THE HYDRAULIC CONDUCTIVITY OF POROUS CONCRETE PAVEMENTS

(Submitted for TRB 2010 – invited for poster presentation)

4.1 ABSTRACT

A laboratory study evaluating the effects of winter surface applications on the hydraulic conductivity of porous concrete pavements is presented. The objectives of the study were to: (1) determine the effects of typical winter surface application (sand and salt, 2:1 ratio by weight) on the hydraulic conductivity of porous concrete specimens, (2) determine the effects of maximum fines infiltration on hydraulic conductivity; and (3) examine the effectiveness of vacuuming as a tool to reclaim hydraulic conductivity after some amount of clogging had occurred. Hydraulic conductivities of virgin specimens ranged from 0.18 cm/s (255 in/hr) to 1.22 cm/s (1,729 in/hr). Reduction in hydraulic conductivity after the winter surface application of 0.12 g/cm^2 was found to be 15%. After maximum clogging had been achieved, reductions in hydraulic conductivity were measured around 35%. Specimens that were vacuumed to reclaim hydraulic conductivity after clogging were on average restored to within 10% of the initial hydraulic conductivity.

4.2 INTRODUCTION

The main use of porous concrete pavements, primarily designed as parking lots, has been as a stormwater management technique. These types of systems have been identified as a best management practice (BMP) for stormwater pollution prevention (EPA, 1999). There are several advantages to choosing porous pavements over more traditional methods of stormwater prevention. Porous pavements are ideal for sites that have existing structural components, when systems such as retention ponds are not a viable solution due to area restrictions. A porous pavement system could easily be retrofitted to the site, as it could replace existing parking areas and serve a dual purpose as both a stormwater BMP and parking lot (Leming, et al., 2007).

Porous pavement systems are effective stormwater management tools for multiple reasons. One of the main benefits is that these systems are able to capture the "first flush" from a storm event, or approximately the first inch of rainfall that occurs (Tennis, et al., 2004). This "first flush" is generally the most polluted stormwater that is produced during a storm event, and being able to capture and treat this stormwater significantly reduces the amounts of pollutants that make their way into streams and other water bodies. Porous pavement systems are also able to create short-term detention of rainfall, resulting in a reduced amount of surface runoff, recharging of the groundwater table, and reducing the sediment load that makes its way into water bodies via stormwater (Leming, et. al, 2007). Porous pavements have been shown to be effective in pollutant removal, capable of eliminating up to 95% of the total suspended solids (TSS), 65% of the total phosphorous (TP), 85% of the total nitrogen (TN), and 99% of the metals from stormwater runoff (Schuler, 1987).

Porous concrete pavements are generally designed as retention structures, much like other more traditional stormwater BMP's such as retention ponds. There are two possible categories porous pavement systems fall into, either a passive system or an active system. A passive system is designed to only replace impervious surface with pervious surface, and is not intended to store or treat stormwater runoff from other areas within the selected site. Alternatively, and active system is designed to accommodate stormwater resulting from more than just its own "footprint" (Leming, et al., 2007). An active system is ideal for areas where remediation is a priority, as they can be designed to store and treat stormwater from nearby impervious surfaces.

However, the effectiveness of these systems can be compromised by clogging of the pores. Infiltration of fines, and packing due to vehicular traffic or plowing could potentially reduce the hydraulic conductivity of the system significantly. The objectives of this study are to examine the effects that winter surface applications have on the hydraulic conductivity of porous concrete pavements, by testing in the laboratory: (1) samples after one winter surface application; (2) samples with maximum fines infiltration; and (3) samples after reclaiming some amount of the pore space via vacuuming. Virgin samples were tested previously and the results published separately (McCain and Dewoolkar, 2010). Effects of freeze-thaw on engineering properties of porous concrete as well as field verification of the effects of winter surface application are currently being studied and the results will be published at a later date.

4.3 BACKGROUND

Research into the hydraulic conductivity characteristics of clogged porous concrete systems are reviewed in this section.

4.3.1 Clogging of Porous Concrete Systems

Porous concrete pavements can be severely affected by infiltration of fines into its void spaces. Clogging of these voids can reduce the porosity of the system and reduce its hydraulic conductivity. This occurs primarily due to (Scholz & Grabowiecki, 2007):

- Fines being compacted into the pore spaces by vehicular traffic;
- In active systems, sediment being carried onto the system by stormwater runoff, and infiltrating the pore spaces, and;
- Stresses due to vehicular traffic that result in collapsed pores.

Haselbach et al. (2006) conducted research to develop a theoretical relationship between the effective permeability of a clogged porous concrete sample versus a clean sample. The study also performed physical experiments to confirm the accuracy of the theoretical relationship. Tests were performed to examine both passive and active runoff by simulating rain events in a flume. Specimens were then completely covered by an extra-fine sand with known permeability before testing began. The results showed that there was marked decrease in the permeability of the porous concrete sample, with values before clogging greater than 0.2 cm/s (280 in/hr) and values of the clogged system of approximately 0.004 cm/s (6 in/hr). Although this was a large reduction in permeability, the clogged permeability was still found to be sufficient for a 100-yr 30-minute storm event for the southeastern United States.

Joung and Grasley (2008) also investigated the hydraulic conductivity characteristics of clogged porous concrete samples. The study first determined the hydraulic conductivity of clean samples utilizing a falling head permeameter. In order to clog the sample with fines, a slurry of sand and water was created and then poured through the sample multiple times. When all water had drained from the sample, falling head permeability tests were repeated on the sample to measure the reduction in hydraulic conductivity. The results showed that samples with a void ratio greater than 33% were not affected by clogging sand, whereas samples with a void ratio of less than 33% were affected, reducing the hydraulic conductivity by approximately 40%. The results also showed that the largest incremental decrease in hydraulic conductivity occurred after the first clogging cycle.

Some studies have also evaluated the effects of fines infiltration and clogging in the field. Bean et al. (2007) examined several porous concrete installations across North Carolina, Maryland, Virginia, and Delaware to determine what factors went into creating and maintaining high surface infiltration in the field. Surface infiltration capacity was determined with the use of either a single-ring or double-ring infiltrometer, depending on which was more suitable for the specific site. The study found that porous concrete sites that had no visual evidence of fines infiltration had surface infiltration capacities ranging from approximately 0.2 cm/s (280 in/hr) to 2.0 cm/s (2,800 in/hr), with an average value of about 1.1 cm/s (1,600 in/hr). Alternatively, at those sites where there was significant visual evidence of fines infiltration, the surface infiltration capacity was ranged from 0.003 cm/s (4 in/hr) to 0.008 cm/s (11 in/hr), with an average value of 0.004 cm/s (6 in/hr).

Chopra & Wanielista (2007) also surveyed the effects of fine infiltrations on porous concrete installations as well as the effectiveness of rehabilitation techniques. The study obtained cores from multiple porous concrete pavement facilities in Florida and the surrounding States and determined surface infiltration capacity with the use of a single-ring infiltrometer. The results of rehabilitation maintenance showed that a typical increase in surface infiltration capacity after rehabilitation was at least 200%. Of the three rehabilitation methods that were studied (pressure washing, vacuuming, and a combination of both) the results showed that either pressure washing or vacuuming yielded similar increases in surface infiltration capacity, whereas a combination of both methods was found to be ideal and led to the largest increase in surface infiltration capacity for the sites examined.

Henderson et al. (2008) performed field investigation of surface infiltration capacity at three porous concrete facilities in Canada. At two of the sites, half of the porous concrete parking lots received winter surface applications at a rate similar to conventional parking areas. Surface infiltration capacity was then measured utilizing a Gibson asphalt permeameter. The study found that there was no significant difference in surface infiltration capacity between areas where winter surface applications had been applied and areas that had not seen these materials. The effectiveness of vacuuming as a rehabilitation technique was also examined by vacuuming three locations at one site and performing additional tests. The study found that all three sites saw increased infiltration capacity, with increases of 119%, 287%, and 1.3%.

4.4 RESEARCH METHODS

This section presents the methods that were used to determine the effects of winter surface applications, maximum infiltration of fines and reclamation of pore space on the hydraulic conductivity of porous concrete specimens. These methods were conducted in the laboratory and do not recreate all conditions that would be observed in the field such as thermal issues, vapor transport and snowmelt.

4.4.1 Mix Designs and Sample Preparation

The porous concrete mix designs that were utilized in this study were based on constituents locally available in the central Vermont region along with local experience in constructing porous concrete pavements. All mix designs included a 10 mm (3/8”) crushed stone as coarse aggregate, no fine aggregate, and Lafarge type I-II cement with no supplemental cementitious materials (SCM's). Several admixtures were also utilized as well, and these included a viscosity modifying admixture (VMA), and air entraining agent (AEA), a high range water reducer (HRWR) and a stabilizer. Several different water-cement ratios and combinations of admixtures were used to characterize their effects on clogging of porous concrete samples. Proportions for each mix design can be found in Table 4.1.

Table 4.1: Porous Concrete Mix Designs

Mix Number	Cement (kg/m^3)	Aggregate (kg/m^3)	Water (kg/m^3)	AEA (mL/m^3)	HRWR (mL/m^3)	VMA (mL/m^3)	Stabilizer (mL/m^3)	Water-Cement Ratio
LAB-1	374	1,660	94	77.4	488	1,180	1,180	0.25
LAB-2	374	1,660	109	77.4	488	1,180	1,180	0.29
LAB-3	374	1,660	124	77.4	488	1,180	1,180	0.33
LAB-4	374	1,660	124	77.4	-	1,180	1,180	0.33
LAB-5	374	1,660	124	-	488	1,180	1,180	0.33
FIELD*	374	1,660	109	77.4	488	1,180	1,180	0.29

*****as reported by project documents at Randolph Park-and-Ride, Randolph, VTMixes were prepared in general accordance with the procedure suggested by Schaefer et al. (2006). Specimens were prepared as cylinders, with a diameter of 10.2 cm (4") and length of 15.2 cm (6"). Previous research by McCain & Dewoolkar (2010) suggested that 10.2 cm (4") diameter specimens were ideal for hydraulic conductivity testing. The specimen length of 15.2 cm (6") was chosen as a representative value of porous concrete pavement thickness found in the field. Specimens were cast in general accordance with ASTM C192; *Practice for Making and Curing Concrete Test Specimens in the Laboratory*. To provide as uniform compaction as possible, each specimen was cast in two lifts, and each lift was rodded 25 times with a 10 mm (3/8”) tamping rod. Specimens for all mixes were prepared in laboratory with the exception of the field mix, specimens for which were cast from material provided at the Randolph Park-and-Ride in Randolph, VT.

4.4.2 Hydraulic Conductivity

A falling head permeameter was designed for use with 10.2 cm (4”) diameter specimens, as shown in Figure 4.1. The specimens were enclosed in a mold after being lined by a thin rubber sheet. The mold was secured using hose clamps to prevent any flow along the sides of the specimen that would affect the measured results. The specimen was then secured in the apparatus, and water was added to the downstream pipe in order to expel any air voids that may have been present in the specimen. When the water level had risen above the surface of the porous concrete sample water was added to the upstream water pipe, and the water level was allowed to reach equilibrium (zero head level). The head was then increased to 30 cm (about 12”) and the time it took for the water to fall to a head of 10 cm (about 4”) was recorded. This head difference has been shown to maintain laminar flow in typical porous concrete specimens for the hydraulic conductivities expected (Montes & Haselbach, 2006). Tests were performed a minimum of three times per sample and average results are reported here.

Figure 4.1: A Photograph of the Falling Head Permeameter

4.4.3 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. Visual inspection of the porous concrete surface showed that a representative amount of sand-salt to use on the surface of the porous concrete specimens was about 0.12 g/cm^2 (0.24 lbs/ft^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. A representative sample after WSA is shown in Figure 4.2. 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, but the amount applied can be taken as a conservative estimate, as it represents a significant amount of the surface pores covered with winter maintenance materials. 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. The gradation of the sand used in the winter surface application mix is presented in Figure 4.3.

(a) **(b)** **(c)**

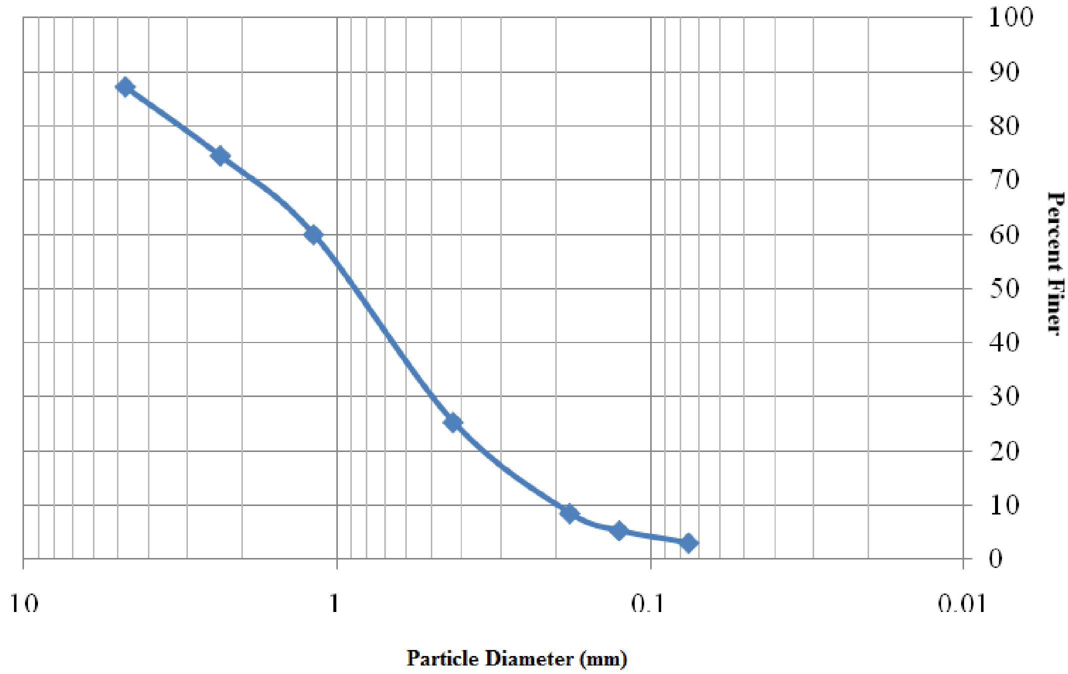
Figure 4.2: Hydraulic Conductivity at Three Stages (a) Virgin Sample, (b) After One WSA, (c) Maximum Infiltration

4.4.4 Maximum Clogging of Porous Concrete Specimens

Specimens were also clogged with as much sandy fines as possible by shaking. The porous concrete samples were enclosed in a rubber mold, as seen in Figure 4.1, slightly taller than the samples. Once the samples were in the mold a layer of sand, approximately 25 mm (1”) thick, was placed on the surface. Samples were then shaken to introduce fines into the pore structure. The specimens were the placed on a shake table with a frequency of 2 Hz and shaken for 60 seconds, and then rotated 90 degrees. This process was repeated four times for a total shaking time of four minutes per sample. Once the sample was shaken, excess material was removed by scraping the surface of the sample with a flat blade, using hand pressure to mimic the removal efficiency of a plow blade. Sand and other fines that had entered into the pores were not removed during the scraping process. Samples were then tested for hydraulic conductivity in the apparatus discussed above. For clogged porous concrete samples the head was only increased to 15 cm (6”) and the time it took for the water to fall to a level of 5 cm (2”) was recorded. Based on the theoretical equations for a falling head permeameter the change in head values would produce identical results to the original head values. Each specimen was tested a minimum of eight times to allow hydraulic conductivity to reach equilibrium.

4.4.5 Reclamation of Hydraulic Conductivity

Specimens were then cleaned in an attempt to restore pore space and hydraulic conductivity. Once samples had been tested for maximum clogging, they were allowed to dry for a period no less than 24 hours. Air dried samples were vacuumed to remove sand from the surface and clogged pores. This was performed with a ShopVAC 2.0 peak horsepower vacuum with a 1” diameter circular hose attachment. The surface of each sample was vacuumed for five seconds in an up and down motion and then rotated 90° and vacuumed for an additional five seconds. This cleaning was intended to simulate field vacuuming, however effects present in the field, such as brushing, were not simulated in the laboratory. Samples were then tested for hydraulic conductivity in the apparatus shown in Figure 4.1. For these tests, the head value was again increased to 30 cm (12”) and the time it took for the water to fall to a head of 10 cm (4”) was recorded. A minimum of three tests per sample were performed.



4.3: Sieve Analysis of the Sand used in Testing

4.5 RESULTS AND DISCUSSION

This section presents the results of experiments performed during the testing process. These results include the effects of one winter surface application on hydraulic conductivity, the effects of clogging the sample as much as possible, attempts at reclaiming lost pore space, and effects of winter maintenance activities.

4.5.1 Hydraulic Conductivity

Results for hydraulic conductivity of virgin porous concrete specimens are presented in another paper, *Porous Concrete Pavements: Mechanical and Hydraulic Properties* (McCain & Dewoolkar, 2010). These results include the effects of sample density, effects of water-cement ratio and effects of selected admixtures as well as field comparisons and comparisons with previous research. Relevant values to determine the effects of winter surface applications and fines infiltration are included in the following tables and figures.

4.5.2 Winter Surface Applications

The effects of one winter surface application are summarized in Table 4.2. Average values for virgin hydraulic conductivity range from 0.18 cm/s (255 in/hr) to 1.22 cm/s (1,729 in/hr). After application of 0.12 g/cm^2 of winter maintenance material, hydraulic conductivity values ranged from 0.16 cm/s (227 in/hr) to 1.05 cm/s (1,488 in/hr). This corresponded to an average reduction of about 15% among the mix designs studied. Figure 4.4 shows the reduction in hydraulic conductivity for all samples tested. The reductions in hydraulic conductivity are plotted versus density in plot (a) and versus hydraulic conductivity of virgin specimens in plot (b).

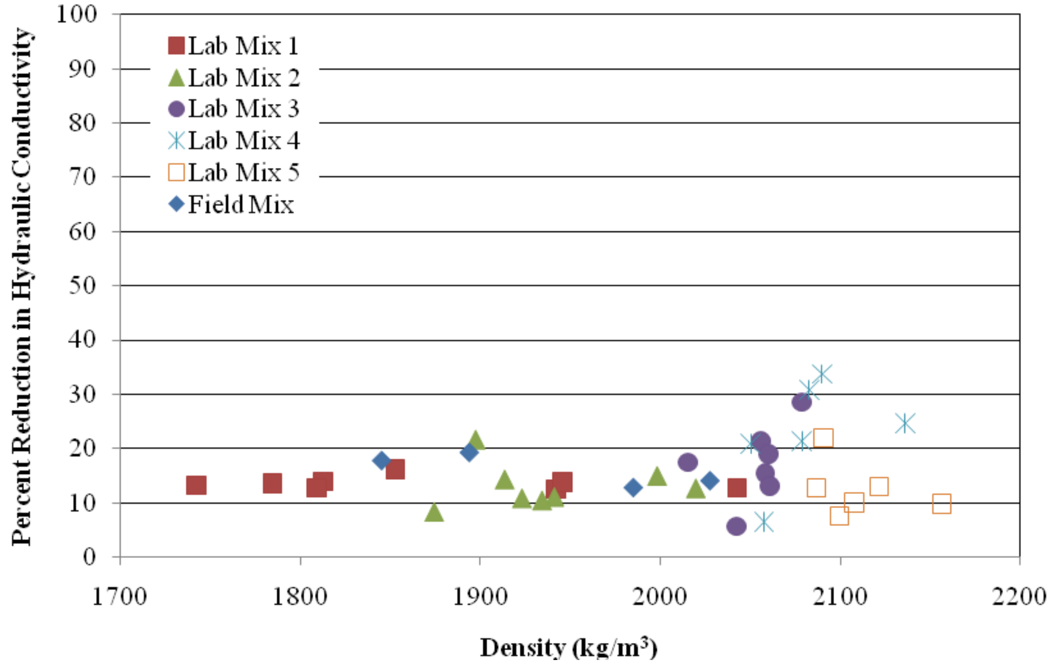
In examining Table 4.2 and Figure 4.4, it is clear that these materials have a marked impact on the hydraulic conductivity of porous concrete pavement specimens.

The average reduction after one winter surface application of about 15% is a significant decrease from the virgin hydraulic conductivity. Even with this reduction, the lowest value was observed to be around 0.2 cm/s (about 280 in/hr), which can be considered adequate to allow water to pass through the system when looking at design storms for northern communities. It could be advantageous to perform similar testing on field cores after winter surface applications have been applied for a season for field verification. Figure 4.4 shows that density of the porous concrete sample does not have a significant effect on the reduction in hydraulic conductivity after one winter surface application, as all samples demonstrated similar reduction in hydraulic conductivity over varying density. Also the initial hydraulic conductivity does not appear to have any significant effect on the percent reduction in hydraulic conductivity, as shown in Figure 4.4. All samples had similar reductions even with initial conductivities that had differed by more than 1 cm/s (1,400 in/hr). It should however be noted that the initial hydraulic conductivity of virgin porous concrete specimens decreased with increased density (McCain & Dewoolkar, 2010).

Table 4.2: Hydraulic Conductivity of Porous Concrete Specimens

Mix	Average Dry Density	Initial *k*		One Winter Surface Application			Maximum Clogging of Specimen			After Vacuuming		
				Average *k*		Average Reduction in *k*	Average *k*		Average Reduction in *k*	Average *k*		Average Reduction in *k*
		(cm/s)	(in/hr)	(cm/s)	(in/hr)	(%)	(cm/s)	(in/hr)	(%)	(cm/s)	(in/hr)	(%)
Lab Mix 1	1,866	1.22	1,729	1.05	1,488	13.9	0.86	1,219	29.5	1.08	1,531	11.5
Lab Mix 2	1,938	1.03	1,460	0.90	1,276	12.6	0.64	907	37.9	0.98	1,389	4.9
Lab Mix 3	2,053	0.32	454	0.27	383	15.6	0.21	298	34.4	0.31	439	3.1
Lab Mix 4	2,082	0.36	510	0.28	397	22.2	0.22	312	38.9	0.33	468	8.3
Lab Mix 5	2,110	0.18	255	0.16	227	11.1	0.1	142	44.4	0.15	213	16.7
Field Mix	1,938	0.93	1,318	0.78	1,106	16.1	0.75	1,063	19.4	0.78	1,106	16.1

(a)



(b)

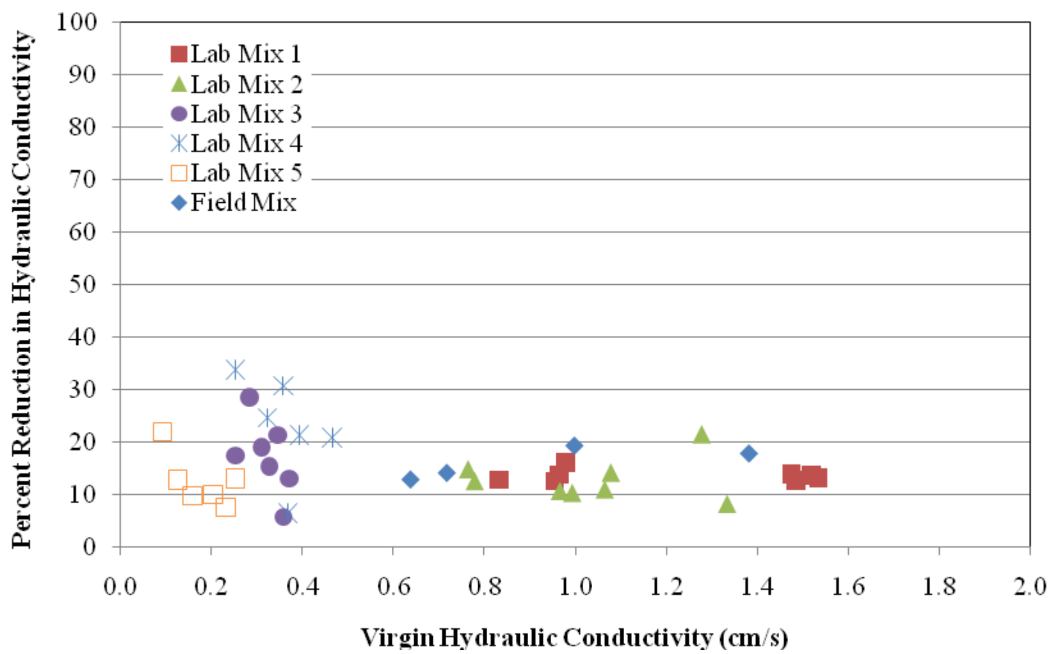


Figure 4.4: Reduction in Hydraulic Conductivity after One WSA

4.5.3 Maximum Clogging

Table 4.2 also summarizes the average values for hydraulic conductivity after maximum clogging had been performed. Average values were determined from three individual tests with results ranging from 0.10 cm/s (142 in/hr) to 1.07 cm/s (1,516 in/hr) for the mix designs studied. This corresponded to an average reduction of about 35% between the virgin samples and fully clogged samples. Figure 4.5 (which is in a format similar to Figure 4.4) shows that sample density had little effect on the reduction of hydraulic conductivity after maximum clogging had taken place

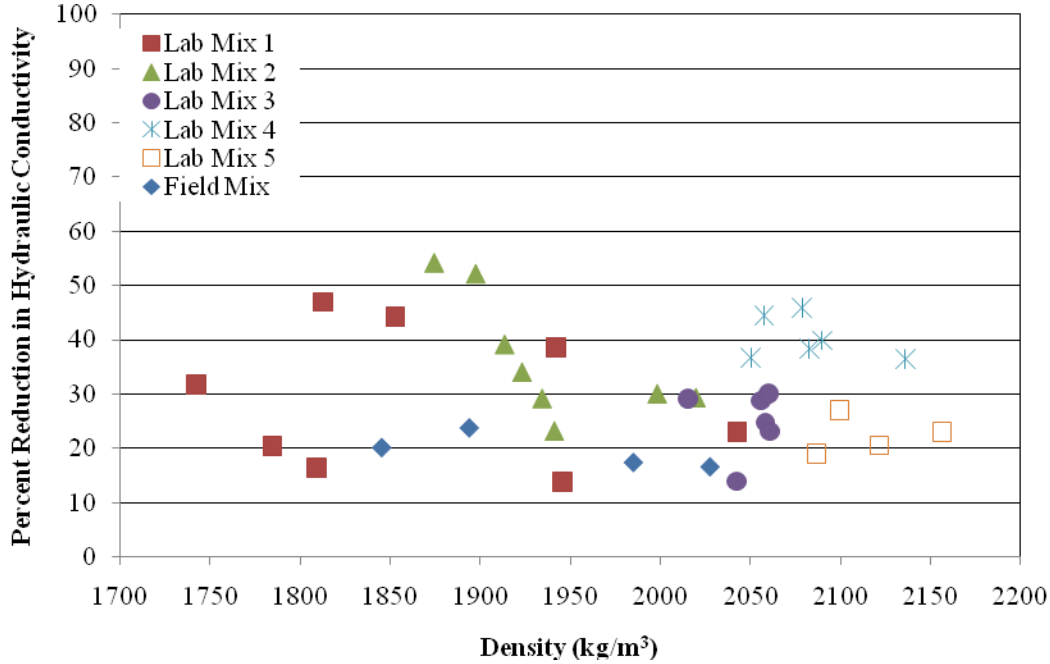
Results presented in Table 4.2 and Figure 4.5 are considered to represent a worst-case scenario, where as much sand or debris as possible is introduced into the pore structure of the porous concrete pavement system. The results show that even when the surface of the porous concrete system is significantly covered with a sand mixture, there is still enough hydraulic conductivity to effectively drain stormwater from the surface. It is assumed that most of the hydraulic conductivity that the system is capable of providing will not be needed during winter months, as rainstorms are uncommon and most water passing through will be due to snowmelt. Figure 4.5 presents results similar to one WSA, in that the initial hydraulic conductivity does not appear to have a significant effect on the percent reduction after maximum clogging has been achieved.

4.5.4 Reclamation of Pore Space

Table 4.2 also presents the results for hydraulic conductivity after attempts had been made to reclaim pore space that had been clogged by sand. These results for hydraulic conductivity ranged from 0.15 cm/s (213 in/hr) to 1.31 cm/s (1,857 in/hr). This represented an average reduction of about 9% between virgin samples and cleaned samples. Figure 4.6 (which is in a format similar to Figures 4.4 and 4.5) shows the reduction in hydraulic conductivity after pore space reclamation. Figure 4.6 summarizes the effects of one winter surface application, the effects of maximum clogging, and the attempted reclamation of pore space on hydraulic conductivity of the mix designs studied. These values represent the average value of all samples categorized by mix design. Differences in hydraulic conductivity were observed between laboratory mix 2 and the field mix, both of which were made with identical mix designs. The observed differences are attributed to different curing conditions for the field mix compared to the laboratory mix.

Table 4.2 and Figure 4.7 show that the method used to reclaim lost pore space and hydraulic conductivity of porous concrete specimens can be an effective tool. Recall that after maximum clogging had been achieved, reductions in hydraulic conductivity for all mix designs studied were around 35%. After the surface of the specimens had been vacuumed, the hydraulic conductivity was increased significantly, with less than a 10% reduction from the virgin samples that were tested previously. Figure 4.6 also shows that density is not an important factor in how much hydraulic conductivity can be reclaimed, as all mixes studied had similar values across a wide range of densities. Vacuuming is one of the suggested methods for increasing in-situ hydraulic conductivity of porous concrete pavement systems, and this research supports the effectiveness of this tool for yearly maintenance. Future work will investigate repeated cycles of clogging and cleaning to determine if vacuuming is an effective tool for long-term maintenance of porous concrete.

(a)



(b)

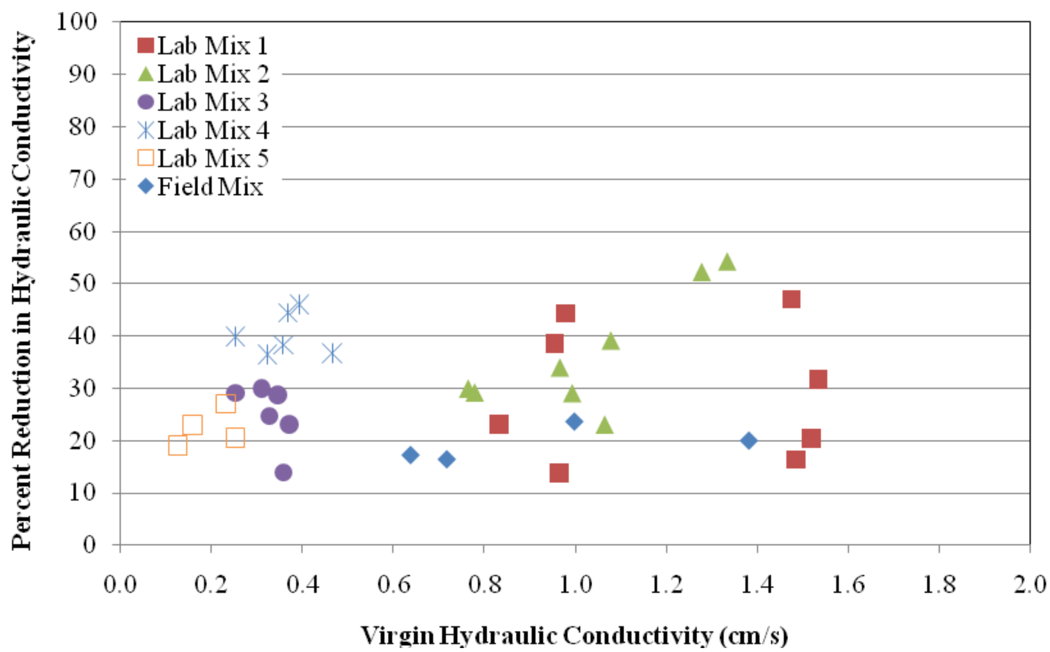
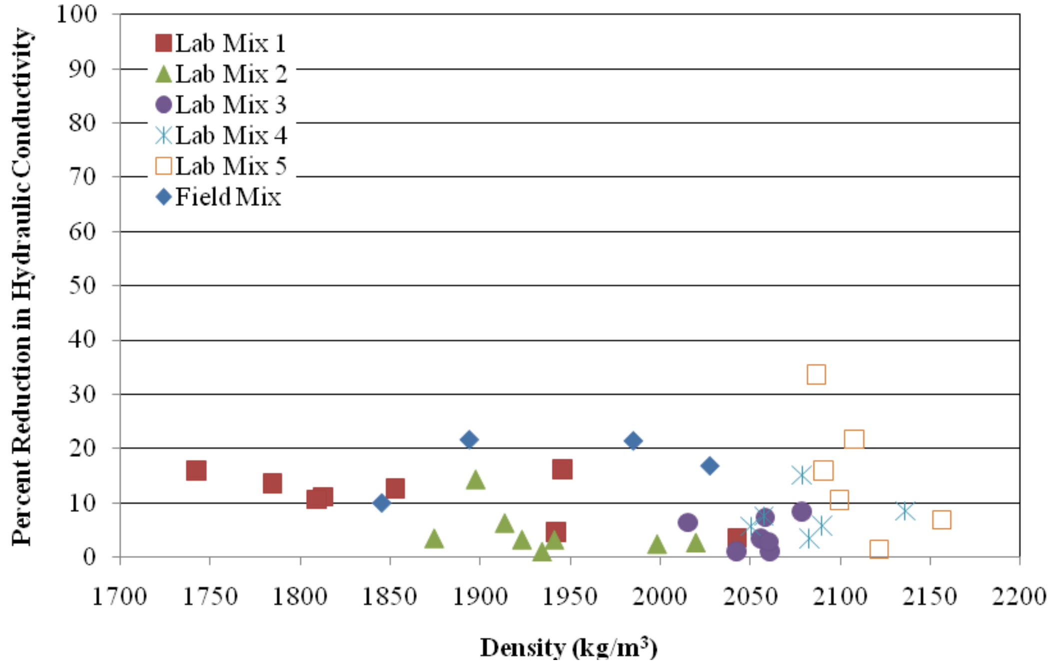


Figure 4.5: Reduction in Hydraulic Conductivity after Maximum Clogging

(a)



(b)

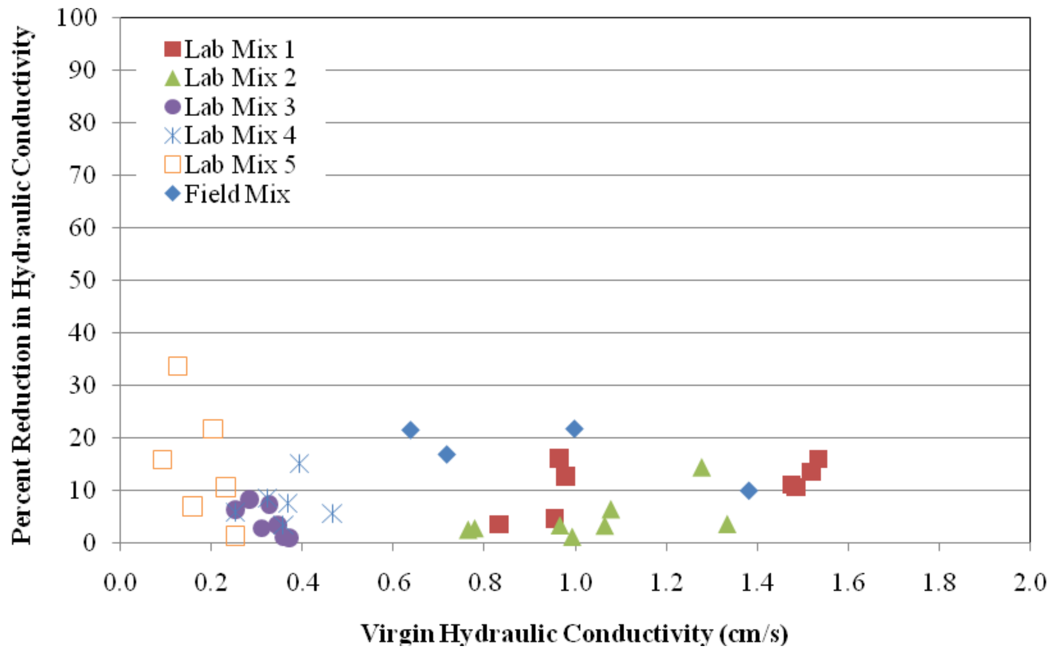


Figure 4.6: Changes in Hydraulic Conductivity after Vacuuming

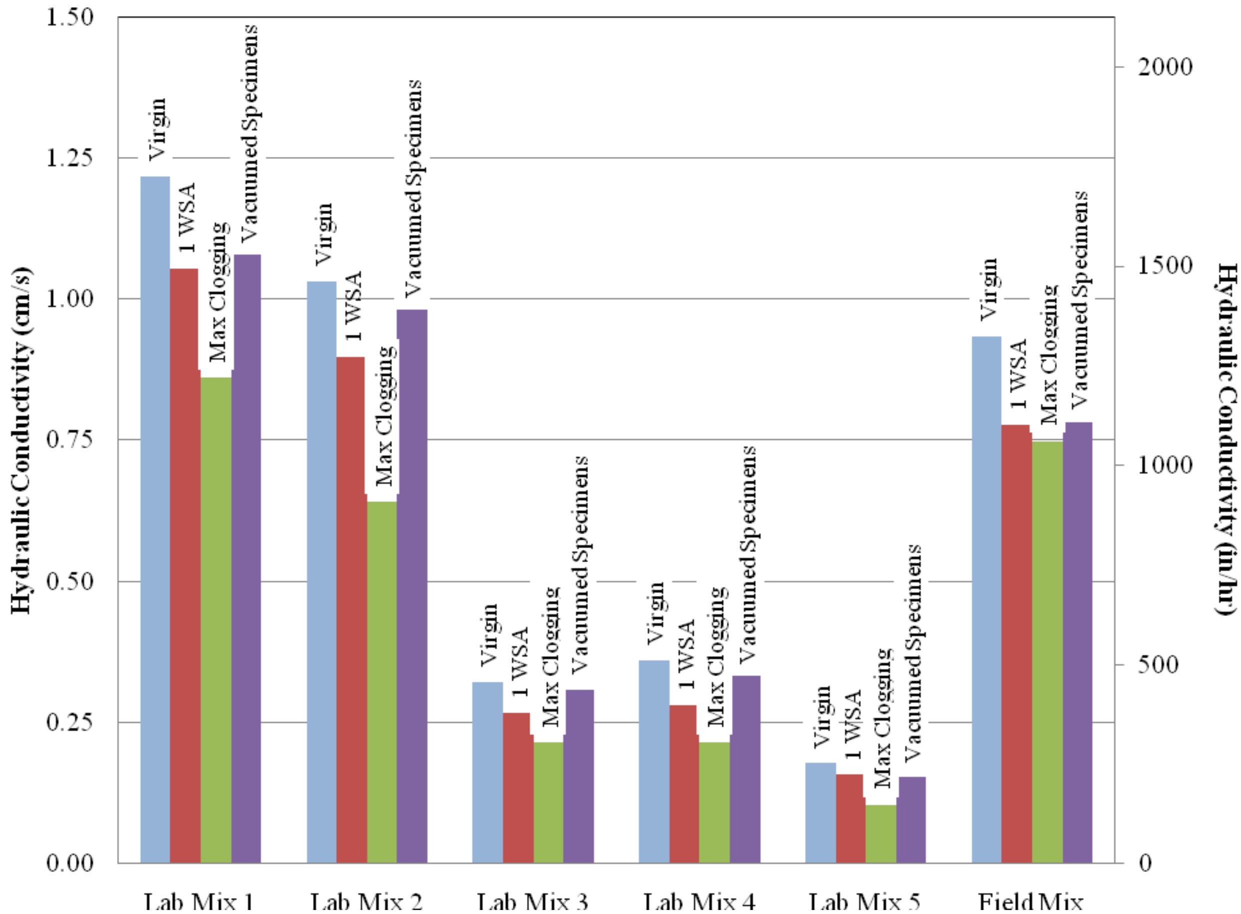


Figure 4.7: Effects of WSA, Max Clogging and Reclamation of Hydraulic Conductivity

4.6 SUMMARY

This laboratory study examined the effects of winter surface applications and fines infiltration on porous concrete specimens. The experiments included falling head permeability tests performed on specimens at four different stages: no winter surface application (virgin), after one winter surface application (0.12 g/cm^2 of sand and salt at 2:1 ratio by weight), after maximum clogging had been achieved, and after being vacuumed to reclaim pore space and hydraulic conductivity. The following conclusions were obtained for the mix designs studied: The following conclusions are drawn for the particular mixes studied:

1) The average reduction in hydraulic conductivity after one winter surface application (2:1 sand to salt mixture, surface application rate of 0.12 g/cm^2) was approximately 15%.
2) After maximum clogging of the porous concrete specimens had been achieved the reduction in hydraulic conductivity was measured to be around 35%. Even though this was considered a significant reduction, it still appears to be sufficient to provide adequate hydraulic conductivity for design storms in Vermont.
3) Vacuuming specimens in an attempt to reclaim pore space and hydraulic conductivity proved to be quite successful, resulting in hydraulic conductivities that were within 10% of the virgin samples that had been tested previously. Field verification will have to be conducted to confirm these results.
4) Sample density appears to have no effect on the reduction in hydraulic conductivity of porous concrete specimens for any amount of winter surface applications and clogging for the samples tested.
5) Sample density also appears to not have an effect on how much hydraulic conductivity can be reclaimed by vacuuming the specimens after maximum clogging has been achieved.

4.7 ACKNOWLEDGEMENTS

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CHAPTER 5

SURFACE INFILTRATION CAPACITY AND THE EFFECTS OF PLOWING ON POROUS CONCRETE PAVEMENTS

5.1 ABSTRACT

A study examining the surface infiltration capacity of porous concrete pavements and the effects of winter maintenance activities and applications on the surface infiltration capacity is presented. The objectives of the study were to: (1) examine the surface infiltration capacity of a recently constructed porous concrete parking facility in Burlington, VT; and (2) determine the effects of winter maintenance activities such as plowing, salting, and sanding on surface infiltration capacity. Preliminary surface infiltration capacity results showed that the constructed facility has adequate capacity for design storms in the region. Preliminary results from the simulated plowing show that plowing with no winter surface applications does appear to have an effect on the surface infiltration capacity of porous concrete, reducing it somewhere between 6% and 15%. Using salt as a winter surface application in addition to plowing appears to yield similar results, reducing the surface infiltration capacity by 10%. Using a 2:1 sand to salt mixture with plowing had a much more marked effect on surface infiltration capacity, leading to reductions of 96%.

5.2 INTRODUCTION

A porous concrete pavement system is an alternative to traditional pavement systems that can potentially reduce the amount of stormwater that makes its way into streams, lakes, and other water bodies (Ferguson, 2005). Traditional pavement systems can collect pollutants such as oil, gas, or anti-freeze which can then be transported into waterways via stormwater runoff. Porous pavement systems are designed to allow for the polluted water to pass through the pavement surface and into a gravel subbase, where it can be stored or treated before making its way into the groundwater table. For this reason, porous concrete pavements are ideally suited for areas near water bodies that are affected by stormwater runoff, or for sites on which the maximum amount of impervious surface has already been reached. Some northern communities have been hesitant to adopt this kind of technology, as there is little data on its effectiveness in a wet, freezing climate. There is also concern about the durability of such systems over the course of regular winter maintenance, such as salting, sanding, and plowing.

This paper focuses on porous concrete pavements. Porous concrete is similar to conventional concrete, with the exception that fine aggregates such as sand are generally excluded from the mix design completely or used in small quantities. This results in the coarse aggregate being bound together by only a thin layer of cement paste. Admixtures are also frequently used to improve the workability and durability of the mix.

The objectives of this study were to: (1) examine the surface infiltration capacity of a constructed porous concrete system in Burlington, VT, and; (2) determine the effects of winter maintenance activities such as plowing, salting, and sanding on the surface infiltration capacity of porous concrete specimens in the laboratory.

5.3 BACKGROUND

Literature related to the measurement of surface infiltration capacity for porous concrete pavements and effects of winter maintenance activities are reviewed in this section. No laboratory studies that particularly focused on the effects of winter maintenance on porous concrete systems were found.

5.3.1 Surface Infiltration Capacity

Several studies (e.g. Bean, et al. and Henderson et al.) have investigated both the performance of porous concrete pavement systems in the field and the performance of similar mix designs in the laboratory. Many of the tests that are performed in the laboratory are not feasible or cannot be performed to determine in-situ properties. To work around these obstacles, several methods of determining the engineering properties of porous concrete pavement systems have been proposed.

To measure the surface infiltration capacity of porous concrete in-situ without having to obtain cores from the field, some 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).

Delatte et al. (2008) developed a surface drainage test for use at porous concrete facilities. The apparatus consisted of a plastic concrete cylinder mold 10 cm in diameter and 20 cm tall (4" by 8"). A 2.2 cm (0.875") hole was drilled in the bottom of the mold to allow water to flow through the cylinder, and the bottom of the mold was lined with foam rubber in an attempt to seal the cylinder against the pavement. The mold was then filled with water, and the time it took for the water to drain through the mold and into the pavement was then measured. Two dozen sites were evaluated in 4 States, and mean values of surface drainage varied from 21 seconds to 136 seconds.

Henderson et al. (2008) used similar methods to assess the in-situ surface infiltration capacity at 16 sites for three porous concrete facilities in Ontario, Canada. The apparatus used was a Gilson Asphalt Permeameter, commonly used for on-site evaluation of asphalt pavement systems to insure that adequate compaction has been achieved. The permeameter was sealed to the porous pavement surface using a plumber's putty, and time measurements were recorded for water to drop a specified distance. Surface infiltration capacity values were then obtained utilizing Darcy's law. Averages for surface infiltration capacity at the three sites ranged from 0.1 cm/s to 0.6 cm/s (140 to 850 in/hr). Henderson et al. (2008) also investigated the performance of the systems after a winter of sanding/salting had been performed and rehabilitation of the system had been attempted. Using a wet-dry vacuum, several sites that been chosen for surface infiltration capacity testing were vacuumed, and the tests were performed again. Increases in surface infiltration capacity ranged from as low as 1.3% to as high as 287%, and no ponding was observed at the sites.

Chopra and Wanielista (2007b) developed a method to determine the infiltration rates of the entire porous concrete system, including the gravel subbase and natural subsoil. A concrete coring drill was used to drill a core with a diameter of approximately 30 cm (12") from 10 porous concrete pavement systems that had been in service from 6-20 years. The core was then left in place, and a steel tube was inserted around the core and embedded into the natural subsoil, much like a single-ring infiltrometer test that is generally performed on soils. This apparatus encouraged one-dimensional flow through the system, and therefore, could be considered more representative of in-situ hydraulic conductivity than other methods that allow for lateral flow within the pavement layer and underlying materials. The test also allowed for determination of whether the infiltration rate was controlled by the subsoil or the pavement surface. The results of the tests showed an average infiltration capacity ranging from 2.8×10^{-4} cm/s to 0.16 cm/s (0.4 to 227 in/hr), with a porous concrete as the limiting factor for six sites and the subsoil as the limiting factor for four sites.

Visual observation has also been used to effectively characterize the performance of porous concrete pavement systems in the field. These observations include damages such as clogging/ponding, raveling, cracking, scaling, and joint separations (Delatte et al., 2008; Henderson et al., 2008). These visual observations can offer valuable information regular maintenance and upkeep of porous concrete pavements, especially as they can be particularly susceptible to clogging due to winter maintenance activities or improper installation practices and cracking or raveling as a result of heavy vehicle traffic. Numerous incidents have been documented with a wide variety of potential causes; another reason regular inspection can benefit the overall performance of porous concrete systems.

5.3.2 Winter Maintenance Activities

Review of the literature has shown that measuring the forces and quantifying the effects of winter maintenance can be a difficult task. Nixon et al. (1997) attempted to use accelerometers in order to determine the forces on a front-mounted plow when scraping ice. Unfortunately, the accelerometers were unable to determine the actual forces applied by the plow, as it was ineffective in cutting through the ice and the data that was acquired was primarily a result of the vibration of the plow itself.

5.4 RESEARCH METHODS

This section reviews the methods that were developed to test the surface infiltration capacity of porous concrete pavements as well as model winter maintenance activities in the laboratory.

5.4.1 Field Site

Surface infiltration capacity testing was performed at a porous concrete parking facility located on Lower College St. in Burlington, VT. The facility was constructed in June of 2009, and tests were able to be performed before the site was opened to traffic. Testing has been repeated multiple times over the course of the study period to observe changes in infiltration capacity over time. A rendering of the study area courtesy of SE Group – Landscape Architects is shown in Figure 5.1.

Figure 5.1: Rendering of Porous Concrete Parking Facility in Burlington, VT (Courtesy of SE Group – Landscape Architects)

5.4.2 Sample Preparation

Specimens for modeling the effects of winter maintenance activities were obtained during the construction of a separate porous concrete parking facility located in Randolph, VT in the summer of 2008. Molds were designed that allowed for specimens to be cast approximately 12” wide by 24” long and 6” deep. This depth was chosen as a representative value for most porous concrete pavement systems, and was also the design depth of porous concrete at the field site in Randolph. All attempts were made to cast the specimens in a similar fashion to the construction methods used in the field. The porous concrete was placed in the mold, then compacted using a steel roller obtained during the construction process. The concrete was field cured under plastic for 7 days, then de-molded and stored until plow testing took place.

5.4.3 Surface Infiltration Capacity

In order to determine the in-situ properties of porous concrete pavements, a field permeameter was designed and built at the University of Vermont to test the surface infiltration capacity of porous concrete pavements. The apparatus consists of a 24” x 24” x ¾” PVC sheet used as a base, and a sheet of foam rubber with the same dimensions attached to the underside. This foam rubber was utilized in order to make as tight a seal as possible with the porous concrete surface without epoxies or putties that would cause permanent clogging of the pore structure. The PVC base was then milled, and a standpipe was attached that allowed for water levels in the standpipe to be observed. Cinderblocks were placed on top of the PVC base to help create a tight seal with the surface. Surface infiltration capacity was measured by filling the standpipe with 15” of water and recording the amount of time required for the water level to drop to 3”. Infiltration capacity was then determined using Darcy’s Law. Although this does not allow for direct comparison with hydraulic conductivity values obtained in the laboratory as water is not confined to vertical flow, it does allow for changes over time to be determined by repeating the tests at the same locations. Figure 5.2 shows the field permeameter in use.

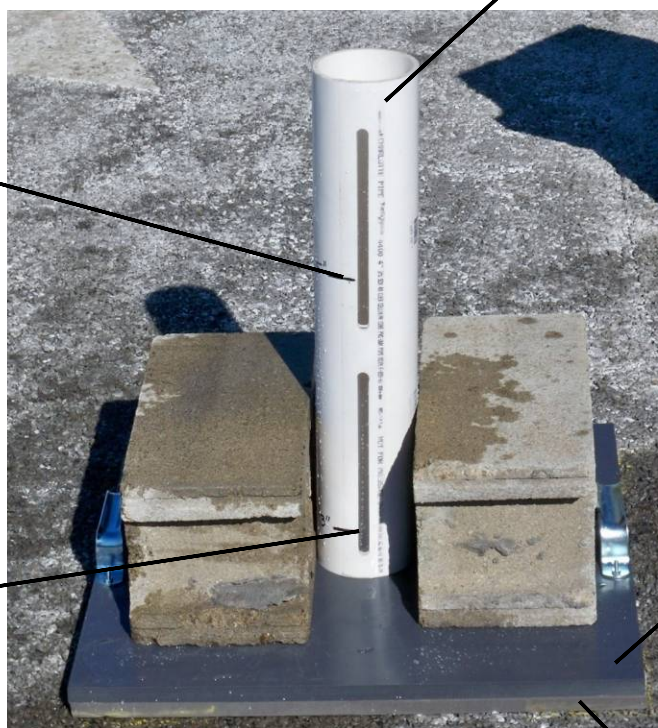

Figure 5.2: Field Permeameter in Use

5.4.4 Plow Modeling

In order to model winter maintenance activities such as plowing, salting, and sanding, a laboratory plow simulator was designed. The apparatus consists of an aluminum frame built using 80/20 ™ extrusions. Attached to the frame is an air cylinder capable of applying up to 2.2 kN (500 lbs) of vertical force, with a steel blade attached. Plowing samples are placed on the frame, and a vertical force of approximately 0.44 kN (100 lbs) is applied. The cast specimens are approximately 30 cm wide, therefore a force of approximately 1.5 kN/m (111 lbs/ft) is exerted on the specimen. C-clamps are then attached to both ends of the specimen, and the sample is pushed back and forth underneath the steel blade 20 times. When 20 cycles have been completed, the infiltration capacity of the specimen is tested using the field permeameter. The specimen is then placed back in the plow modeling apparatus, and the test is repeated a total of 6 times to represent one winter of maintenance activities. This amount of plowing was chosen as a representative value for actual field conditions using log data provided by the Vermont Agency of Transportation (VTrans) during their winter maintenance of the facility in Randolph, VT.

In order to examine the effects of winter surface applications, the procedure described was modified. Initially the virgin surface infiltration capacity of the porous concrete specimen was measured. Before the specimen was placed in the plow modeling apparatus, a winter surface application was applied. On one specimen, 0.08 g/cm^2 of rock salt was applied to the surface, and on another specimen the same amount of a 2:1

sand to salt mixture was applied. This amount was chosen visually as a representative amount of winter surface application in the field. The 2:1 sand to salt ratio is typical of what one would find for a conventional pavement system in Vermont. Specimens were then placed in the plow modeling apparatus and tested for 20 cycles. After each surface infiltration capacity test, another winter surface application was applied. Figure 5.3 shows the plow apparatus that was developed, and Figure 5.4 shows the apparatus in use.

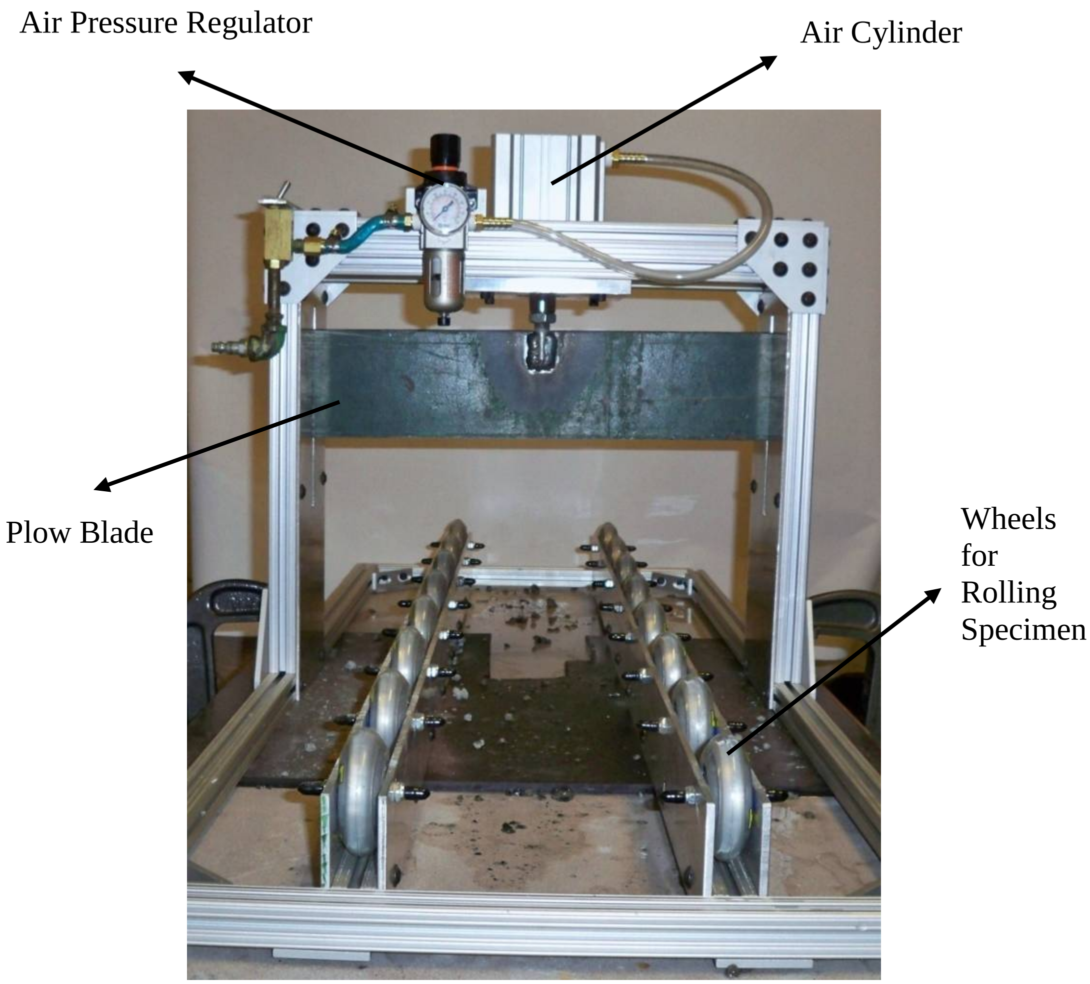

Figure 5.3: Plow Modeling Apparatus

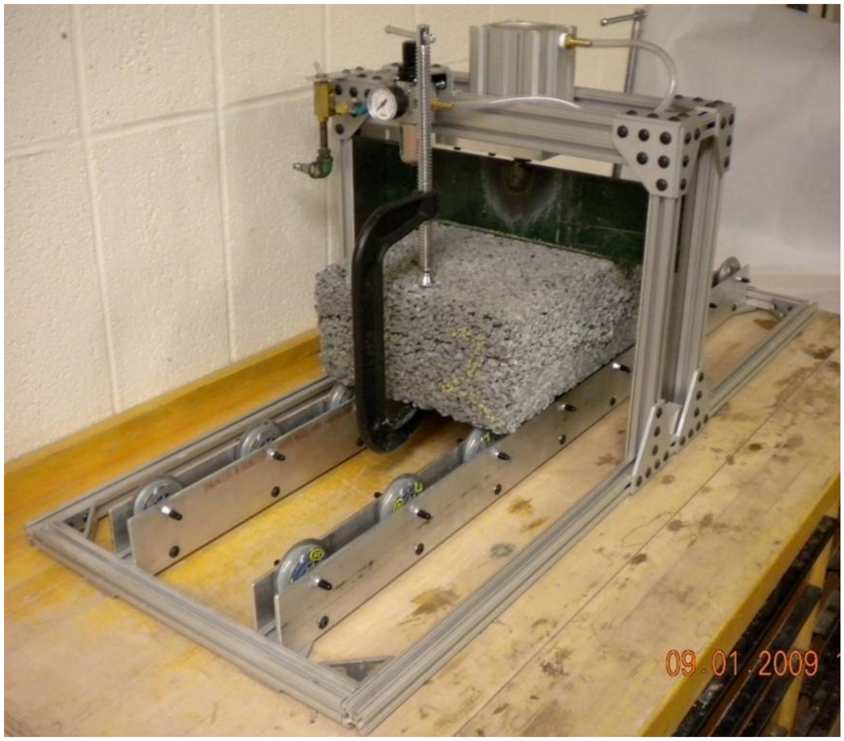

Figure 5.4: Plow Modeling Apparatus in Use

5.5 RESULTS AND DISCUSSION

5.5.1 Surface Infiltration Capacity

The results for surface infiltration capacity testing for the porous concrete facility in Burlington, VT are summarized in Table 5.1. At each location tests were repeated a minimum of 4 times. Values obtained for surface infiltration capacity range from about 2.5 to 7.5 cm/s (3,500 to 10,600 in/hr).

Table 5.1: Surface Infiltration Capacity (cm/s) Results from the Burlington, VT Site

		Site Location							
		A	B	C	D	E	F	G	H
Date Tested	5/25/2009	6.32	n/a	5.20	7.48	4.87	5.42	4.49	n/a
	5/26/2009	6.42	n/a	5.49	6.88	5.37	6.21	3.85	6.33
	6/4/2009	6.44	n/a	5.35	6.88	5.28	5.14	2.94	5.99
	6/11/2009	5.97	n/a	5.88	7.33	5.58	5.07	4.00	6.01
	6/18/2009	6.76	n/a	4.67	7.69	4.07	4.79	2.72	5.54
	7/1/2009	4.95	5.29	4.43	6.44	4.21	4.91	3.72	5.99
	7/15/2009	5.15	5.06	4.69	6.28	4.37	4.92	3.58	6.23
	8/5/2009	3.49	n/a	4.39	6.79	4.25	4.24	2.78	5.28

In examining Table 1, it appears that the porous concrete facility in Burlington, VT was installed successfully. All sites initially showed and continue to show surface infiltration capacity rates that are more than adequate to infiltrate design storms for the region. A representative 10-yr 24-hr design storm for Vermont is around 10 cm/hr (4 in/hr) (Leming et al., 2007). There does appear to be some decrease in surface infiltration capacity over time for each location, as shown in Figure 5.5. However, even with this decrease the system is still capable of infiltrating design storms. The reduction in infiltration capacity is most likely due to fines infiltration, as fines can be blown onto the porous concrete surface or carried on by vehicles. Simple remediation techniques such as pressure washing or vacuuming the surface would most likely increase the surface infiltration capacity near the levels that were initially measured. The site will continue to be monitored in the future.

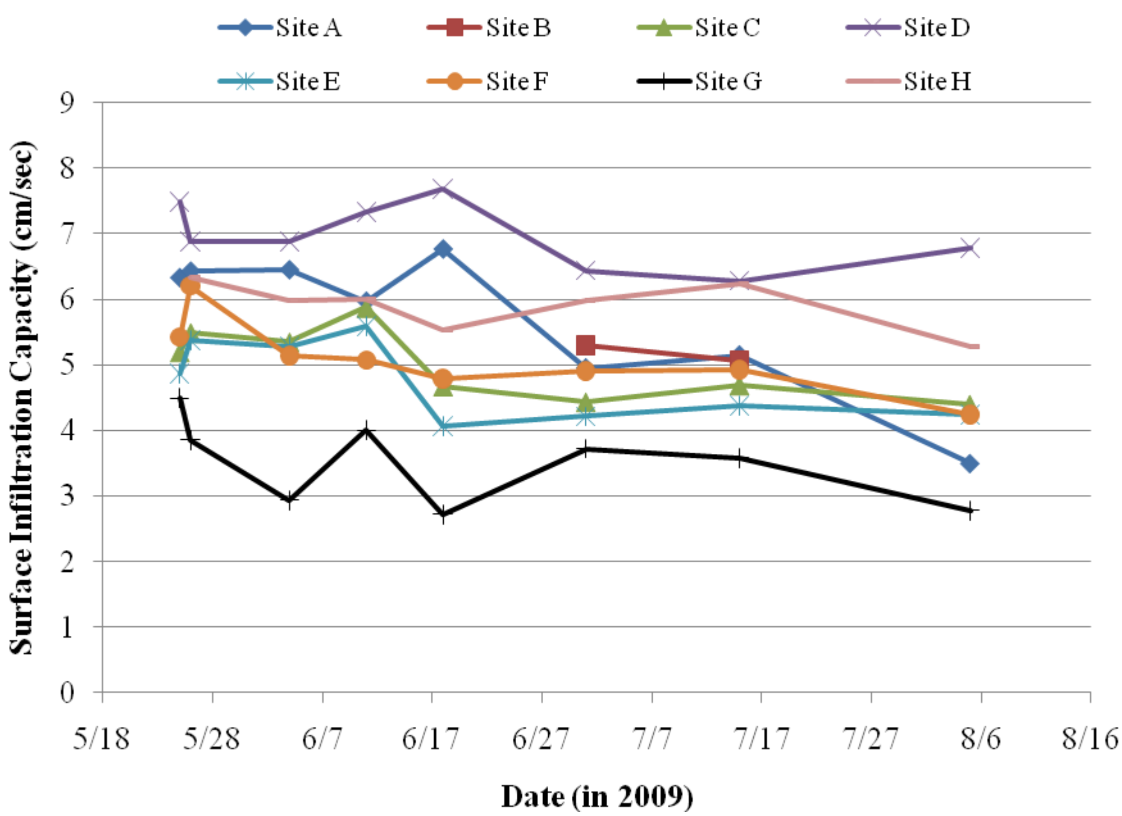

Figure 5.5: Surface Infiltration Capacity in Burlington, VT

5.5.2 Plow Modeling Apparatus

Preliminary results of plow modeling in the laboratory are summarized in Table 5.2. Recall that samples 1 and 2 were tested in the plow apparatus with no winter surface applications. Salt was applied to sample 3 before each plowing cycle, after surface infiltration capacity had been tested. A 2:1 sand to salt mixture was applied to sample 4 in the same manner.

Table 5.2: Surface Infiltration Capacity (cm/s) after Plow Simulations

	Sample 1	Sample 2	Sample 3	Sample 4
Virgin	9.24	7.19	5.68	5.05
1 cycle (20 reps)	8.31	7.12	5.25	2.65
2 cycles (40 reps)	8.41	6.61	5.50	1.24
3 cycles (60 reps)	7.99	6.74	5.18	0.43
4 cycles (80 reps)	7.69	6.41	5.05	1.06
5 cycles (100 reps)	7.59	6.58	5.18	0.24
6 cycles (120 reps)	7.73	6.70	5.11	0.20

The results show that plowing the surface of the porous concrete surface does appear to have an effect on the surface infiltration capacity. Samples 1 and 2 with no winter surface applications had reduction in infiltration capacity of 16% and 7%, respectively. There was also visual wear on the surface of the porous concrete, as seen in Figure 5.6. Using only rock salt as a winter surface application yielded similar results to the first two samples, with a reduction of surface infiltration capacity of approximately 10%. This is most likely due to the salt dissolving and passing through the specimen during the surface infiltration testing, giving similar results to the first two samples.

Using a 2:1 sand to salt mixture did have a marked impact on the surface infiltration capacity of the specimen that was tested. Reduction in infiltration capacity was 96%, and visual inspection of the specimen surface showed that nearly all the surface pores were clogged. Previous research done by McCain et al. (2009) showed that maximum clogging of cylindrical porous concrete specimens was only on the order of 40%. This shows that plowing the surface contributes to the clogging of the specimen, most likely by packing portions of the sand mixture into the pores. Sand particles that normally would wipe off the surface or was small enough to pass through the pores were packed into the surface pores and thus contributed to clogging. A plot of the surface infiltration capacity for Sample 4 is shown in Figure 5.6.

Figure 5.6: Comparison of Porous Concrete Surface after 6 Cycles of Plow Testing: Virgin Sample (left) after 6 Cycles (right)

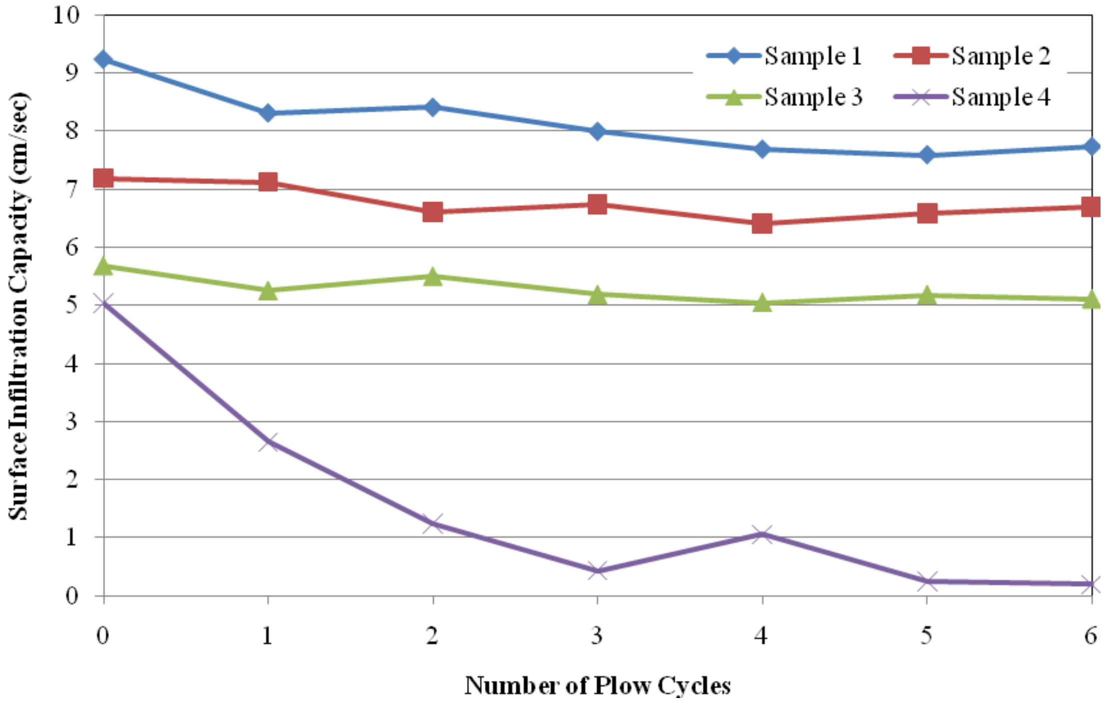

Figure 5.7: Surface Infiltration Capacity for all Plow Specimens

5.6 SUMMARY

This study examined field surface infiltration capacity of porous concrete pavements and the effects of plowing on the surface infiltration capacity of porous concrete laboratory specimens. The experiments included the use of a field permeameter at a local porous concrete facility, and the use of a plow modeling apparatus in the laboratory. The following conclusions are drawn for the preliminary data obtained up to this point for this ongoing study:

1) The field permeameter showed that the surface infiltration capacity of the porous concrete facility studied was adequate for design storms in the region after construction and following three months of operation.
2) Surface infiltration capacity appeared to decrease over time following construction in May 2009 to August of 2009, potentially due to fines infiltration.
3) Plowing simulations on the surface of porous concrete pavement specimens appeared to reduce the surface infiltration capacity.
4) Use of salt as a winter surface application yielded similar results to no winter surface applications after plowing.
5) A 2:1 sand to salt ratio reduced the surface infiltration capacity of porous concrete after plowing by 96%, and therefore should be avoided

5.7 ACKNOWLEDGEMENTS

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 Floyd Vilmont and Eric Adam Woods for their help and guidance in designing and building the field permeameter as well as the plow modeling apparatus. The authors would also like to thank the City of Burlington Public Works Department for their assistance in these research efforts.

CHAPTER 6

CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1 CONCLUSIONS

The following summarizes the conclusions that were drawn from this study. Average strength of the porous concrete specimens ranged from 6.2 to 26.7 MPa (910 to 3,380 psi) depending on the mix design investigated. Average values for hydraulic conductivity of laboratory cast specimens were between 0.18 and 1.22 cm/s (250 and 1,730 in/hr) depending on the mix design investigated. Both compressive strength and hydraulic conductivity showed a clear linear dependence on specimen density, and all values were within the expected range found in the literature.

Specimen size appeared to have an effect on both compressive strength and hydraulic conductivity. Based on the data specimens with a diameter of at least 10.2 cm (4”) are suggested for laboratory testing procedures.

Water-cement ratio played a strong role in both the compressive strength and hydraulic conductivity of the mix designs investigated. In general, increased water content corresponded to an increased density, increase in compressive strength, and decrease in hydraulic conductivity. Admixtures such as HRWR and AEA had little effect on the compressive strength and hydraulic conductivity of laboratory specimens as compared to water-cement ratio.

Field cores from the park-and-ride facility in Randolph, VT showed a higher variability in hydraulic conductivity than laboratory prepared specimens, primarily due to differences in the compaction methods used for laboratory cast specimens and field sites.

Surface applications did appear to have an effect on the hydraulic conductivity of laboratory cast specimens. A 2:1 sand to salt mixture with an application rate of 0.12 g/cm^2 reduced hydraulic conductivity by approximately 15%. Clogging the surface pores with as much sand as possible led to reductions of around 35 – 40 %. Although these are considered marked reductions, values of hydraulic conductivity were still well above typical design storms for the region. Attempts at reclaiming hydraulic conductivity utilizing a vacuum were successful and were capable of restoring the hydraulic conductivity to within 10% of the initial values. Unlike compressive strength and virgin hydraulic conductivity, specimen density did not appear to effect the reduction in hydraulic conductivity for any amount of surface applications, clogging, and reclamation for the mixes investigated.

Preliminary results from the field permeameter show that the porous concrete facility in Burlington, VT had adequate surface infiltration capacity for design storms in the region immediately following construction in May of 2009 until August 2009. Surface infiltration capacity did appear to decrease over this time period, presumably due to fines infiltration. Preliminary results of simulated plowing on the surface of porous concrete pavements also appeared to affect the surface infiltration capacity of porous concrete pavements in the laboratory, resulting in reductions between 7% and 16%. Use of salt as a winter surface application yielded similar results to only plowing, resulting in surface infiltration capacity reductions of 10%. Winter surface applications consisting of a 2:1 sand to salt mixture had a much more marked effect on surface infiltration capacity, leading to a reduction of 96%. For this reason, it is suggested that winter surface applications containing sand be avoided during regular winter maintenance.

6.2 RECOMMENDATIONS

Based on the study presented here, the following recommendations are made for future porous concrete installations in northern communities in an effort to improve their performance and make them a more viable tool in these regions. These recommendations may have to be revised once the freeze-thaw resistance of the mixes studied is determined.

1) Compressive strength and hydraulic conductivity testing show that porous concrete pavement systems can be effective in northern climates.
2) Established construction and installation practices should be carefully followed to ensure that proper density is achieved to balance compressive strength and hydraulic conductivity characteristics.
3) Admixtures such as AEA and HRWR had little effect on the compressive strength and hydraulic conductivity of porous concrete pavements, but should be used to improve the workability of the mix and potentially protect against freeze-thaw damage.

4) Vacuuming can be used as an effective tool to rehabilitate porous concrete systems and improve their hydraulic conductivity and surface infiltration capacity characteristics.
5) Field sites should be monitored as surface infiltration capacity appears to reduce over time, and regular maintenance may be necessary.
6) Plowing the surface may have an effect on surface infiltration capacity and should be monitored.
7) Winter surface applications containing sand should be avoided, particularly when plowing is performed as regular winter maintenance. Applications containing only salt could be utilized instead.

Additional research on the following is recommended:

1) Additional investigation into the effects of plowing on the surface of porous concrete pavements.
2) Continued field observations on constructed porous concrete facilities to determine changes in surface infiltration capacity over time.
3) Effects of freeze-thaw on the mix designs investigated in this study.
4) Similar investigations into a wider variety of mix designs containing different aggregates, admixtures, or supplementary cementitious materials.
5) Additional methods for reclamation of hydraulic conductivity and surface infiltration capacity such as pressure washing.

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APPENDIX A: PROCEDURES

8.1 Mix Design (as proposed by Kevern et al., 2006)

1. Prepare a 'butter batch' of 0.5 $ft^3$with the same proportions as the mix that is going to be made, making sure to use the same procedure described below;

2. Pour the coarse aggregate (CA) into the mixer;

3. Add approximately 5% of the cement (by mass) to the mixer and mix for 1 minute, or until the CA is completely coated with a thin coat of cement;

4. Add the remaining cement, water and admixtures to the mixer;

5. Mix the concrete for 3 minutes;

6. Allow the mix to rest for 2 minutes, and;

7. Mix for an additional 2 minutes before casting.

8.2 Sample Preparation (in general accordance with ASTM C192)

NOTES:

- Cylinder molds are available at A.H. Harris in Williston, VT. Generally 3" x 6" and 4" x 8" molds are available, and other sizes can be ordered as needed.
- Molds for hydraulic conductivity test specimens will need to be cut down to 6" using the bandsaw in the shop.

- Molds for freeze-thaw specimens are hand-made. 10’ sections of 3” thin wall PVC can be purchased at local hardware stores (ACE Hardware in S. Burlington, VT) and then cut down to 11” sections. In order to easily remove samples from mold, a cut should also be made lengthwise to open the mold after concrete has cured. To seal the bottom of the mold, clear plastic sheeting and duct tape is used.

1. After mixing is complete, empty the mixer into an appropriately sized wheelbarrow;

2. Scoop concrete into the cylinder mold (2 layers for 3” samples or smaller, 3 layers for 4” samples or larger), and tamp each layer 25 times with an appropriately sized tamping rod;

3. After each layer has been tamped, rap the side of the mold 9 times (evenly around the entire circumference) with the tamping rod;

4. For the final layer, tamp only 15 times, then add enough concrete so that it rises above the top of the mold. Tamp an additional 10 times, and then roll the tamping rod over the top of the mold, scraping off excess material and creating a level surface, and;

5. Place specimens in a fog room at 98% relative humidity for 26-28 days. Specimens should remain under a plastic sheet so that they do not come in direct contact with water.

8.3 Compressive Strength Testing (in general accordance with ASTM C39)

1. Remove compressive strength testing specimens from the fog room approximately one day before testing is going to take place;

2. Place samples in the oven WITH THE HEAT TURNED OFF and only the blower active;

3. Allow samples to sit in the oven for 24 hours and dry completely;

4. Record the mass of each specimen so that density can be calculated;

5. Place appropriately sized end caps (located under the computer attached to the 60-kip Tinius-Olsen;

6. For the 60-kip Tinius-Olsen compression testing machine:

    a. Flip the appropriate breaker in the breaker box located in the back of the structures lab (note that it may take a minute for the 60-kip machine to turn on);

    b. Turn on the computer attached to the 60-kip machine;

    c. Make sure the Tinius-Olsen is on the 60-kip channel;

    d. Open the MTestW program on the computer desktop;

    e. In the test setup window open My Documents\McCain and find the test setup appropriate for the cylinder size being tested;

f. Zero the strain, load, and deflection windows using the ‘Zero’ command in the program;

g. Use the ‘Lower’ and ‘Slow’ setting on the 60-kip machine to start applying the load at a rate of approximately 0.025 to 0.05 in/min (or lower if necessary);

h. The program will automatically start recording data once the load reaches 50 lbs;

i. After the specimen has failed, the test may need to be manually stopped by pressing F9 or the stop command in the program;

j. Save the file in the .raw file format with an appropriate name (i.e., Lab Mix 6 specimen 3 would be named LM6-3);

7. For the 300-kip Tinius-Olsen compression testing machine:

    a. Flip the appropriate breaker in the breaker box located in the back of the structures lab;

    b. Turn on the blue load gauge on the 300-kip console;

    c. Use the buttons on the left side of the 300-kip machine to position the load frame. DO NOT LET THE LOAD FRAME COME INTO CONTACT WITH THE SPECIMEN, make sure to leave approximately ¼” of space between the frame and the top of the specimen;

d. Close the ‘Release’ valve on the 300-kip console by turning it all the way to the right;

e. Press the ‘Zero’ button on the blue load gauge;

f. With the load speed dial all the way to the left, press the ‘Start’ button on the 300-kip console (note that the left side of the speed dial is the slowest, and the right side is the fastest);

g. Continue until the sample has failed, then record the maximum load to calculate the ultimate stress;

h. Turn the ‘Release’ valve to the left to release the hydraulic pressure built up during the test, and;

8. Label the sample and then store it appropriately.

8.4 Hydraulic Conductivity Testing

- More thin rubber sheeting can be found in the cabinet under the direct shear machine

1. Select the appropriately size falling head permeameter for the specimen size being tested;

2. Wrap the specimen with the thin rubber sheet before enclosing it in the appropriately sized plastic cylinder mold;

3. Use the modeling clay to fill the gap in the plastic cylinder mold;
4. Take 2 hose clamps, and tighten one clamp approximately 1”-2” from both the top and bottom of the specimen;
5. Smooth out the clay filler and remove any excess;
6. Place the specimen and mold into the rubber PVC connector on the U-shaped piece of the falling head permeameter and tighten the hose clamp attached to the rubber PVC connector;
7. Attach the upstream piece of the permeameter by sliding the rubber PVC connector on top of the specimen and mold;
8. Fill the permeameter from the downstream end, slowly enough to expel any air voids within the porous concrete pavement specimen, making sure to check for any leaks (especially where the specimen connects to the permeameter);
9. Fill the upstream end of the permeameter with water, and then allow the system to reach an equilibrium;
10. Mark the level of water on the upstream end, representing the zero head level
11. Using tape or other non-permanent method, mark the upstream end of the permeameter at 10 cm and 30 cm above the zero head level;
12. Fill the upstream end with water, and measure the time it takes for the water level to fall from 30 cm to 10 cm;

13. Repeat step 12 at least 3 times to get an average time value, and;

14. Using Darcy's law calculate hydraulic conductivity, *k.*

8.5 Winter Surface Applications

1. Repeat steps 1-13 under the Hydraulic Conductivity Testing procedure;

2. Remove the upstream piece of the falling head permeameter;

3. Apply 0.12 g/cm^2 of a 2:1 sand to salt mixture evenly across the surface of the specimen;

4. Reattach the upstream piece of the permeameter, and;

5. Repeat steps 11 – 14 from the Hydraulic Conductivity Testing procedure.

8.6 Maximum Clogging of Pores

1. Allow sample to air dry for a period of no less than 24-hours after testing with one WSA;

2. Place sample in cylindrical plastic mold with 1" headspace between top of sample and top of plastic mold;

3. Fill top headspace with sand mixture provided by VTrans;

4. Place sample with sand on shaker table and secure sample in shaker table with provided attachments;

5. Shake sample for one minute at a frequency of 2 Hz, then rotate sample 90° and repeat shaking. Continue until sample has been turned 360° (samples are shaken for a total of four minutes);
6. Remove samples from shaker table, with care to not invert the sample, and;
7. Follow procedure set forth for hydraulic conductivity testing taking care not to disturb sand while loading sample into the apparatus.

8.7 Reclamation of Hydraulic Conductivity

1. Allow sample to air dry for a period of no less than 24-hours after testing for maximum clogging;
2. Vacuum sample with a 2.0 peak horsepower vacuum (circular hose 1" in diameter) for 5 seconds to remove sand. Rotate sample 90 degrees and vacuum for an additional five seconds, and;
3. Follow procedure set forth for hydraulic conductivity testing.

8.8 Winter Maintenance Modeling

NOTES

- This procedure requires special specimens to be cast. This specimen preparation procedure will be included in this description

1. Specialized molds need to be created that will allow for specimens 12” wide by 24” long and 6” deep. This can be achieved by creating a wooden form;
2. Prepare the mix design and pour it into the mold in a single layer;
3. In order to compact the concrete in a manner similar to that in the field, a roller should be used that applies approximately 100 lbs per linear foot to achieve the recommended 10 psi of pressure;
4. Cover the form tightly with plastic sheeting and allow it to cure in the field for approximately 7 days;
5. Remove the concrete from the mold, and allow to cure for at least another 21 days, yielding a cumulative curing time of at least 28 days;
6. Using the field permeameter, measure the surface infiltration capacity of the concrete specimen;
7. Place the appropriate amount of winter surface applications on the surface of the specimen;
8. Place the specimen on the plow modeling apparatus;
9. Apply the appropriate amount of pressure on the sample using the air cylinder for the plow pressure desired;
10. Manually slide the sample back and forth 10 times, and;
11. Repeat steps 6-10 for the number of plowing cycles desired.

8.9 Proposed Freeze-Thaw Procedure (in general accordance with ASTM C666)

NOTES

- This procedure should be compared to both f-t in water and f-t in air to determine any differences between those procedures set forth in ASTM.

1. Record the mass of completely dry f-t specimens;
2. Submerge specimens underwater for 30 seconds;
3. Allow excess water to drain for an additional 30 seconds before recording saturated mass;
4. Place specimens in the f-t chamber and begin f-t cycles;
5. After 10 cycles have been completed, take the specimens out of the chamber and record the mass, and;
6. Repeat steps 2-5 until 300 cycles have been completed or samples have lost greater than 15% of their initial mass.

8.10 Surface Infiltration Capacity

1. Choose and mark an appropriate testing site or locate an existing one;
2. Place the field permeameter on the site;

3. Using a 5 gallon bucket, fill the standpipe of the permeameter above the 15” mark on the standpipe;

4. Record the time for the water level to fall from 15” to 3” inches, and;

5. Repeat steps 3 and 4 at least 3 times to obtain an average value.

APPENDIX B: ALL COMPRESSIVE STRENGTH DATA

9.1 LAB MIX 1

3 inch			4 inch			6 inch		
density	Strength		density	Strength		density	Strength	
kg/m^3	psi	MPa	kg/m^3	psi	MPa	kg/m^3	psi	MPa
-	724	4.99	-	959	6.61	-	647	4.46
-	980	6.76	-	909	6.27	-	909	6.27
-	946	6.53	-	1,101	7.59	-	799	5.51
1,784	1,071	7.38	-	1,040	7.17	-	909	6.27
1,770	893	6.16	1,845	954	6.58	1,882	560	3.86
1,820	1,134	7.82	1,791	688	4.74	1,911	767	5.29
1,799	852	5.87	1,836	828	5.71			
			1,806	767	5.29			

9.2 LAB MIX 2

3 inch			4 inch			6 inch		
Density	Strength		Density	Strength		Density	Strength	
kg/m^3	psi	MPa	kg/m^3	psi	MPa	kg/m^3	psi	MPa
1,950	2,278	15.71	2,006	2,250	15.51	2,031	2,417	16.67
1,993	2,313	15.95	2,109	1,862	12.84	2,022	2,383	16.43
2,014	2,383	16.43	1,991	2,197	15.15	2,021	2,233	15.40
2,007	2,601	17.93	1,985	2,244	15.47	1,982	2,150	14.82
1,935	2,365	16.31	1,958	1,965	13.55	1,988	2,200	15.17
1,871	1,951	13.45	1,927	1,912	13.18	1,977	1,875	12.93
1,871	1,802	12.42	1,873	1,463	10.09	1,987	2,418	16.67
1,899	1,819	12.54	1,909	1,764	12.16			
1,935	2,329	16.06						
1,928	2,207	15.22						

9.3 LAB MIX 3

4 inch		
density	strength	
kg/m^3	psi	MPa
2,156	3,409	23.51
2,170	3,535	24.37
2,149	3,208	22.12
2,143	3,323	22.91
2,147	3,141	21.66
2,156	3,292	22.70
2,127	2,974	20.51
2,164	3,308	22.81

9.4 LAB MIX 4

4 inch		
density	strength	
kg/m^3	psi	MPa
2,121	2,968	20.47
2,099	2,684	18.51
2,110	2,651	18.28
2,118	2,688	18.54
2,078	2,542	17.53
2,102	2,926	20.18

9.5 LAB MIX 5

4 inch		
density	strength	
kg/m^3	psi	MPa
2,108	3,660	25.23
2,166	3,891	26.83
2,141	3,523	24.29
2,145	3,782	26.08
2,157	4,366	30.10
2,144	4,141	28.55
2,103	3,788	26.12

9.6 LAB MIX 6

4 inch		
density	strength	
kg/m^3	psi	MPa
2,194	3,495	24.10
2,188	3,632	25.04
2,190	3,485	24.03
2,225	3,813	26.29
2,196	3,620	24.96
2,205	3,639	25.09
2,170	3,316	22.87
2,179	3,158	21.78
2,188	3,726	25.69

9.7 FIELD MIX					
3 inch			4 inch		
density	strength		density	strength	
kg/m^3	psi	MPa	kg/m^3	psi	MPa
1,964	2,972	20.49	2,085	2,712	18.70
1,993	2,950	20.34	2,067	2,699	18.61
1,971	2,460	16.96	2,073	2,713	18.71
1,928	2,174	14.99	2,070	2,746	18.93

APPENDIX C: HYDRAULIC CONDUCTIVITY TESTING & WINTER SURFACE APPLICATION DATA

10.1 LAB MIX 1					
3 inch					
density (kg/m^3)	w/o (cm/s)	w/o (in/hr)	w/sand (cm/s)	w/sand (in/hr)	% change
2,023	0.76	1,074	0.64	900	16.2
2,040	0.91	1,294	0.75	1,066	17.6
2,004	0.86	1,220	0.77	1,086	11.0
2,018	0.92	1,301	0.75	1,059	18.6
1,899	1.31	1,859	1.20	1,699	8.6
1,856	1.50	2,127	1.33	1,881	11.6
1,899	1.25	1,776	1.15	1,628	8.3
1,813	1.40	1,989	1.26	1786	10.2
4 inch					
density (kg/m^3)	w/o (cm/s)	w/o (in/hr)	w/sand (cm/s)	w/sand (in/hr)	% change
1,853	0.98	1,387	0.82	1,163	16.1
1,942	0.95	1,353	0.84	1,184	12.5
2,043	0.83	1,181	0.73	1,030	12.7
1,946	0.96	1,367	0.83	1,179	13.8
1,742	1.53	2,175	1.33	1,889	13.2
1,813	1.47	2,090	1.27	1,800	13.9
1,809	1.49	2,106	1.30	1,838	12.7
1,785	1.52	2,152	1.31	1,860	13.6
6 inch					
density (kg/m^3)	w/o (cm/s)	w/sand (in/hr)	w/sand (cm/s)	w/sand (in/hr)	% change
1,762	0.95	1,350	0.81	1,154	14.5
1,812	0.78	1,100	0.65	923	16.1
1,990	0.68	971	0.54	767	21.0
1,918	0.86	1,212	0.71	1,003	17.3

10.2 LAB MIX 2					
3 inch					
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**w/sand (cm/s)**	**w/sand (in/hr)**	**% change**
1,960	0.59	838	0.55	781	6.9
1,938	0.79	1,126	0.73	1,037	7.9
1,931	0.77	1,098	0.67	955	13.0
1,926	0.94	1,335	0.82	1,167	12.6
1,882	1.03	1,455	0.94	1,337	8.1
1,930	0.86	1,224	0.79	1,119	8.6
1,894	0.97	1,369	0.83	1,178	13.9
1,883	1.10	1,560	0.99	1,400	10.2
4 inch					
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**w/sand (cm/s)**	**w/sand (in/hr)**	**% change**
1,941	1.06	1,509	0.95	1,344	11.0
2,020	0.78	1,103	0.68	965	12.6
1,998	0.76	1,083	0.65	922	14.8
1,923	0.97	1,369	0.86	1,223	10.7
1,913	1.08	1,528	0.93	1,312	14.2
1,897	1.28	1,812	1.00	1,422	21.5
1,934	0.99	1,408	0.89	1,263	10.3
1,874	1.33	1,891	1.23	1,736	8.2
6 inch					
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**w/sand (cm/s)**	**w/sand (in/hr)**	**% change**
1,978	0.96	1,361	0.83	1,175	13.7
2,060	0.79	1,125	0.50	705	37.3
2,042	0.82	1,163	0.65	927	20.3
1,994	0.90	1,276	0.74	1,056	17.2
2,024	0.91	1,285	0.78	1,106	14.0
2,003	0.97	1,375	0.85	1,200	12.7
2,006	1.02	1,439	0.80	1,129	21.5

10.3 LAB MIX 3 4 inch					
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**w/sand (cm/s)**	**w/sand (in/hr)**	**% change**
2,079	0.28	403	0.20	288	28.6
2,015	0.25	360	0.21	297	17.5
2,058	0.33	465	0.28	393	15.4
2,042	0.36	508	0.34	479	5.7
2,061	0.37	526	0.32	457	13.1
2,056	0.35	489	0.27	385	21.3
2,060	0.31	441	0.25	357	19.0

10.4 LAB MIX 4 4 inch					
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**w/sand (cm/s)**	**w/sand (in/hr)**	**% change**
2,050	0.47	660	0.37	523	20.9
2,090	0.25	359	0.17	238	33.7
2,079	0.39	558	0.31	439	21.3
2,136	0.32	458	0.24	345	24.7
2,083	0.36	508	0.25	352	30.8
2,058	0.37	521	0.34	488	6.5

10.5 LAB MIX 5					
4 inch					
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**w/sand (cm/s)**	**w/sand (in/hr)**	**% change**
2,091	0.09	131	0.07	102	22.0
2,108	0.20	289	0.18	260	10.0
2,156	0.16	224	0.14	202	9.8
2,122	0.25	358	0.22	312	13.0
2,087	0.13	179	0.11	156	12.7
2,100	0.23	328	0.21	303	7.5

10.6 FIELD MIX					
3 inch					
density (kg/m^3)	w/o (cm/s)	**w/o (in/hr)**	**w/sand (cm/s)**	**w/sand (in/hr)**	**% change**
1,981	0.81	1,141	0.74	1,042	8.7
2,143	0.85	1,208	0.78	1,103	8.7
2,072	0.73	1,033	0.62	882	14.6
2,108	0.83	1,173	0.73	1,038	11.5
4 inch					
density (kg/m^3)	w/o (cm/s)	**w/o (in/hr)**	**w/sand (cm/s)**	**w/sand (in/hr)**	**% change**
1,845	1.38	1,957	1.13	1,607	17.9
1,894	1.00	1,415	0.80	1,141	19.3
2,027	0.72	1,018	0.62	874	14.1
1,985	0.64	905	0.56	789	12.9

APPENDIX D: MAXIMUM CLOGGING AND HYDRAULIC CONDUCTIVITY RECLAMATION DATA

11.1 Lab Mix 1 4 inch								
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**CLOGGED (cm/s)**	**CLOGGED (in/hr)**	**CLEANED (cm/s)**	**CLEANED (in/hr)**	**% change clogged**	**% change cleaned**
1,853	0.98	1,387	0.55	773	0.85	1,212	44.3	12.7
1,942	0.95	1,353	0.59	831	0.91	1,291	38.6	4.6
2,043	0.83	1,181	0.64	908	0.80	1,139	23.1	3.5
1,946	0.96	1,367	0.83	1,179	0.81	1,147	13.8	16.1
1,742	1.53	2,175	1.05	1,486	1.29	1,828	31.7	15.9
1,813	1.47	2,090	0.78	1,108	1.31	1,859	47.0	11.1
1,809	1.49	2,106	1.24	1,762	1.33	1,883	16.3	10.6
1,785	1.52	2,152	1.21	1,712	1.31	1,861	20.4	13.5

11.2 Lab Mix 2 4 inch								
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**CLOGGED (cm/s)**	**CLOGGED (in/hr)**	**CLEANED (cm/s)**	**CLEANED (in/hr)**	**% change clogged**	**% change cleaned**
1,941	1.06	1,509	0.82	1,160	1.03	1,461	23.2	3.2
2,020	0.78	1,103	0.55	780	0.76	1,074	29.3	2.7
1,998	0.76	1,083	0.53	758	0.75	1,057	30.0	2.4
1,923	0.97	1,369	0.64	903	0.93	1,325	34.0	3.2
1,913	1.08	1,528	0.66	930	1.01	1,432	39.2	6.3
1,897	1.28	1,812	0.61	866	1.09	1,551	52.2	14.4
1,934	0.99	1,408	0.70	997	0.98	1,393	29.2	1.0
1,874	1.33	1,891	0.61	866	1.29	1,826	54.2	3.5

11.3 Lab Mix 3 4 inch								
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**CLOGGED (cm/s)**	**CLOGGED (in/hr)**	**CLEANED (cm/s)**	**CLEANED (in/hr)**	**% change clog**	**% change clean**
2,079	0.28	403	0.02	25	0.26	369	93.9	8.3
2,015	0.25	360	0.18	255	0.24	337	29.1	6.4
2,058	0.33	465	0.25	350	0.30	431	24.7	7.3
2,042	0.36	508	0.31	437	0.35	502	13.9	1.1
2,061	0.37	526	0.29	405	0.37	521	23.1	1.0
2,056	0.35	489	0.25	348	0.33	472	28.8	3.4
2,060	0.31	441	0.22	309	0.30	429	30.0	2.8

11.4 Lab Mix 4 4 inch								
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**CLOGGED (cm/s)**	**CLOGGED (in/hr)**	**CLEANED (cm/s)**	**CLEANED (in/hr)**	**% change clog**	**% change clean**
2,050	0.47	660	0.30	418	0.44	623	36.7	5.6
2,090	0.25	359	0.15	215	0.24	338	39.9	5.8
2,079	0.39	558	0.21	301	0.33	474	46.0	15.1
2,136	0.32	458	0.21	291	0.30	419	36.5	8.5
2,083	0.36	508	0.22	313	0.35	491	38.3	3.4
2,058	0.37	521	0.20	290	0.34	482	44.4	7.5

11.5 Lab Mix 5 4 inch								
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**CLOGGED (cm/s)**	**CLOGGED (in/hr)**	**CLEANED (cm/s)**	**CLEANED (in/hr)**	**% change clog**	**% change clean**
2,091	0.09	131	0.01	21	0.08	110	84.0	15.9
2,108	0.20	289	0.02	22	0.16	226	92.4	21.7
2,156	0.16	224	0.12	173	0.15	209	23.1	6.9
2,122	0.25	358	0.20	285	0.25	353	20.5	1.4
2,087	0.13	179	0.10	145	0.08	119	19.0	33.7
2,100	0.23	328	0.17	239	0.21	293	27.0	10.5

11.6 Field Mix 4 inch								
density (kg/m^3)	**w/o (cm/s)**	**w/o (in/hr)**	**CLOGGED (cm/s)**	**CLOGGED (in/hr)**	**CLEANED (cm/s)**	**CLEANED (in/hr)**	**% change clog**	**% change clean**
1,845	1.38	1,957	1.10	1,565	1.24	1,762	20.0	9.9
1,894	1.00	1,415	0.76	1,080	0.78	1,108	23.7	21.7
2,027	0.72	1,018	0.60	850	0.60	847	16.5	16.8
1,985	0.64	905	0.53	749	0.50	711	17.3	21.4

APPENDIX E: PART NUMBERS AND DISTRIBUTORS

12.1 Falling Head Permeameters:

Permeameters were created using appropriately sized PVC piping, elbows, and connectors. Parts are available at local distributors such as Home Depot and Lowe's.

12.2 Field Permeameter:

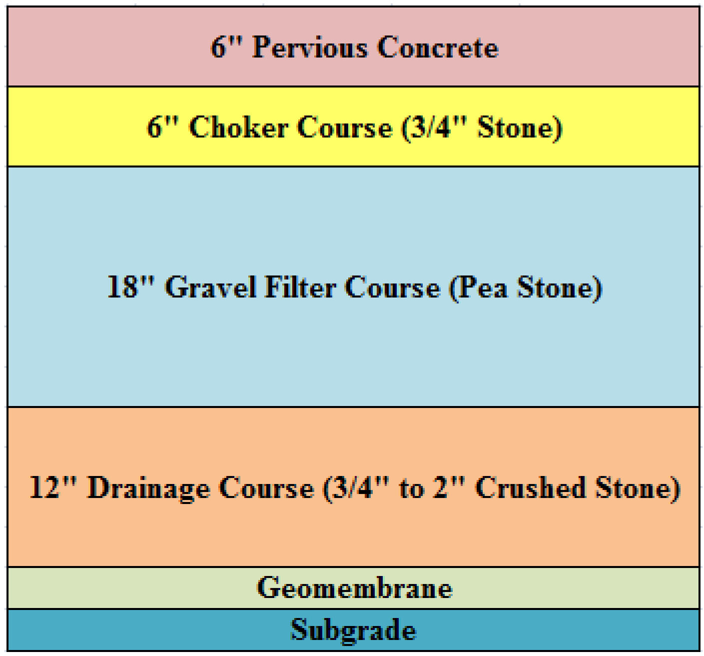
PVC standpipe obtained from local distributor. PVC base and foam rubber liner ordered from www.mcmaster.com. PVC base is part number 8747K152, description is GRAY PVC (TYPE I) SHEET, 3/4" THICK, 24" X 24". PVC base and the sight for the standpipe were milled at the University of Vermont by Floyd Vilmont.

12.3 Plow Apparatus:

Frame built using 80/20 extrusions. Design software for AutoCAD available at www.8020.net and is installed on several computers Votey 228. Extrusions, connectors, and hardware were ordered from a distributor, Action Automation & Controls (www.actionauto.com). Air cylinder and additional components were ordered from SMC Corporation of America (www.smcusa.com) through the local distributor Fastenal in Williston, VT. The plow blade was welded and assembled by Floyd Vilmont at the University of Vermont.

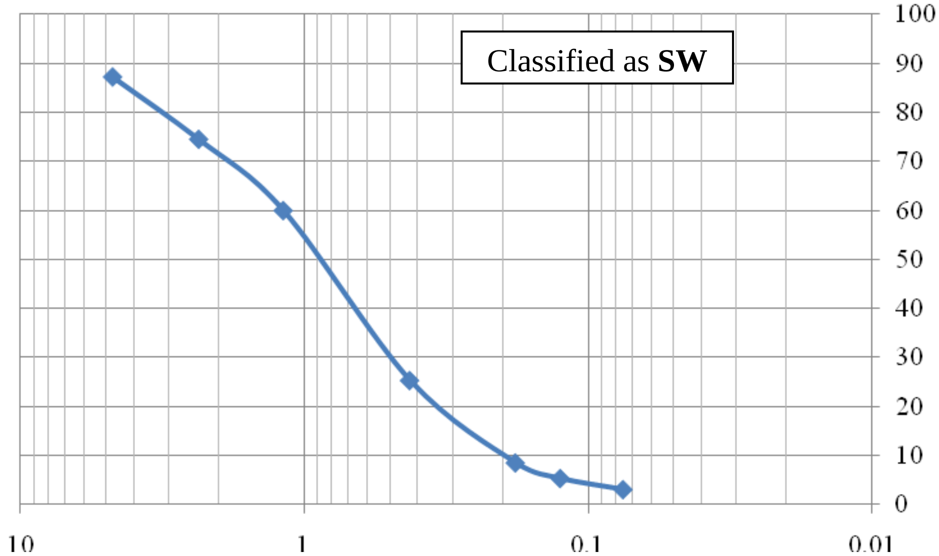
APPENDIX F: BURLINGTON, VT DESIGN

13.1 Pavement and Subbase design for lower College St. in Burlington, VT



APPENDIX G: SIEVE ANALYSIS FOR WINTER SURFACE APPLICATIONS

14.1 Sieve Analysis for Sand Obtained from Montpelier Town Garage



14.2 Sieve Analysis for Salt Obtained from Montpelier Town Garage