Porous Concrete Pavements: Mechanical and Hydraulic Properties

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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.

Key Words: Porous concrete, Pervious Concrete, Size effects, Compressive strength, Hydraulic conductivity

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.

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.

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).

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).

RESEARCH METHODS

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

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 1.

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 1, along with the mix design used in the field.

Table 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)
LAB-1	374	1,660	94	77.4	488	1,180	1,180
LAB-2	374	1,660	109	77.4	488	1,180	1,180
LAB-3	374	1,660	124	77.4	488	1,180	1,180
LAB-4	374	1,660	124	77.4	-	1,180	1,180
LAB-5	374	1,660	124	-	488	1,180	1,180
FIELD*	374	1,660	109	77.4	488	1,180	1,180

*****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 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.

Test Procedures

Compressive Strength

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

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

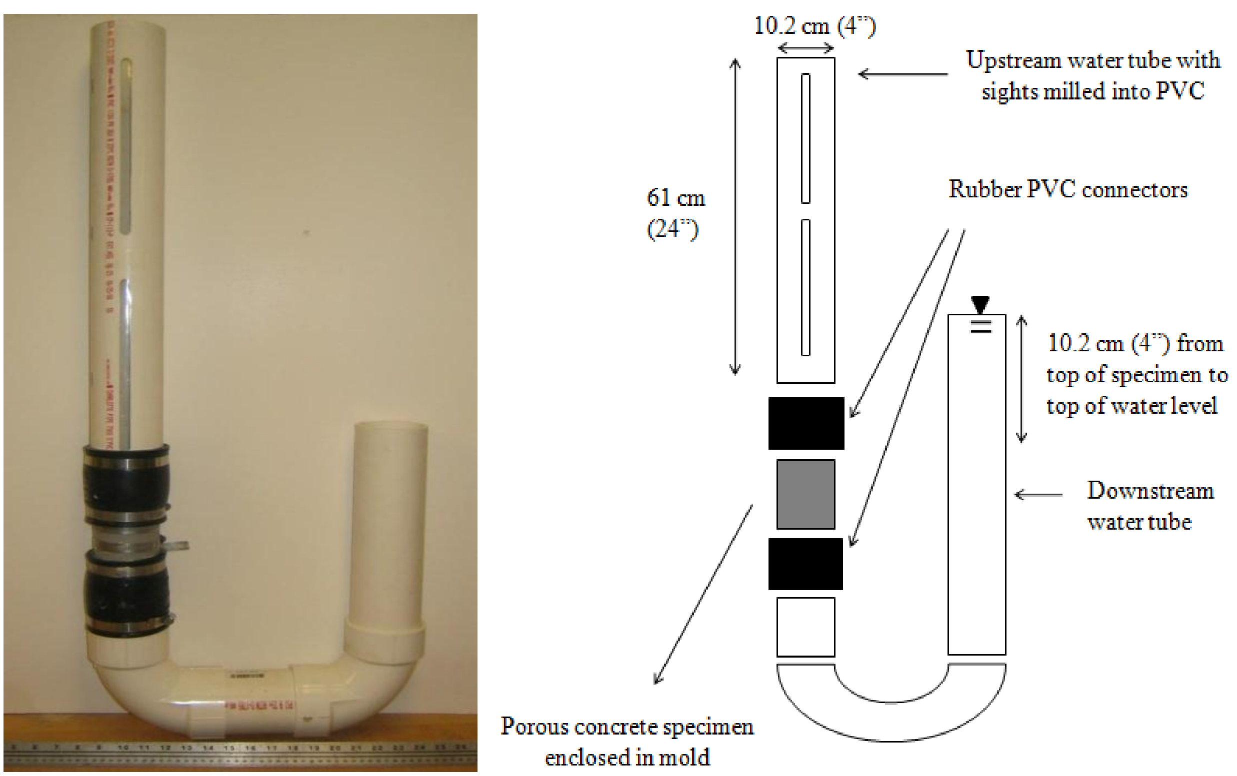

Figure 1: Falling head permeameter used for 10.2 cm (4") diameter specimens. Photo (left), Schematic (right)

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).

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.

Size Effects

The effects of sample size were evaluated for Lab Mix 2 and are shown in Figure 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.

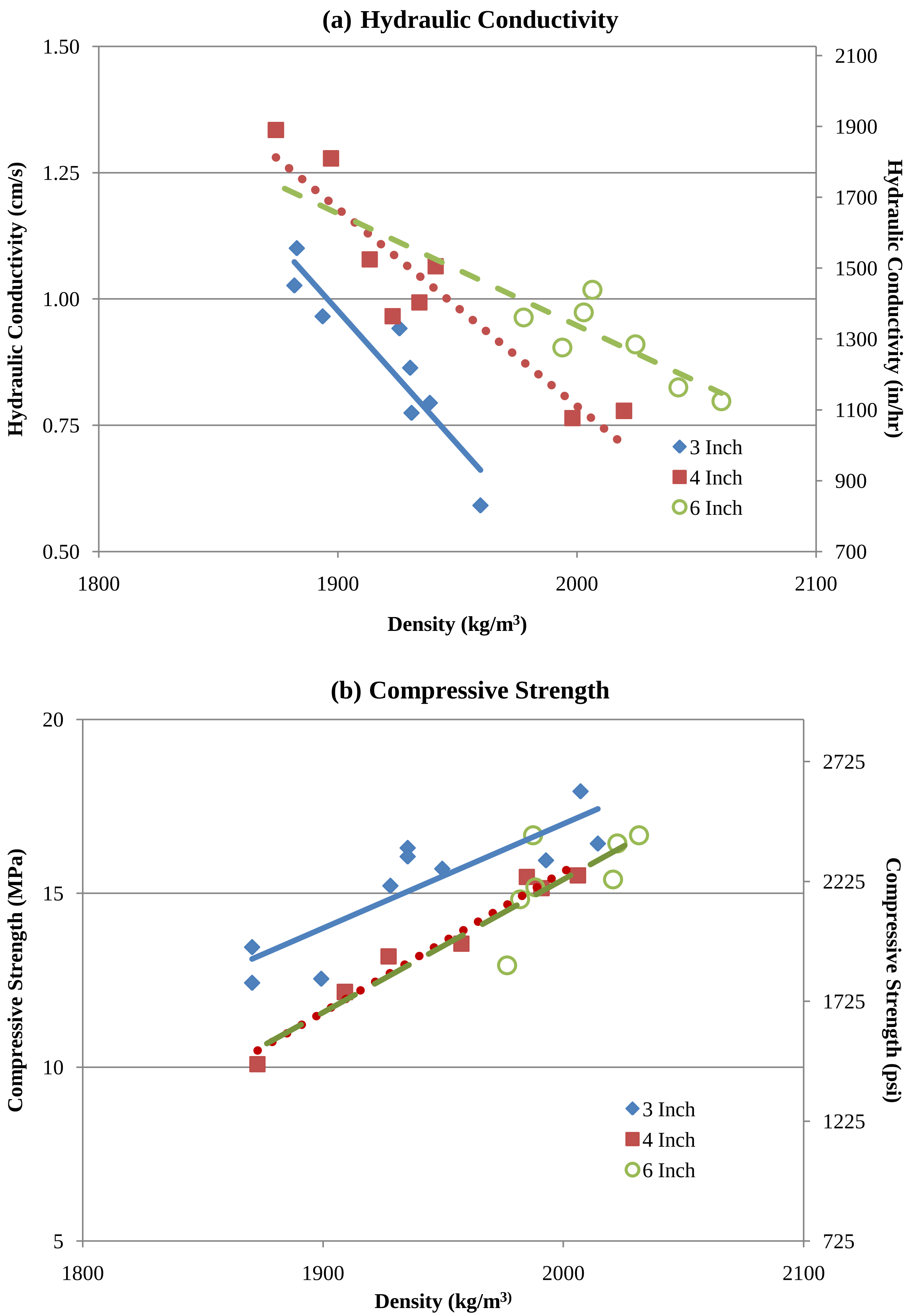

Figure 2: Specimen Size Effects (Data from Lab Mix 2)

Strength

The results of the 28-day compressive strength tests for all mix designs are summarized in Table 2 and Figure 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. Table 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 interface, 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 2: 28-day Compressive Strength Values

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

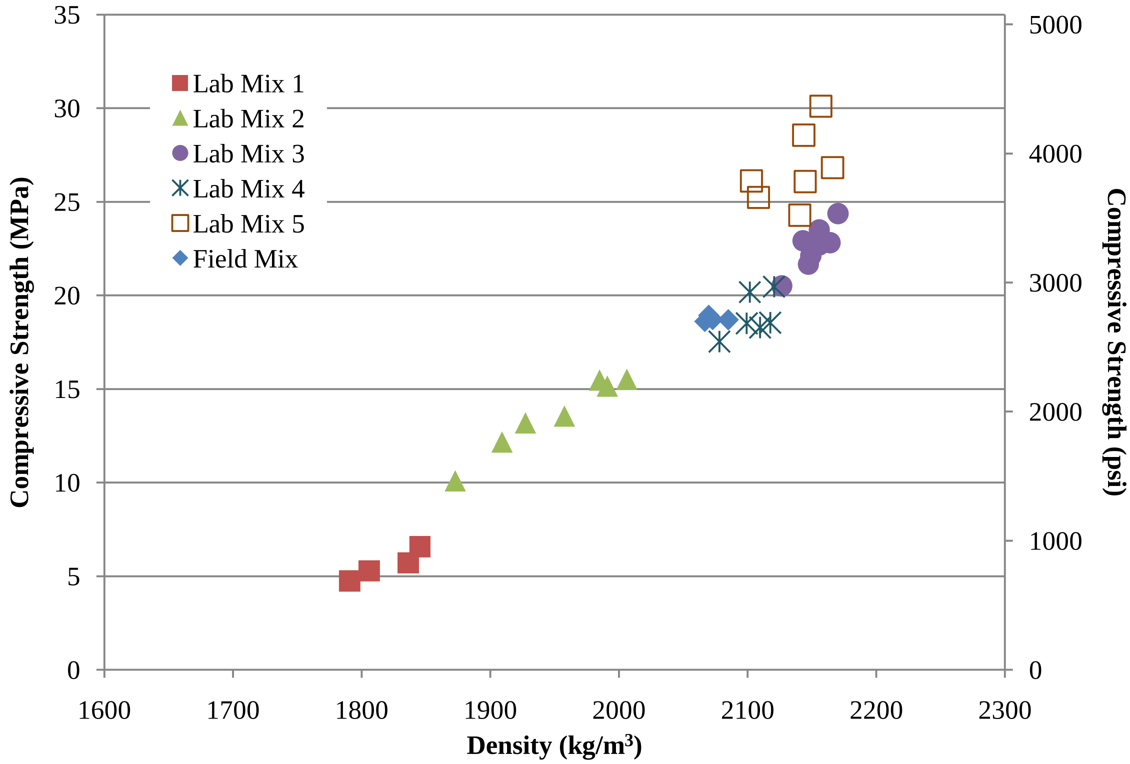

Figure 3: 28-day Compressive Strength

Hydraulic Conductivity

Table 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 4. Figure 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: Falling Head Test Results

Mix	Ave. Dry Density	Ave. Hydraulic Conductivity	
	(kg/m^3)	(cm/s)	(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

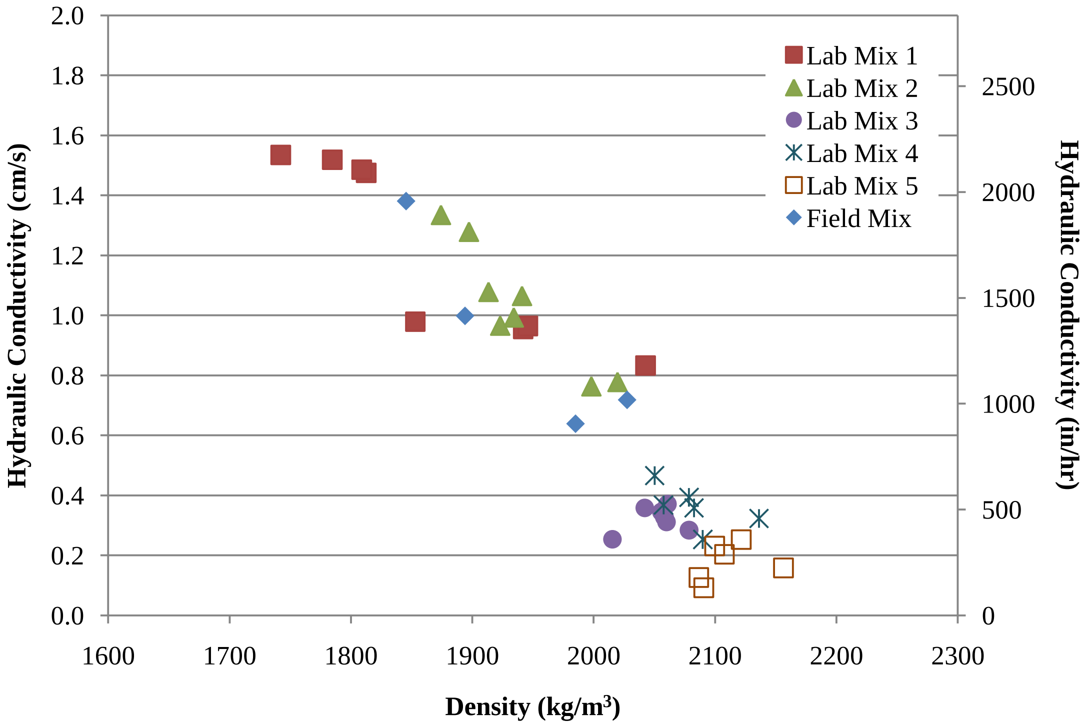

Figure 4: Hydraulic Conductivity for Laboratory Specimens

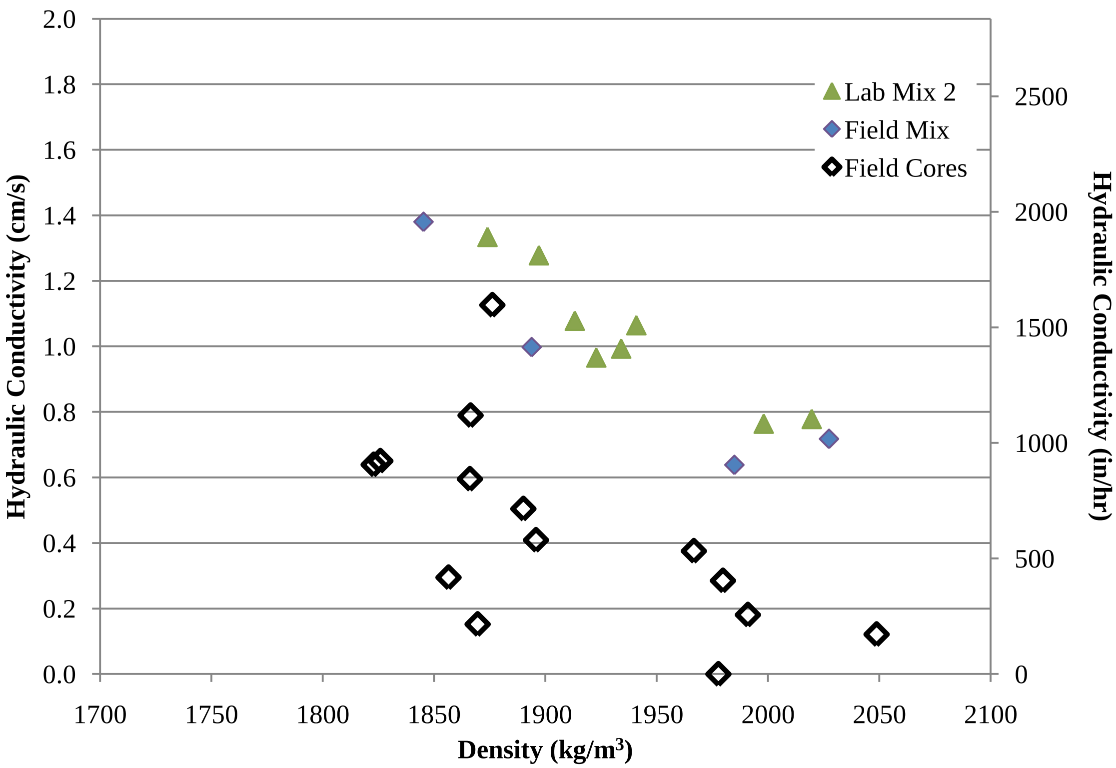

Figure 5: Hydraulic Conductivity Laboratory and Field Comparison

DISCUSSION

Size Effects

In examining Figure 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.

Effects of Density

Figures 3 and 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.

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 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 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.

Effects of Admixtures

Lab Mixes 3-5 investigated the role of two admixtures, HRWR and AEA. Figures 3 and 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.

Field Comparisons

Comparison of Lab Mix 2, the Field Mix, and the field cores shown in Figure 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 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 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 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.

Comparison to Literature

Figures 6 and 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 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.

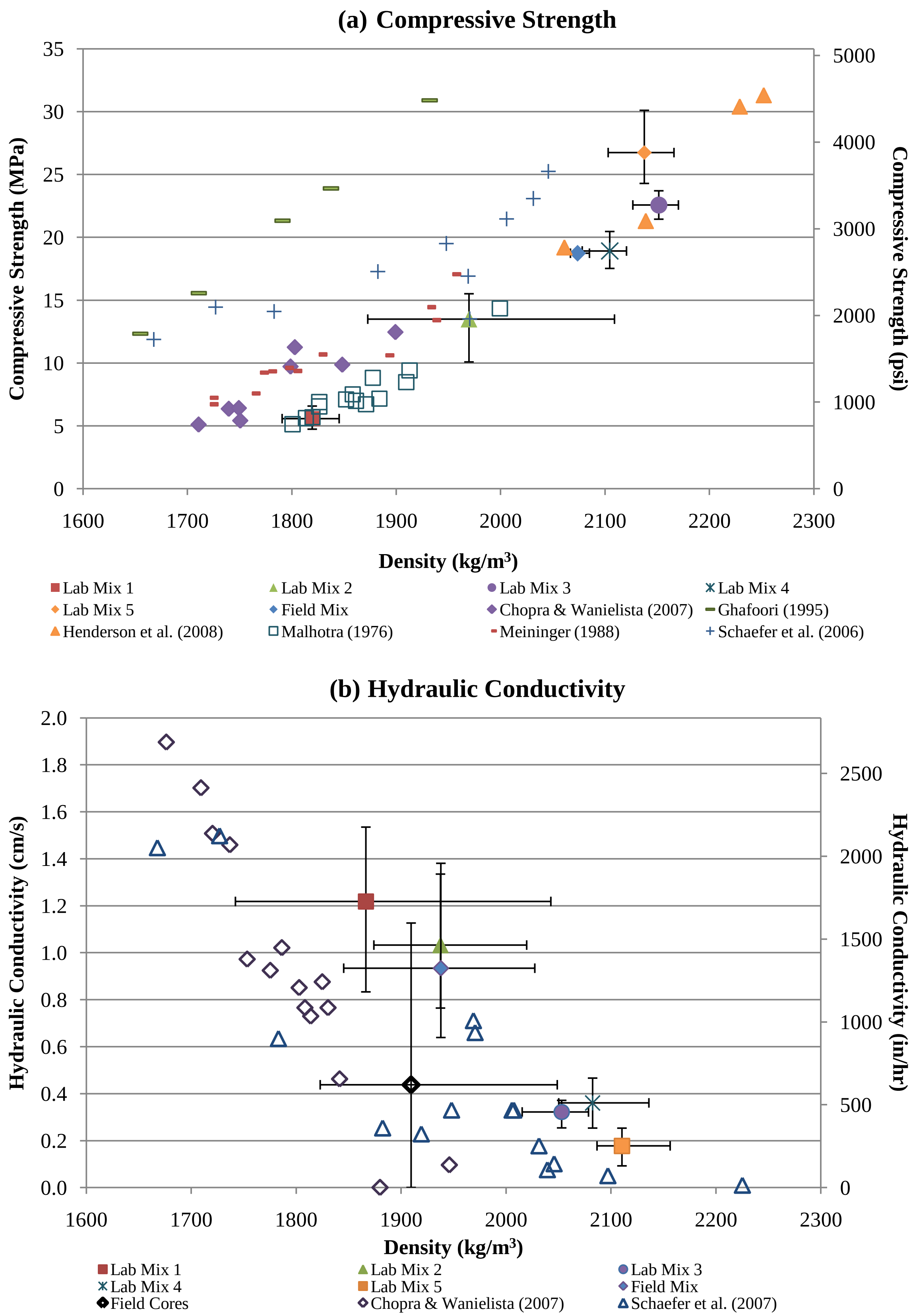

Figure 6: Comparison with Reported Values

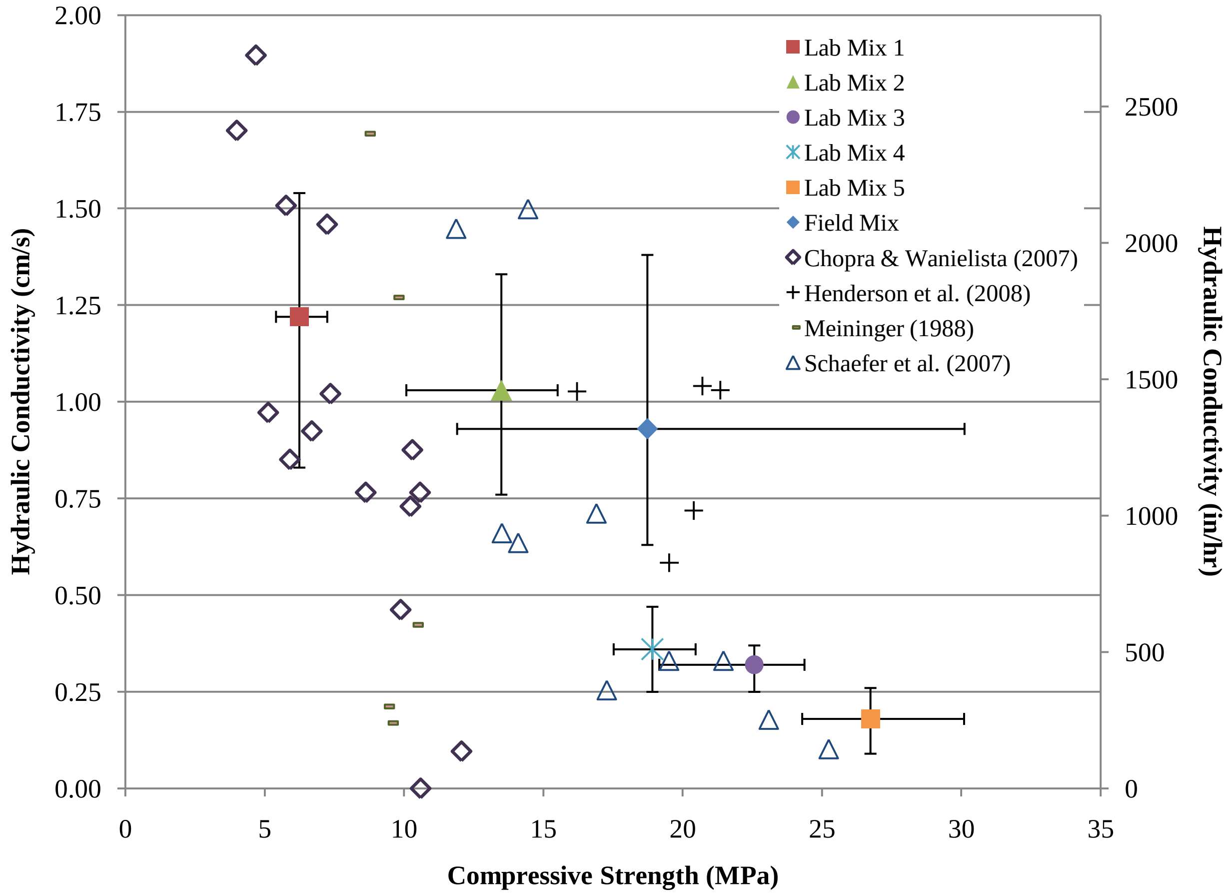

Figure 7: Relationship between Hydraulic Conductivity and Compressive Strength

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 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.

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