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Portland Cement Pervious Concrete Pavement:

Field Performance Investigation on Parking Lot and Roadway Pavements

Final Report

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Report to the RMC Research & Education Foundation

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ABSTRACT

Portland Cement Pervious Concrete (PCPC) has an excellent performance history in the Southeastern U.S., but until recently has seen little use in environments with significant freeze-thaw cycles. Therefore, assessment of actual field performance is important. This project documents field observations, and nondestructive testing results of PCPC sites located in the states of Ohio, Kentucky, Indiana, Colorado, and Pennsylvania. PCPC is most often used as a pavement for parking lots. Field performance depends on the quality of the mixture as well as proper control of construction and curing. In addition to field observations and nondestructive testing, laboratory testing was performed on cores removed from some of the test sites. Generally, the PCPC installations evaluated have performed well in freeze-thaw environments, with little maintenance required.

Construction, use, and maintenance information was obtained during the site visits. The field investigation plan encompassed a thorough visual inspection for signs of distress, two types of surface infiltration measurements, and ultrasonic pulse velocity (UPV) testing at the Ohio, Kentucky, and Indiana sites. At the Colorado and Pennsylvania sites, only one type of surface infiltration test was made. Visual inspection documented cracking and surface raveling, as well as areas that appeared to be clogged. One type of field infiltration test, developed during this research project, used the time to drain a 4 by 8 inch plastic cylinder through a ¾ inch hole down into the pavement. The second test was used to identify whether pavements required maintenance. The UPV was used in indirect transmission mode, because only the surface of the pavement was accessible.

At six of the sites, it was possible to extract cores for laboratory testing. The cores were brought back to the laboratory and tested for void ratio, hydraulic conductivity, and direct transmission UPV. Direct transmission is considered to be more reliable than indirect transmission for UPV. Once these tests were completed, some of the specimens were tested for compressive or splitting tensile strength. Some of the cores were cut into top and bottom specimens, to compare the properties through the pavement thickness. The data are recorded in tables and plots. Significant differences were observed between cores from pavements that used gravel and crushed limestone coarse aggregates. The use of gravel as a coarse aggregate may facilitate more effective and uniform compaction. The laboratory hydraulic conductivity results were plotted against the field drainage times, so that in the future the field test may be used to estimate PCPC infiltration capability.

The installations have not shown any signs of freeze-thaw damage. Some pavements have had surface raveling, which generally stops after a few months of use. Saw cut joints had less raveling than tooled joints. A few have cracks, which may be attributed to overloading or long spaces between joints. Some of the pavements had very poor infiltration capability due to improper installation.

Most of the installations are performing well, but it is also true that many in the area are relatively new. Therefore, they should be examined again in the future, probably at 5 and 10 years from the publication of this report. This report serves as a benchmark of the pavement condition observed at the time of this study.

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Portland Cement Pervious Concrete (PCPC) has an excellent performance history in the Southeastern U.S., but until recently has seen limited use in environments with significant freeze-thaw cycles. Therefore, assessment of actual field performance is important. This project documents field observations, and nondestructive testing results of PCPC sites located in the states of Ohio, Kentucky, Indiana, Colorado, and Pennsylvania. PCPC is most often used as a pavement for parking lots. Field performance depends on the quality of the mixture as well as proper control of construction and curing. In addition to field observations and nondestructive testing, laboratory testing was performed on cores removed from some of the test sites. Generally, the PCPC installations evaluated have performed well in freeze-thaw environments with little maintenance required.

The research goals included developing recommendations as to how to build PCPC pavements in freeze-thaw environments, and how to prevent clogging. Observations suggest that providing sufficient drainage under PCPC pavements to keep them from becoming saturated in freezing weather, as recommended by the NRMCA, is likely to be effective. Site specific observations of clogging patterns provided insight into sources of clogging, and how these may be avoided.

Construction, use, and maintenance information was obtained during the site visits. This included mixture constituents and proportions, admixtures, type of compaction used, and any difficulties noted during construction. Most of the sites had not yet had maintenance treatments performed. Information about vehicle traffic, including heavy vehicle overloads, was also obtained.

The field investigation plan encompassed a thorough visual inspection for signs of distress, two types of surface infiltration measurements, and ultrasonic pulse velocity (UPV) testing at the Ohio, Kentucky, and Indiana sites. At the Colorado and Pennsylvania sites, only one type of surface infiltration test was made. Visual inspection documented cracking and surface raveling, as well as areas that appeared to be clogged. One type of field infiltration test, developed during this research project, used the time to drain a 4 by 8 inch plastic cylinder through a ¾ inch hole down into the pavement. The second test was used to identify whether pavements required maintenance. The UPV was used in indirect transmission mode, because only the surface of the pavement was accessible.

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facilitate more effective and uniform compaction. The hydraulic conductivity results were plotted against the drainage times, so that in the future the field test may be used to estimate PCPC infiltration capability.

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The installations are generally performing well, but it is also true that many that were evaluated are relatively new. Therefore, they should be examined again in the future, probably at 5 and 10 years from the publication of this report. This report serves as a benchmark of the pavement condition observed at the time of this study.

More information is provided in two MSCE Theses published in December 2007 at Cleveland State University. These may be obtained as PDF files by emailing n.delatte@csuohio.edu.

- Miller, Dan (2007) *Field Performance of PCPC Pavements in Severe Freeze-Thaw Environments,* MSCE Thesis, Cleveland State University, December 2007.

- Mrkajic, Aleksandar (2007) *Investigation and Evaluation of PCPC using Non-Destructive Testing and Laboratory Evaluation of Field Samples,* MSCE Thesis, Cleveland State University, December 2007.

CHAPTER 1: INTRODUCTION

Interest and use of portland cement pervious concrete (PCPC) pavements is increasing in climates subject to severe winter environmental conditions. Because much of the experience with these pavements has been in warmer climates, some questions have been raised as to the durability of the material under freeze-thaw attack. Although some laboratory tests suggest that PCPC is not freeze-thaw durable when saturated, proper design can insure the concrete is not saturated under field conditions. The best predictor of future field performance is actual past field performance.

In Northeast Ohio, interest in pervious concrete has been increasing. Extensive flooding in this region during the summer of 2006 will no doubt increase the level of interest substantially. Several demonstration projects have been completed.

This research was carried out by visiting pervious concrete installations and performing visual and non-destructive testing to assess infiltration capability, in-field strength and consistency, and long-term durability. Approximately two dozen pervious concrete installations were visited in order to assess their field performance. At some of the sites, it was possible to extract cores for subsequent laboratory testing.

Many of the PCPC installations visited were in Ohio and Indiana, which are subject to severe freeze-thaw cycling. The pavements are often subjected to plowing, salting, and sanding during the winter. The winter maintenance treatments have potential for causing damage to PCPC pavements.

Methods for field and laboratory testing of PCPC are in various stages of development. During the field visits, detailed visual inspections provided a lot of information, particularly about the structural and surface condition. Hydraulic conductivity, drain test, and infiltration rate test were performed to estimate water infiltration and clogging. Ultrasonic pulse velocity (UPV) tests were also performed on the surface, in order to estimate void ratio and compressive strength.

The potential for clogging of these pavements is also a consideration, because if they become totally or nearly totally clogged they would be greatly less effective in handling storm water. Some of the pavements evaluated in this study had very poor drain times. Attempts were made to determine whether this was the result of improper installation, or due instead to clogging by debris over time. Few of the pavements had had any maintenance performed since construction.

This report provides much of the data and conclusions from this research. More detailed observations, photographs, and raw data are provided in two companion documents, Miller (2007) and Mrkajic (2007).

Goals and Objectives

The main objective of this study was to document the performance of pervious concrete pavements in freeze-thaw environments, in order to provide guidance as to how to construct durable PCPC pavements in these climates. The secondary objective was to evaluate clogging of these pavements, and to estimate the effectiveness of maintenance procedures for restoring infiltration capability to clogged installations where no preventive maintenance program was enacted.

Significance of the Project

This project will help facilitate broader use of pervious concrete for pavements throughout North-America. This technology has been widely used across the southeastern U.S., particularly in Georgia and Florida. As the use expands into regions where pavements are susceptible to freezing and thawing, questions of durability must be addressed. Other field performance issues, such as clogging, are of interest in all regions.

Organization of this Report

This report is divided into seven chapters, including this introduction. Chapter 2 provides the literature review. Chapter 3 documents the information available on existing projects, and lists the projects selected for site visits. The field investigation techniques used in the visits are discussed in Chapter 4. Observations from the site visits are provided in Chapter 5. Chapter 6 discusses the results from field and laboratory testing. Finally, the summary and conclusions are provided in Chapter 7.

CHAPTER 2: LITERATURE REVIEW

The literature search included reviews of published and unpublished literature, field performance reports, and other published and unpublished documents. Quite a lot has been published over the last two years about PCPC. An extensive bibliography is provided at the end of this report. However, the literature on field performance remains limited.

Pervious Pavement Systems, Durability, and Environment

When assessing the durability of pervious concrete pavements in cold climates, there are two aspects that may be considered. One is the durability of the pervious concrete itself, as tested in a saturated state by ASTM C 666 Procedure A, with or without modification. This test is harsh, and it has been recognized for some time that some pervious concrete or roller compacted concrete mixtures perform poorly in ASTM C 666 despite the fact that the same mixtures may have a satisfactory field performance record. Clearly, however, a pervious concrete mixture that passes ASTM C 666 will be durable in the field. This would typically require air entrained paste.

The other aspect is the durability of the system. If the pavement system drains well enough to keep the pervious concrete from being saturated, then the harsh conditions represented by the ASTM C 666 test do not apply. This is, therefore, the goal of the system design.

The NRMCA has defined four exposure climate categories based on moisture (wet or dry) and temperature (freeze or hard freeze). The categories and recommended precautions are described below (NRMCA 2004 pp. 2 – 3). Ohio, Indiana, and most of the other areas covered by this report would be considered Hard Wet Freeze.

Dry Freeze and Hard Dry Freeze

Dry freeze are areas of the country that undergo a number of freeze-thaw cycles (15+) annually but there is little precipitation during the winter. If the ground stays frozen as a result of a long continuous period of average daily temperatures below freezing, then the area is referred to as hard dry freeze area. Since pervious concrete is unlikely to be fully saturated in this environment, no special precaution is necessary for successful performance of pervious concrete. However, a 4– to 8–in. thick layer of clean aggregate base below the pervious concrete is recommended as an additional storage for the water. Many parts of the Western USA at higher elevations come under this category.

Wet Freeze

This includes areas of the country that undergo a number of freeze-thaw cycles annually (15+) and there is precipitation during the winter. Since the ground does not stay frozen for long periods it is unlikely that the pervious concrete will be fully saturated. No special precaution is necessary for successful performance of pervious concrete but a 4 to 8-in. thick layer of clean aggregate base below the pervious concrete is recommended. Many parts of the middle part of the Eastern United States come under this category.

Hard Wet Freeze

Certain wet freeze areas where the ground stays frozen as a result of a long continuous period of average daily temperatures below freezing are referred to as hard wet freeze areas. These areas may have situations where the pervious concrete becomes fully saturated. The following precautions are recommended to enhance the freeze-thaw resistance of pervious concrete: 1. Use an 8- to 24-in. thick layer of clean aggregate base below the pervious concrete; 2. Attempt to protect the paste by incorporating air-entraining admixture in the pervious mixture; 3. Place a perforated PVC pipe in the aggregate base to capture all the water and let it drain. Not every situation warrants all the 3 safeguards. The safeguards are organized in the order of preference."

Design Elements

Elements of the design of pervious concrete pavement systems include pavement thickness, joint spacing, and drainage details (design of open or closed system). For parking lots, a pavement thickness of 6 inches has typically been used. Thicker pavements have been used where heavy traffic is anticipated. Joint spacing is generally about 20 feet, although some pavements have been built without joints (Tennis et al. 2004). Overall site layout is also important.

Pervious pavement systems may be open or closed, depending on the type of underlying soil. Open systems, preferred for groundwater recharge, allow water to pass through into the underlying soil. Closed systems, where an impermeable membrane is placed under the subbase to direct water to pipes, may be preferred in some cases. This represents a particularly conservative approach if there are concerns about water quality in the soil or about increasing moisture levels under adjacent pavements, or if the underlying soil is clay. Figure 1 and Figure 2 illustrate a closed system.

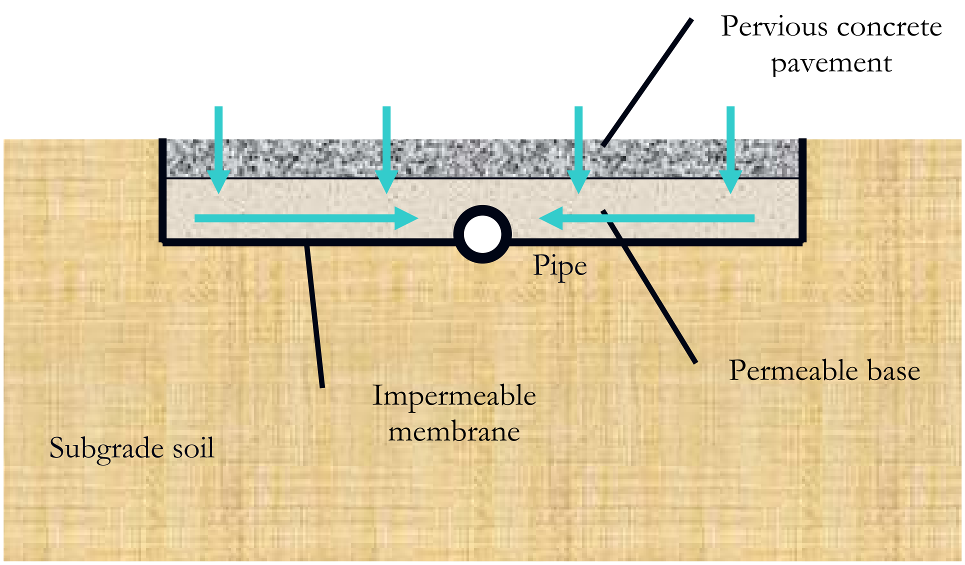

Figure 1: Pervious Concrete Pavement as a Closed System

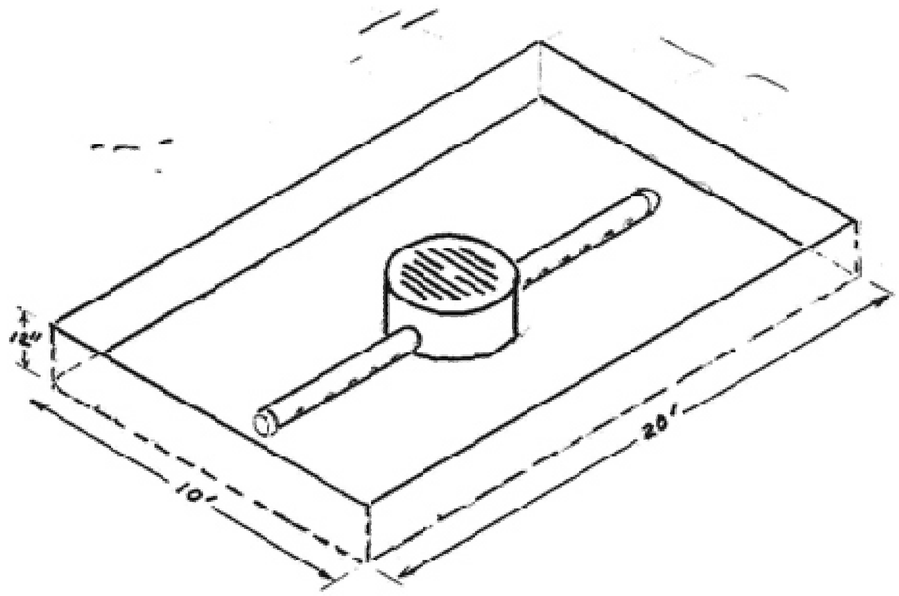

Figure 2: Miniature Storm Water Detention System (figure courtesy ORMCA)

The overall site layout refers to whether the pervious pavement drains itself only, or whether it also drains adjacent impervious pavement, such as conventional asphalt and concrete. A system such as that shown in Figure 2 can drain a large area of impervious pavement, but may be prone to clogging from the debris carried onto it. Nearby landscaping may be a source of loose soil that may clog a pervious pavement. Care should be taken to prevent muddy water from flowing onto pervious concrete.

Pervious Concrete Materials and Mixtures

Schaefer et al. (2006) provide considerable information on developing durable PCPC mixtures. Pervious concrete is a mixture of coarse aggregate, cement, water, and possibly admixtures. PCPC typically has zero to one inch slump and water to cement ratio between 0.25 and 0.35 (Schaefer et al. 2006). Fine aggregates may be added to improve strength. Although, the use of natural sand can improve strength, at the same time it reduces infiltration capability. Table 1 shows typical pervious concrete mixture designs used in the United States.

Table 1: Typical mixture designs for PCPC in the United States (NRMCA 2004)

Constituent or Property	Typical Range
Cement Content	300 to 600 lbs/yd^3
Coarse Aggregate Content	2,400 to 2,700 lbs/yd^3
Fine Aggregate Content	None
Water-Cement Ratio	0.27 to 0.43

Aggregates

Limestones or rounded river gravels are typically used as the coarse aggregates. The size and shape of coarse aggregates have significant influence on strength, and infiltration capability of PCPC. Cement is typically either type I or type II portland cement, depending on location and availability. Clean coarse aggregate and potable water promote bonding, ensuring strength and durability (Schaefer et al. 2006).

The single sized aggregates used in the PCPC mixtures typically range from those retained on No. 4 (3/16-in) sieve up to ¾-inch aggregates. Coarse aggregate gradations commonly follow ASTM C 33 standards; No. 67, No. 8, and No. 89. Larger gradations provide a rougher surface, frequently smaller sized aggregates are used for aesthetic purposes. Higher strengths are generally achieved with rounded gravels (Tennis et al. 2004).

Admixtures

In many cases, admixtures are used to improve pervious concrete properties. High range water reducers (HRWR) may be used to improve paste appearance (sheen) and workability. Special consideration must be provided in obtaining dosage quantities, since paste could become very fluid, with a tendency to segregate at the bottom of the sample (Flores et al. 2006). This phenomenon is called drain down (Crouch et al. 2006).

Hydration controlling admixtures (HCA) slow the rate of hydration and extend the life of fresh pervious concrete. At ambient temperature conditions, a dosage of 5 fl oz/cwt of the HCA provides between 60 and 90 minutes of extra working time. Hydration controlling admixtures can eliminate inconsistencies and performance variability that may be brought on by the need to re-temper mixtures at the job sites (Bury et al. 2006).

Along with the HCA, VMA or viscosity modifying admixtures may be beneficial to the performance of pervious concrete. The use of VMAs results in better flow, quicker discharge time from a truck, and easier placement and compaction. Furthermore, VMAs prevent drain down, and may increase both compressive and flexural strength of pervious concrete. It should be noted that not all VMAs are made with pervious concrete in mind, and therefore, care should be taken when choosing the right VMA for pervious installation (Bury et al. 2006).

In California, Youngs (2006) reported that latex modifiers allowed harder surface finishing using Bunyan screeds, which in return produced “table-top” surface, and almost eradicated surface raveling. Latex modifiers assist in binding the cement paste to the aggregate. Mixtures with latex modifiers might allow utilization of pervious concrete in high speed pavement applications (Youngs 2006).

Consideration of Subgrade Type

Early pervious concrete pavements were built on freely draining sandy soils, so that the water could flow straight through the pavement and into the soil. If, however, the soil does not drain well, an open graded crushed stone reservoir base may be placed under the pavement to retain water. This technique may also be used to keep the pervious concrete dry where there is a risk of freeze-thaw damage. These types of installations, where the water flows directly downward through the pavement layers, may be referred to as open systems. NRMCA has published software for analyzing hydraulic performance of open systems.

However, at many of the sites visited during this study, the soils drain very poorly. If this is the case, a closed system, as shown in Figure 1, may be used. After passing through the pavement and the base, water is directed by an impermeable geotextile into a slotted drain pipe, which leads into the storm sewer system. Because a closed system can retain a considerable amount of water, it is a useful design for preventing local flooding. This type of installation was used at the Cleveland State University Lot D demonstration site.

In cases where a small pervious concrete installation is used to enhance the drainage of a large parking lot, a closed system may be modified by using a deeper stone reservoir, perhaps several feet deep. This concept was developed by the Ohio Ready Mixed Concrete Association as a miniature storm water detention system (Figure 2), which is discussed in more detail at http://www.ohioconcrete.org/Pervious%20Concrete.htm.

This type of installation has been used at the Cleveland State University Administration Building parking lot, built in July 2007, as well as in four small strips on city streets in Seven Hills, Ohio, a suburb of Cleveland. These small strips, installed in October 2007, are used to intercept storm water flowing longitudinally down residential streets in order to prevent flooding of homes and basements.

Construction Processes

The quality of PCPC installed depends in large part on the training and experience of the installer. Therefore, contractor certification has important implications for performance. The pervious concrete must be compacted properly and quickly protected.

Typical field quality control tests for conventional concrete, such as slump and air content, are not useful for pervious concrete. The unit weight test has been used as a measure of consistency (Tennis et al. 2004). Visual observation is also useful as an indicator of the consistency of the paste film on the surface of the aggregates.

Static and vibrating rollers and screeds may be used to compact pervious concrete. If the concrete is not compacted well enough, or is placed too dry, the aggregates will not bond well and the pavement will be susceptible to raveling. If, on the other hand, the concrete is placed too wet or is overcompacted, the surface will be sealed and the pavement will not be permeable. Once the pavement has been placed and compacted, joints may be installed with a jointing tool. Alternatively, the joints may be saw cut later.

Due to the open nature of pervious concrete, it must be protected from drying out. Plastic should be placed and secured on the surface as soon as possible following the placement, and kept in place for seven days. If the pervious concrete dries out prematurely, this would be likely to promote severe raveling.

Freeze-Thaw Durability

Several references address the topic of freeze-thaw durability. Laboratory work on freeze-thaw durability has been undertaken at Iowa State University (Scheafer et al. 2006) and by BASF/Master Builders/degussa (2005).

Freeze and thaw damage developed in PCPC is primarily in form of paste deterioration (Yang et al. 2006). In cold weather climate, 4% to 8% air entrainment should provide satisfactory freeze-thaw resistance (Schaefer et al. 2006).

Lack of data and lack of consensus on proper laboratory testing methods is the main obstacle that prevents use of PCPC in cold weather regions (Schaefer et al. 2006). Yang et al. (2006, p. 14) reported a few key ways moisture conditions influence the freeze and thaw durability of PCPC. "Partially saturated pervious concrete exhibited high durability when it is frozen and thawed in air. The practical implication of this finding is that in the field, pervious concrete is durable to cyclic freezing and thawing when there is no continuous water uptake. However, precipitation may be retained in pervious concrete when there is clogging or the subbase stays frozen in cold climate. Once the pore and air void system in the paste reaches its critical degree of saturation, further freezing would induce damage."

As with numerous other testing methods which work well on conventional PCC, standardized testing by ASTM C 666 may not represent actual field conditions as the large open voids are kept saturated during the test, and the rate of freeze/thaw is much too rapid (Tennis et al. 2004). Even after 80 cycles of slow freezing and thawing (one cycle/day), PCPC maintained more than 95% of relative dynamic modulus, while testing at a much quicker rate (five to six cycles/day), mixtures showed less than 50% relative dynamic modulus. Furthermore, the rapid draining characteristic of PCPC should lead to better performance in the field than in the laboratory. It is recommended that in freeze-thaw environment a minimum of 6 in. of a drainable rock base, such as 1-in. crushed stone, should be installed (Tennis et al. 2004).

PCPC failure when subjected to freeze-thaw cycles is a result of either aggregate deterioration or cement paste failure. Mixtures containing limestone failed through deterioration of the aggregate, but mixtures containing smaller size river gravel failed due to aggregate deterioration and splitting. Better freeze-thaw resistance was shown in mixtures that contained sand and/or latex than those that did not. The best performance, with 2% mass loss after 300 cycles, was observed in mixtures that contained single sized river gravel with 7% sand replacement (by weight of the coarse aggregate).

Low compaction energy led to failure through aggregate and paste, while samples prepared at regular compaction energy failed through the aggregate. Compaction energy seemed to have a significant effect on the freeze-thaw durability of PCPC. Freeze-thaw test results indicate that a mass loss of about 15% represents a terminal serviceability level for a pavement surface. Iowa State results suggest that well designed pervious concrete mixtures can meet the strength, infiltration capability, and freeze-thaw resistance requirements for cold weather climates (Schaefer et al. 2006).

Clogging

Clogging may occur on the surface due to debris or from the bottom (in the base) due to penetration of fines into the drainable base. Only the first can be readily observed from the surface. Subsurface clogging is generally addressed through filter fabrics, and the condition of these cannot be inspected without removing part of the pavement.

Maintenance such as annual vacuuming or pressure washing is recommended to remove surface debris and restore infiltration capability (Tennis et al. 2004, p. 21). Haselbach et al. (2006) have addressed sand clogging of pervious pavement.

Books and Reports

A number of books and reports have been published about porous and pervious pavements in general and pervious concrete pavements in particular. These are listed in the "Books and Reports" section of the "References and Bibliography" section in this interim report.

Ferguson's *Porous Pavements* addresses all types of these pavements, with a chapter specifically on pervious concrete (Ferguson 2005). The most comprehensive reports specifically on pervious concrete pavements are *Pervious Concrete Pavements* by Tennis et al. (2004), published by PCA, and ACI 522R-06 *Pervious Concrete* (ACI Committee 522 2006).

Issues of freeze-thaw durability have been addressed by the NRMCA report *Freeze Thaw Resistance of Pervious Concrete* (NRMCA 2004) and by materials in a binder assembled by Master Builders/degussa *Product Information: Pervious Concrete* (Master Builders/degussa 2005). The Mindess et al. book *Concrete* (2003) is a useful reference for all aspects of concrete technology.

Some academic research on pervious concrete pavement has also been published. The National Concrete Pavement Technology Center at Iowa State University completed an extensive laboratory study (Schaefer et al. 2006). At least two Master's theses have been published on the topic (Harber 2005, Mulligan 2005).

Two reports have been recently published by the NRMCA (Wanielista et al. 2007, Chopra et al. 2007). These reports address construction, maintenance, and hydraulic performance assessment of PCPC pavements in the southeast.

Papers and Presentations

A number of journal technical papers have been published on pervious concrete pavement, many by Haselbach at the University of South Carolina and co-workers (Montes et al. 2005, Haselbach et al. 2006, Valavala et al. 2006). Other papers have been published by Booth and Leavitt (1999), Yang and Jiang (2003), and Luck et al. (2006). These are listed under "Technical Papers" in the "References and Bibliography" section.

One key source of recent material is the Proceedings of the 2006 NRMCA Concrete Technology Forum: Focus on Pervious Concrete, held in Nashville, TN, May 24 – 25, 2006.

These are listed in a special section under "References and Bibliography." Fourteen of the papers are of interest to this research project.

Other References

Other available sources on pervious concrete pavements include magazine articles and web sites. Many of these have appeared in the last two to three years. Several address specific project case studies – for example, Pool (2006). These are listed in the "Other Sources" and "Web Sites" sections under "References and Bibliography." One important source is "Pervious Concrete Links and Information" from the Ohio Ready Mixed Concrete Association. This site provides locations and contact information for a number of projects in the hard wet freeze region as well in other parts of the U.S. An additional source of research information is Brown (2007) "Pervious Concrete Research Compilation: Past, Present and Future" http://www.rmc-foundation.org/newsite/images/Pervious%20Concrete%20Research%20Compilation.pdf

CHAPTER 3: EXISTING PROJECT SEARCH AND SITES INVESTIGATED

The purpose of this search was to identify existing projects of various ages, in areas of differing soils, environmental conditions, and geographical locations. It was important to include projects that would represent many possible conditions of weather, subgrade, materials, and design. Written and telephone surveys were used to document the performance of and concerns with pervious concrete pavements.

NRMCA Project Survey 2004 and others

Table 2 through Table 4 list dry freeze/hard dry freeze, wet freeze, and hard wet freeze candidate projects, respectively, discussed by the NRMCA (2004), as well as other sources.

Table 2: Dry Freeze and Hard Dry Freeze Pervious Pavement Sites

Site Description	Year Built	Location	Freeze Thaw Information	Source for Information
Kozileski's Law Office/DePauli Engineering parking lot	1991	Gallup, N.M.	210 cycles/year, average 60 days below freezing	NRMCA 2004, Frank Kozileski
Milligan's driveway	1993	Gallup, N.M.	Same as above	Same as above
Residential home alley and side yard	1994	Gallup, N.M.	Same as above	Same as above
Lake Tahoe projects			Over 100 cycles/year	Andy Youngs

Table 3: Wet Freeze Pervious Pavement Sites

Site Description	Year Built	Location	Freeze Thaw Information	Source for Information
Brasher's Auto Auction parking lot (~ 15 acres)	1985	Salt Lake City, UT	90 cycles/year	NRMCA 2004
Finely Stadium parking lot extension	1997	Chattanooga, TN	50 cycles/year	NRMCA 2004
Western Carolina Retinal Associates parking lot	2002	Asheville, NC	90 cycles/year	NRMCA 2004
University of North Carolina commuter parking lots	2002	Chapel Hill, NC	90 cycles/year	NRMCA 2004
Athens Regional Park walking path and parking area	2003	Athens, TN	90 cycles/year	NRMCA 2004
Hennessy Porsche alley and side yard	2003	Roswell, GA	50 cycles/year	NRMCA 2004
Tennessee projects	Various	Various sites, TN		Alan Sparkman
Kentucky projects	Various	Various sites, KY		John McChord
North Carolina projects	Various	Various sites, NC		William Arent
Columbia Gorge project		Near Stevenson, WA		Scott Erickson

Table 4: Hard Wet Freeze Pervious Pavement Sites

Site Description	Year Built	Location	Freeze Thaw Information	Source for Information
Penn State University Visitor's Center sidewalk	1999	State College, PA	120 cycles/year, average 90 days below freezing	NRMCA 2004, Phil Kresge
Fred Fuller Park, Kent, Ohio	2003	Kent, OH		Warren Baas, ORMCA
Cleveland State University Parking Lot D	2005	Cleveland, OH		
Collingwood Concrete Saranac Plant		Cleveland, OH		Warren Baas, ORMCA
Lakota East High School crosswalk		Monroe, OH		Warren Baas, ORMCA
Other Ohio parking lots	Various	Various sites		Warren Baas, ORMCA
Kettering bus stop		Kettering, OH		Warren Baas, ORMCA
Lakewood Park path		Lakewood, OH		Warren Baas, ORMCA
MN Road Research Facility		Albertville, MN		Kevin MacDonald
Northern Kentucky Sanitation District parking lot		KY		George Robinson
Indiana projects	Various	Various sites IN		Pat Kiel

Status Update 2006

An update on the sites discussed in the 2004 NRMCA report, as well as others, was reported by Warren Baas of the Ohio Ready Mixed Concrete Association in 2006. The report is available on the web site http://www.ohioconcrete.org/Pervious%20Concrete.htm:

"MN Road Research Facility – Kevin MacDonald kmacdonald@cemstone.com
We have noted that the freeze thaw performance is dependent on the paste to aggregate bond, and on the presence of frost susceptible particles in the coarse aggregate. The laboratory results were predictive of the field performance.

Northern Kentucky Sanitation District – George Robinson grobinson@sd1.org
Our office parking lot, having pervious concrete and pervious asphalt, is well maintained and closely monitored. Debris collected by suction of the mechanical sweeper is saved and analyzed. Our snow plow's steel blade has not marred the pervious concrete surface. We have not had any cracking issues, nor any freeze-thaw damage.

Tennessee Concrete Association – Alan Sparkman asparkman@trmca.org
I have not observed any freeze-thaw damage in any of our installations here in Tennessee. Our oldest project is about 10 years old and still in good shape. I have only observed two small areas in that lot (about 2 square feet) that show any kind of damage after 10 years. Our other

installations go back about five years and I visit them periodically, but not regularly. I have not observed freeze-thaw damage in any of these installations to date.

We will be doing a much more formal evaluation of existing pervious projects over the summer using an intern from MTSU. He will be visiting as many sites as we can locate to do a condition survey and also do infiltration testing to see what kind of clogging the sites are experiencing once in service. We will have a report done by the end of August or so.

Indiana Ready Mixed Concrete Association – Pat Kiel pkiel@irmca.com
The IRMCA has been working intensively with pervious concrete throughout the state of Indiana over the past three plus years. We are aware of several projects that are over 5 years old in the state, and have a total of over 25 projects that we are aware of in Indiana, (some of which were placed on less than ideal sub-bases), we have no knowledge of any freeze – thaw damage to any of these projects.

California Nevada Cement Promotion Council – Andy Youngs andy.youngs@cncpc.org
I began to investigate pervious concrete in March of 2000. Due to the potential for it to become an environmental godsend for Lake Tahoe, freeze/thaw durability was of particular concern to me. I did an ad hoc survey of industry colleagues and found that the pervious concrete sites (some in New Mexico and Pennsylvania were said to be over 10 years old) which proved to be durable in these climates had two things in common – use of air-entraining admixtures and placement on at least six inches of drain rock.

In the west, we have several installations which have been through two, three or four winters. All were placed with air-entrainment and on at least eight inches of ¾" crushed rock. All have exhibited no freeze/thaw or snowplow damage. Those in the Tahoe Basin can experience over 100 freeze/thaw cycles annually.

In freeze/thaw environments I typically recommend the use of a ½" x 3/8" crushed rock placed with either a weighted Bunyan Screed with cross-rolling; or with a Texas Screed followed by compaction with a vibratory plate compactor.

Gallup Sand & Gravel Co. – Frank Kozeliski fakoz@cia-g.com
As of this date the pervious concrete has not fallen apart due to freeze thaw. The parking lot which is about 15 years old has some mud and dirt on the surface but water still seeks its way through the pervious. Some of the other pervious on a little hill is still intact and there is no break up due to freeze thaw. It just works with no problem. All this work was done by my brother and myself with the kids helping. None of use are certified. I guess I need to get certified.

We are using a 1/2" maximum size aggregate for drainage under astro grass. This is fake grass for out west where it does not rain and the grass stays green all year long. The water drains through the pervious.

Kentucky Ready Mixed Concrete Association – John McChord jmcchord@krmca.org
Kentucky has no formalized lab study on freeze-thaw resistance of pervious concrete. No in place project has shown signs of this type of distress. The oldest project of any consequence has gone through 3 winters.

Stoney Creek Materials NW – Scott Erickson Scott@stoneycreekmaterials.com
We have a project installed in the Columbia Gorge near Stevenson Washington that is exposed to very extreme weather including ice storms and freeze thaw cycles. It has been installed since 2003 and as of a few months ago looked to be in perfect condition.

Carolinas Ready Mixed Concrete Association – William Arent arent@crmca.com
We have installations that have been in place for over tens years in areas that have experienced multiple freeze-thaw cycles with no apparent damage."

Project Selection for Field Visits

Two dozen sites were selected for field visits. At six, or 25 % of the sites, it was possible to obtain cores. The sites are described in detail in Chapter 5.

Table 5: Sites Selected for Field Visits

States	**Number**	**Sites Visited**
Indiana	5	A Charter School (Gary), a Keystone Concrete storage pad (Churubusco), the Kuert Concrete corporate office (South Bend), a sidewalk at Rieth Village, Merry Lea Environmental Learning Center of Goshen College (Albion), and a patio break area at Patterson Dental Supply (South Bend)
Kentucky	2	The Boone County Farmer's Market (Burlington) and the Northern Kentucky Sewer District Sanitation District #1 (Fort Wright)
Ohio	12	Ball Brothers Contracting (Monroe), Bettman Natural Resource Center (Cincinnati), Cleveland State University Lot D (Cleveland), Collinwood Concrete Saranac Plant (Cleveland), Fred Fuller Park (Kent), Harrison Concrete Plant Office Parking Area (Harrison), Indian Run Falls Park (Dublin), John Ernst Patio (Tipp City), Kettering Bus Stop (Kettering), Lakewood Bike Path (Lakewood), Phillips Companies Parking Lot (Beavercreek), and Cleveland State University Administration Building (Cleveland)
Colorado	4	A Safeway, a Wal-Mart, and two concrete plant installations (Bestway and Ready Mixed) (all Denver)
Pennsylvania	1	Penn State Visitor's Center (State College)
Total	24	

CHAPTER 4: FIELD AND LABORATORY INVESTIGATION TECHNIQUES

For this research, the field evaluations included visual observation, a drain time/infiltration rate test, and Ultrasonic Pulse Velocity (UPV). It was possible to remove cores from some of the field installations. Cores were brought back to the laboratory and tested for void ratio, hydraulic conductivity, UPV, and either compressive or splitting tensile strength.

Six out of 22 sites visited allowed coring. Twelve cores were taken from each of the sites, except for the site in Gary, Indiana, where 20 cores were taken due to the size of the project. The cores were taken in accordance with ASTM Standard C 42/C 42M-99. The core barrel was 4 inches in diameter and extracted a core sample with a diameter of 3.75 inches.

Visual Observation

Visual observations provided information about overall performance of the pervious concrete. For consistency, a questionnaire was filled out for each site visited, incorporating information about the total area of the pervious concrete, and general description of the surrounding topography. Analysis of the surrounding topography led to easier detection of clogged areas, and suggested possible reasons for any observed clogging. The questionnaire included information about separation distance of expansion joints and whether joints, if used, were tooled or saw cut.

The extent of raveling on the surface and along joints was observed and described as minimal, medium (significant) or high (extensive). The surface was also examined for cracks and visual indications of clogging. Owners were questioned about maintenance. Figure 3 illustrates an example of surface raveling observed in the field.

Figure 3: Surface raveling (observed at Charter School, Gary, Indiana)

The questionnaire also incorporated information regarding volume of heavy-vehicle traffic. Photographs of the pavements and key features were taken. Based on the initial results, areas of pervious concrete were chosen for further nondestructive testing. Visual inspection also provided valuable information about durability and possible construction errors.

Drain Time/Infiltration Rate Test

A simple drain time/infiltration apparatus was developed as part of this research. The equipment consisted of a stop watch, water, and a 4 by 8 plastic concrete cylinder mold. Foam rubber was attached to the bottom to seal the cylinder against the pavement, and a hole was drilled for water to flow out. A hole diameter of 7/8 inch seemed to work well. The time to drain the cylinder with nothing underneath (free flow) was 5 seconds. The apparatus is shown in Figure 4. In some cases, the pavement was relatively impermeably and water simply flowed across the surface, as shown in Figure 5.

The time to drain the cylinder into the pavement through the hole was measured. Care should be taken not to allow water to freely flow around the parameter of the mold. Thus, pressure should be applied on top of the mold during testing. The test may also be used before and maintenance to quantify the effectiveness of a maintenance technique. As part of this research, drain time was calibrated to hydraulic conductivity. The best-fit equation is provided in Chapter 6. Hydraulic conductivity is often called permeability in pavement engineering.


Figure 4: Drain time Apparatus

Maintenance/Infiltration Test

Maintenance of pervious concrete typically consists of vacuuming and/or pressure washing. Pressure washing may drive sediment further into the pores of pervious concrete. Prior to performing any maintenance on pervious concrete, it is first necessary to determine if the surface is clogged, and to what extent.

Figure 5: Sheet flow across clogged surface (observed at Rieth Village, Albion, Indiana)

The following equation was developed by Youngs (2006), to determine if the pervious concrete site in question needed maintenance or not. The test is intended to simulate a 100 year, 24 hour storm. This test does not work well on sloping or over-compacted surfaces.

$$IR = \frac{19{,}958{,}400}{(a)(T)} \sim \frac{20{,}000{,}000}{(a)(T)}$$

$$MR = (DS)(SF)(FC)$$

a= area of wet spot in square inches
T= time to empty one gallon of water onto the pervious pavement in seconds
FC= flow concentration (area drained/ area of pervious concrete)
DS= Design Storm in inches (usually the 100 year, 24 hour storm event)
SF= Safety Factor (usually 2 or 3)
IR= Infiltration Rate in inches of rain per day
MR= Maintenance Rate in inches per day
If IR>MR, no maintenance is required
If IR<MR, cleaning of the pervious concrete is required

Materials required are a sprinkler can, a stopwatch, a tape measure, and water. Prior to testing it is necessary to determine 100 year, 24 hour storm, and establish the size of the flow concentration onto the pervious concrete. The testing technique involves measuring the area of the wet spot on the pervious concrete, and timing flow of water out of the sprinkler can.

Ultrasonic Pulse Velocity (UPV)

UPV measures the velocity of an acoustic compression wave through concrete. It has a long history of use with conventional concrete, but has not been used much with PCPC. UPV is based on the modulus of elasticity and density of the material, and the variability of the wave speed indicates the variability of these properties within a concrete pavement or structure (Mindess et al., 2003).

If the mass density of the material and the velocity of the waves are known, the elastic properties of the material can be estimated. In the UPV, test an ultrasonic pulse is typically generated at one end of the test specimen, and the time of its travel from one end to another is measured. Knowing the distance between these two points, the velocity of the pulse can be determined. UPV is most accurate when opposite sides of a specimen may be accessed, and least accurate when only one side may be accessed (Mindess et al., 2003).

For this research, only the pavement surface could be accessed in the field, so a direct reflection technique was used with the two transducers 2 inches apart. Opposite sides of cores were tested in the laboratory through direct transmission.

Void Ratio

The void ratio was determined by calculating the difference in weight between air dried and saturated samples, using following equation in consistent force (F) and length (L) units (Schaefer et al. 2006, p. 22).

$$V_r = \left[1 - \left(\frac{W_2 - W_1}{\rho_w \times Vol}\right)\right] \times 100\%$$

Where,

V_r = total void ratio, %
W_1 = weight under water, F
W_2 = dry weight, F
Vol = volume of sample, L^3
ρ_w = density of water, F/ L^3

Initial determination of the void ratio was used to divide samples for further testing. Typically four samples were chosen for hydraulic conductivity testing, four for compressive strength testing, and remaining four for splitting tensile testing.

Hydraulic conductivity

Samples tested for hydraulic conductivity were sliced in half, and hydraulic conductivity was repeated on the top and bottom parts. Later, the top and bottom parts were tested in splitting tension. Specimens were prepared by wrapping them in plastic and then in duct tape, as shown in Figure 6.

Figure 6: Sealed specimen for hydraulic conductivity testing

The hydraulic conductivity of the samples was determined using the falling head method. A new apparatus was built specifically for testing the pervious concrete samples. The apparatus is shown in Figure 7. The coefficient of permeability was determined using the following equation found in many soil and pavement texts (Schaefer et al., 2006, p. 22).

$$k = \frac{aL}{At}\ln\left(\frac{h_1}{h_2}\right)$$

Where,

k= coefficient of permeability (hydraulic conductivity), L/T

a = cross-sectional area of the standpipe, L^2

L = length of sample, L

A = cross-sectional area of specimen, L^2
t = time for water to drop from h1 to h2, T
h_1 = initial water level, L
h_2 = final water level, L
ln = the natural logarithm

Figure 7: Laboratory hydraulic conductivity testing

Compressive and splitting tensile strength

Compressive strength and splitting tensile strength tests were performed according to ASTM C39, and ASTM C496, respectively.

CHAPTER 5: OBSERVATIONS FROM FIELD SITE VISITS

This section provides information about the sites visited, as well as the visual observations made at each site. More extensive details about the installations are provided by Miller (2007) and Mrkajic (2007). Test results from surface infiltration and UPV are provided in Chapter 6.

Indiana Site Visits

The Indiana site visits included a Charter School (Gary), a Keystone Concrete storage pad (Churubusco), the Kuert Concrete corporate office (South Bend), a sidewalk at Rieth Village, Merry Lea Environmental Learning Center of Goshen College (Albion), and a patio break area at Patterson Dental Supply (South Bend).

Charter School, Gary, Indiana

This charter school uses pervious concrete pavement for a parking lot and driveway. The pervious driveway begins approximately 30 ft from Clark Road, and leads back to the parking area for the school, as shown in Figure 8. This pavement was built in July, 2006.

Figure 8: Charter School, Gary, Indiana

The pervious concrete parking area is sloped to the center, where there is conventional concrete with three storm drains to catch any water or debris. There is also a fire hydrant near the northwest corner of the parking lot. This hydrant is significant because of the firehouse that is adjacent to the charter school. The fire department uses this hydrant to fill their fire truck with water, and also flushes the hydrant regularly. The school has also begun renovations, so construction vehicles and other delivery vehicles also frequently cross the pervious concrete. This area also is subjected to school bus traffic. The area of damaged pervious concrete is shown in Figure 9.

Figure 9: Surface damage from heavy vehicles near fire hydrant

There is little clogging. There is one area of the pervious where a gravel driveway washes onto the pervious concrete and clogs it, and there are also some areas where the pervious concrete appears to have been over compacted during construction. Other than the area damaged by heavy traffic, the parking lot is performing well. There is also some raveling, which is shown in Figure 3, as well as a minor amount of cracking. Damaged areas of this pavement have since been removed and replaced. Twenty core samples were taken from different areas of the pervious concrete for further testing.

Keystone Concrete, Churubusco, Indiana

This installation is a small storage pad, completed in August 2004. It consists of three test strips of different materials, and is used to store rolls of flexible drainage pipe, as shown in Figure 10. It was placed with an asphalt paver to a thickness of 4 inches, and compacted with a vibratory screed. At present, it is clogged with leaves and other debris. There is no traffic applied to the installation, and there was no observed cracking or raveling. Twelve core samples were removed.

Figure 10: Keystone Concrete storage pad, Churubusco, Indiana

Kuert Concrete Corporate Office, South Bend, Indiana

Two parking lot strips at the Kuert Concrete corporate office were completed in July, 2005. This installation is shown in Figure 11. One is colored red, and both are 6 inches thick and 80 feet long. The pavement was placed with a Bunyan Screed and was well compacted but permeable.

The rest of the parking lot is conventional concrete and drains onto the pervious concrete. The building roof downspouts also drain onto the conventional concrete, and then onto pervious concrete. The pavement showed little clogging. There are two full width cracks, but no raveling. The pervious concrete was not provided with joints, and one of the cracks is a sympathy crack initiated by a joint in the adjacent concrete pavement. Twelve core samples were obtained from the colored section.

The red strip is clogged with asphalt shingle debris. After installing pervious concrete roof was replaced, and down spouts which empty directly onto the parking lot carried a lot of debris which eventually ended up in the pervious concrete pores. Power washing had not been able to restore the infiltration capability. No other maintenance has been performed so far. The owner plans to remove and replace the red section, and leave the gray section in place.

Figure 11: Kuert Concrete Corporate Office, South Bend, Indiana

Rieth Village, Merry Lea Environmental Learning Center of Goshen College, Albion, Indiana

Rieth Village is an environmental conservatory with a platinum LEED rating. It was built in April 2006 by Goshen College as a place where students could live, study, and conduct research. The pervious concrete installation is a sidewalk leading to the learning center, shown in Figure 12.

Figure 12: Rieth Village environmental learning center, Albion, Indiana

The surface of the sidewalk appears to have been sealed off during construction, either due to a wet mixture or over compaction. The sidewalk is shown in Figure 13. Due to the uneven terrain, it was difficult for the installers to use a Bunyan Screed. The concrete supplier also observed that the mixture may have been too wet. Water dumped onto the surface flowed across the pavement, not into it, as shown in Figure 5. There was no observed raveling. One crack was found at the intersection of three paths. To date, no maintenance has been performed.

Figure 13: Surface sealed by wet mixture or over compaction

Patterson Dental Supply, South Bend, Indiana

The Patterson Dental Supply installation is a small patio behind the building, as shown in Figure 14. The patio was completed in June, 2004. This installation drains well and does not show any clogging. Minor aggregate polishing, raveling, and cracking were observed. One crack starts at a re-entrant corner, which would be expected. No maintenance has been performed to date.

Kentucky Site Visits

The Kentucky site visits included the Boone County Farmer's Market (Burlington) and the Northern Kentucky Sewer District Sanitation District #1 (Fort Wright).

Boone County Farmer's Market, Burlington, Kentucky

The Boone County Farmer's Market parking stalls were placed in January 2006. This pavement is shown in Figure 15. The overall design uses conventional concrete for the driving surface and shopping area, brick for some of the decorative areas, and pervious concrete for the parking stalls. A Bunyan Screed was used. Much of the pervious concrete is clogged with silt, and some portions were over compacted during installation. Some raveling was observed, particularly at joints. One crack was found, which may be due to overloading by a heavy landscape truck. No maintenance has been performed. Overall, this installation drains well.

Figure 14: Patterson Dental Supply pervious concrete patio

Figure 15: Boone County Farmer's Market, Burlington, Kentucky

Northern Kentucky Sewer District Sanitation District #1, Fort Wright, Kentucky

This parking lot installation, shown in Figure 16, was completed in January 2004. Most of the pavement is asphalt, with pervious concrete parking stalls. The parking lot also includes an engineered wetland. This parking lot has light to moderate clogging from debris. Part of the lot was also sealed by over compaction during construction. The parking lot has been vacuumed twice to remove loose surface aggregate and maintain infiltration capability. There is no cracking, but there is some minor raveling and polishing of the surface.

Figure 16: Kentucky Sewer Sanitation District #1, Fort Wright, Kentucky

Ohio Site Visits

The Ohio site visits included Ball Brothers Contracting (Monroe), Bettman Natural Resource Center (Cincinnati), Cleveland State University Lot D (Cleveland), Collinwood Concrete Saranac Plant (Cleveland), Fred Fuller Park (Kent), Harrison Concrete Plant Office Parking Area (Harrison), Indian Run Falls Park (Dublin), John Ernst Patio (Tipp City), Kettering Bus Stop (Kettering), Lakewood Bike Path (Lakewood), Phillips Companies Parking Lot (Beavercreek), and Cleveland State University Administration Building (Cleveland).

Ball Brothers Contracting, Monroe, Ohio

At Ball Brothers Contracting, pervious concrete is used for a storage yard (Figure 17). The pavement was placed in January 2004, and is used to store wall forms for concrete basements. Much of the storage pad is clogged with debris. The clogging is concentrated at the joints. At some spots the surface was over-consolidated and sealed off during construction. Overall, the surface still drains reasonably well. There is some raveling at joints and corners.

There are also two cracks, possibly caused by heavy vehicles. The only maintenance applied has been snow and ice removal, which caused some abrasion of the surface. The extent of clogging suggests that power washing or vacuuming should be attempted to restore infiltration capability.

Figure 17: Ball Brothers Contracting, Monroe, Ohio

Bettman Natural Resource Center, Cincinnati, Ohio

The Bettman Natural Resource Center, part of the Cincinnati park district, placed a pervious concrete parking lot in October 2006, as shown in Figure 18. The pavement was placed in three distinct sections.

Silt is carried onto the pavement by runoff from adjacent landscaping beds. This clogging is mostly at the outside edges of the pavement. This pavement was also overcompacted during installation. Raveling is light to moderate, and was observed mainly at joints. No cracks are visible. Vehicle traffic is light. Some of the surface has been damaged by aggressive power washing to remove mulch.

Cleveland State University Lot D, Cleveland, Ohio

On August 22 and 24, 2005, part of an existing asphalt parking lot was removed in order to construct a demonstration pervious concrete pavement site. A 12 by 50 foot (3.66 by 15.2 m) strip of existing parking lot near a drop inlet was removed, and 6 inches (150 mm) of subbase was placed and compacted. On the 22nd, half of the strip was paved with 6 inch (150 mm) thick pervious concrete. Two days later, a seminar and demonstration were held for approximately 200 participants, and the other half of the test section was placed. The installation is shown in Figure 19.

Figure 18: Bettman Natural Resource Center parking lot, Cincinnati, Ohio

Figure 19: CSU Parking Lot D Demonstration Project

A vibrating screed was used until it broke down, and the section was finished with a hand screed. The joints were tooled with a pizza-cutter type roller, and the pavement was moist cured under plastic for seven days. Asphalt was later used to fill in around the edges to prevent premature deterioration.

This demonstration project was built as a closed system, with an impermeable plastic membrane to carry water to a perforated plastic pipe leading to a drop inlet, as shown in Figure 1. The reason for using a closed system was that the remainder of the existing asphalt parking lot was in poor shape, and there were concerns about introducing additional moisture under it. This provides a miniature storm water detention system, as shown in Figure 2.

This patch drains a much larger area of a badly deteriorated asphalt parking lot, and therefore collects a lot of sediment. Traffic from nearby university construction projects also contributes to the debris. Overall, due to the debris, drainage has been fair to poor. There is very little raveling or polishing, and no cracks. The portion placed at the end (north side) with the hand screed has not shown any additional distress. The parking lot has been aggressively salted and plowed, but this has not caused any damage. The parking lot is heavily used by passenger vehicles.

Collinwood Concrete Saranac Plant, Cleveland, Ohio

Collinwood Concrete is a major supplier of pervious concrete for projects in and near Cleveland. Their first installation was at their own Saranac plant, Figure 20. This pavement is 9 inches thick and is subject to heavy vehicle loading by concrete delivery trucks. It is also clogged with debris from vehicles and from conventional concrete pavement that drains onto it. Raveling is light to moderate, and there is no cracking. No maintenance has been performed.

Figure 20: Collinwood Concrete Saranac Plant, Cleveland, Ohio

Fred Fuller Park, Kent, Ohio

The Fred Fuller Park demonstration project (Figure 21) was installed on December 23, 2003, and is the oldest installation in northeast Ohio. It consists of 6 inches of pervious concrete over 8 inches of # 57 base. The parking lot has completed four Northeast Ohio winters without any visible freeze-thaw damage. The surface condition of the project is shown in Figure 22. The two parking stalls receive very light traffic. There is no cracking, and little raveling. No maintenance has been performed.

Figure 21: Fred Fuller Park demonstration project

Harrison Concrete Plant Office Parking Area, Harrison, Ohio

A strip of pervious concrete was placed at the end of the Harrison Concrete Plant office in September, 2006. This installation is shown in Figure 23. It is adjacent to a conventional concrete parking lot, and joints were matched to prevent sympathy cracking. There is some clogging from soil, but little raveling and no cracking.

Figure 22: Surface Condition, Fred Fuller Park

Figure 23: Harrison Concrete Plant, Harrison, Ohio

Indian Run Falls Park, Dublin, Ohio

Pervious concrete handicapped parking stalls at Indian Run Falls Park are shown in Figure 24. These were placed in May 2006.

Figure 24: Indian Run Falls Park, Dublin, Ohio

Some areas of the pavement surface seem to have been closed off by over-compaction during installation. There is considerable debris on the parking lot. There is also severe raveling, particularly at joints. Some of the surface aggregate has popped off. It does not appear that any maintenance has been performed so far.

John Ernst Patio, Tipp City, Ohio

A pervious concrete patio was placed in the location of a persistent wet spot of a private residence in October 2006 (Figure 25). There is very little clogging or raveling so far.

Kettering Bus Stop, Kettering, Ohio

Pervious concrete was installed in September 2004 at a bus stop adjacent to Kettering Memorial Hospital (Figure 26). Although there is no visual evidence of clogging, water flows rather slowly through the pavement. It may have been over-compacted during installation. There is no cracking and very little raveling.

Figure 25: John Ernst Pool Patio, Tipp City, Ohio

Figure 26: Bus Stop outside Kettering Memorial Hospital, Kettering, Ohio

Lakewood Bike Path, Lakewood, Ohio

A bike path in a park on the shores of Lake Erie in Lakewood, Ohio, was placed in November 2005. The path is shown in Figure 27. The pervious concrete was placed to allow water to get to the roots of the trees on either side of the path.

Figure 27: Park bike path, Lakewood, Ohio

Clogging is light to moderate along the path. There is some raveling and some evidence of surface sealing due to over-compaction during construction. There are no cracks. Overall, this installation drains well.

Phillips Companies Parking Lot, Beavercreek, Ohio

Phillips Companies placed a pervious concrete parking lot in January 2006 (Figure 28). A pervious asphalt sidewalk was also installed nearby. A car rental company washes its vehicles adjacent to the pervious concrete strip. There is some light to moderate clogging. Part of the surface also appears to be sealed from over-compaction. There is no cracking, and limited raveling at the joints.

Cleveland State University Administration Building, Cleveland, Ohio

Following the success of Parking Lot D, the Cleveland State University Architect's Office decided to construct a second pervious concrete parking lot on campus, next to the new Administration Building. The original design called for pavers over a stone reservoir several feet thick, but it was estimated that the total cost of a pervious concrete parking lot would be lower because of savings in labor costs. This parking lot was built starting in July 2007, along with another public demonstration. Three placements were made. The second placement is shown in

Figure 29. A colored strip of pervious concrete was placed between the others. Specimens of the concrete delivered were taken to the Cleveland State University laboratories to prepare test specimens.

Figure 28: Phillips Companies parking lot, Beavercreek, Ohio

Figure 29: Cleveland State University Administration Building Parking Lot

Approximately seven days after construction, the curing plastic was removed and contractor vehicles began using the parking lot. Because the administration building complex was not yet complete, a significant amount of loose soil has washed on to the pavement, and there is local but severe clogging.

Colorado Site Visits

The Colorado site visits were all in Denver. These included a Safeway, a Wal-Mart, and two concrete plant installations (Bestway and Ready Mixed). Only visual observations and 4 by 8 cylinder mold drain time tests were performed at the Colorado sites.

Denver Safeway

The Denver Safeway parking lot is shown in Figure 30. The entire parking lot is pervious concrete. There was no evidence of raveling, but some of the panels furthest away from the store entrance had cracks between the widely spaced joints. Surface drainage times of about 20 seconds were measured in a lightly used corner, with 35 – 40 seconds in the more heavily trafficked interior. One small section was clogged by an oil stain, with a drain time of 76 seconds. Overall, this parking lot provided good drainage.

Figure 30: Safeway Parking Lot, Denver, Colorado

Denver Wal-Mart

Pervious concrete was used for part of a parking lot at a Wal-Mart on the east side of Denver, shown in Figure 31. This parking lot used multiple paving materials, with the pervious concrete used for a strip some distance away from the store. There was no visual evidence of cracking or clogging. Drainage times measured in the parking stalls were 17, 19, 22, 23, and 34 seconds. One spot that had been clogged with coarse landscaping mulch had a drain time of 35 seconds, suggesting that this particular clog with large particles had not significantly decreased the infiltration capability of the parking lot. This parking lot also provided good drainage.

Figure 31: Wal-Mart Parking Lot, east side of Denver, Colorado

Bestway Concrete

One ready mixed concrete plant in downtown Denver had placed two strips of pervious concrete (Figure 32). One, colored green, was next to the office. The other was at the edge of the parking lot, consisting of eight parking spaces. No cracks were observed. However, the pervious concrete strip that was not colored had drain times of 57 and 99 seconds, indicating that the surface had probably been sealed off during construction.

Ready Mixed Concrete

Another ready mixed concrete facility in downtown Denver had a large pervious concrete parking lot. There was some surface raveling at some of the joints, which appeared to be cold joints. Drainage times measured were 14, 15, and 17 seconds, and one area that appeared to be clogged with fines had a 25 second drain time. This installation, therefore, had very good drainage.

Figure 32: Bestway Concrete parking lot, Denver, Colorado

Pennsylvania Site Visit

The only Pennsylvania site visited was at the Pennsylvania State University Visitors Center sidewalk, State College. This site is shown in Figure 33. This was constructed in 1999 (NRMCA 2004). Therefore, this was the oldest installation that the researchers were able to investigate in person.

There is no evidence of cracking or raveling, so the sidewalk is in good structural condition with no evidence of freeze-thaw damage. However, the surface appeared to be closed off. This was confirmed by two drainage time tests which left large wet spots spread across the sidewalk, shown in Figure 33. Although the structural condition of the sidewalk is satisfactory, the infiltration capability appears to be very low. The Visitors Center also has a large permeable asphalt parking lot, which is also completely sealed off.

Summary of Field Visit Observations

The majority of the sites visited were in Indiana, Kentucky, and Ohio. Of these, twelve of the sites used pea gravel as the coarse aggregate, and six sites used crushed limestone. Pea gravel compacts more easily, and therefore may be prone to over-compaction. Based on visual observations, most of the clogging was due to over compaction or a wet mixture at the time of placement. Sand and other debris also caused clogging. Heavy clogging at two of the sites was due to muddy trucks and other equipment.


Figure 33: Pennsylvania State University Visitors Center sidewalk

Seven of the pervious concrete sites, four in Indiana, two in Ohio, and one in Colorado, have cracks due to either a lack of expansion joints, or due to heavy vehicular traffic, as in the case of the Charter School and Ball Brothers Contracting. Typically, expansion joints are cut at 15 to 20 feet. However, the length of the installation at Kuert concrete was 80 feet without expansion joints.

Raveling was observed mostly at the Charter School and Indian Run Falls Park. The raveling at the Charter School occurred near a fire hydrant that was used to fill a city fire truck, and was also flushed regularly. The abuse from the fire truck, school busses, and the flushing of the hydrant deteriorated the pervious concrete completely. This section of pervious concrete has been replaced with conventional concrete. The raveling at Indian Run Falls Park was due to extreme temperatures at the time of placement, and a dry mixture in the first batch of pervious concrete.

Drain time rates ranged from 8 seconds to over 120 seconds. A good infiltration rate is 20 seconds or less, anything between 20 and 60 seconds is a fair infiltration rate, and anything over 60 seconds is a poor infiltration rate.

These installations showed that wet mixtures or overcompaction may lead to a sealed surface, and dry mixtures or undercompaction may lead to raveling. Table 6 provides a summary of the field observations.

Table 6: Summary of Field Site Observations

Project	Clogging	Raveling	Cracked	Jointing method
Charter School	Moderate	Minimal	Yes	Rolled
Keystone Concrete	Severe	Minimal	No	N/A
Kuert Concrete	Minimal	Minimal	Yes	N/A
Merry Lea College	Severe	Minimal	Yes	Rolled
Patterson Dental	Moderate	Minimal	Yes	Rolled
Boone Cty. Market	Moderate	Minimal	Yes	Rolled
Sanitation Dist. #1	Moderate	Moderate	No	Rolled
Ball Brothers Contract.	Severe	Minimal	Yes	Rolled
Bettman NRC	Moderate	Moderate	No	Rolled/Sawed
Cleveland State	Severe	Minimal	No	Rolled
Collinwood Concrete	Severe	Minimal	No	Rolled
Fred Fuller Park	Severe	Minimal	No	N/A
Harrison Concrete	Minimal	Minimal	No	Rolled
Indian Run Falls	Minimal	Moderate	No	Rolled
John Ernst Patio	Minimal	Minimal	No	N/A
Kettering Hospital	Severe	Minimal	No	N/A
Lakewood Park	Minimal	Minimal	No	Rolled
Phillips Companies	Severe	Minimal	No	Sawed

Mixture Designs and Field Compaction Methods

The mixture proportions and field compaction methods used are shown in Table 7, for those installations where the information was available. Quantities of cementitious materials, water, and coarse aggregate are given per cubic yard. No fine aggregate was used.

Table 7: Mixture Designs and Field Compaction Methods

LOCATION	Cementitious (lbs.)	Water (lbs.)	Coarse Aggregate	w/c ratio	Binder/Agg Ratio	Compaction Method
Ball Brothers	600 *	180	2400	0.30	0.33	Vibratory Screed Static Roller
Bettman Center	700 *	200	2800	0.29	0.32	Bunyan Screed
Boone Market	600 *	180	2400	0.30	0.33	Vibratory Screed Board
Charter School	NA *	NA	NA	NA	NA	Bunyan Screed
Cleveland State Lot D	600 **	168	2850	0.28	0.27	Vibratory Screed Static Roller
Ernst Pool	520 *	142	2641	0.27	0.25	Static Roller with Extra Weight
Fred Fuller Park	707 **	208	2700	0.29	0.34	No Compaction
Harrison Concrete	500 *	150	2858	0.30	0.23	Truss Screed Static Roller
Indian Run Falls	630 **	130	2780	0.21	0.27	Bunyan Screed
Kentucky Sanitation	600 *	186	2600	0.31	0.30	Bunyan Screed
Kettering Hospital	500 *	134	2785	0.27	0.23	Manual Pipe Roller
Keystone Concrete	672 *	184	2700	0.27	0.32	Asphalt Paver
Kuert Concrete	500 **	148	2480	0.30	0.26	Bunyan Screed
Lakewood Park	600 **	168	2850	0.28	0.27	Manual Pipe Roller
Merry Lea	520 *	184	2700	0.35	0.26	Bunyan Screed
Patterson Dental	NA *	NA	NA	NA	NA	Bunyan Screed
Phillips	500 *	134	2785	0.27	0.23	Manual Pipe Roller
Collinwood Concrete	600 **	168	2850	0.28	0.27	Manual Pipe Roller

Note: * Gravels, ** Limestone

CHAPTER 6: FIELD AND LABORATORY TESTING RESULTS AND DISCUSSION

Extensive testing was carried out at sites in Indiana, Kentucky, and Ohio. The tests are shown in Table 8. At the Pennsylvania site and the four Colorado sides, only surface infiltration tests were performed. This chapter presents a summary of test results. More detailed results for individual installations are provided by Mrkajic (2007).

Table 8: Project Sites and Test Methods Used at Each Installation

Project Name and Location	Installation Date	UPV	Drain Time	Infiltration Rate	Core Samples
INDIANA					
Charter School, Gary, IN	July-06	X	X	X	X
Keystone Concrete, Churubusco, IN	August-04	X	X		X
Kuert Concrete, South Bend, IN	July-04	X	X	X	X
Merry Lea Environmental Learning Center, Albion, IN	July-05	X	X		
Patterson Dental Supply, South Bend, IN	June-05	X	X		
KENTUCKY					
Boone County Farmer's Market, Burlington, KY	January-06	X	X	X	
Sanitation District #1 Fort Wright, KY	January-04	X	X	X	
OHIO					
Ball Brothers Contracting, Monroe, OH	January-04	X	X	X	
Bettman Natural Resources Center, Cincinnati, OH	October-06	X	X	X	
Collinwood Concrete Saranac Plant, Cleveland, OH	Unknown				X
Cleveland State University Lot D, Cleveland, OH	August-05	X	X	X	X
Ernst Patio, Tipp City, OH	October-06	X	X		
Fred Fuller Park, Kent, OH	December-03	X	X	X	
Harrison Concrete Plant, Harrison, OH	July-06	X	X		
Indian Run Falls Park, Dublin, OH	May-06	X	X	X	
Kettering Bus Stop, Kettering, OH	September-04	X	X	X	
Lakewood Park Path, Lakewood, OH	November-05	X	X	X	
Phillips Companies, Beavercreek, OH	May-06		X	X	X

Field Test Results

Results from UPV and drain time in the field are summarized below in Table 9, as well as in Figure 34 through Figure 36.

Table 9: UPV and Drain time Results

LOCATION	UPV (ft/s)				Drain time (sec.)			
	Average	S.D.	Max	Min	Average	S.D.	Max	Min
Ball Brothers	13,200	1,400	15,800	8,012	70	23	117	23
Bettman Center	12,000	1,300	16,800	8,500	57	30	125	14
Boone Market	13,100	975	15,100	10,250	56	20	85	15
Charter School	13,100	450	14,100	11,600	44	27	149	10
Cleveland State Lot D	12,800	550	13,700	11,100	66	20	112	23
Ernst Pool	13,600	740	14,900	12,400	33	14	80	14
Fred Fuller Park	13,600	925	14,700	11,600	136	24	180	93
Harrison Concrete	13,600	1,850	15,800	9,500	21	10	52	8
Indian Run Falls	12,600	800	14,500	9,600	29	11	65	11
Kentucky Sanitation	11,300	1,600	13,600	8,300	45.5	12	69	19
Kettering Hospital	12,900	475	14,100	12,200	68	15	90	39
Keystone Concrete	13,000	560	13,700	11,800	103	12	125	85
Kuert Concrete	12,970	465	13,700	11,100	31	18	90	9
Lakewood Park	13,100	465	14,100	11,700	36	13	73	19
Merry Lea	11,900	380	13,100	11,300	77	21	141	44
Patterson Dental	12,500	850	14,100	11,300	42	13	67	21
Phillips	NA	NA	NA	NA	64	14	120	31

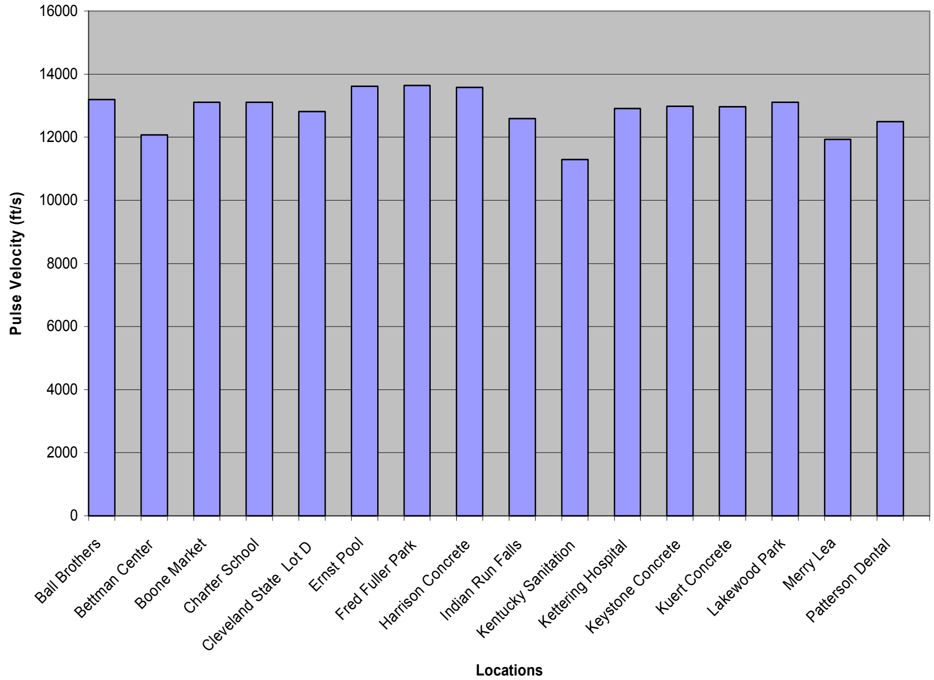

Figure 34: Average Ultrasonic Pulse Velocity in the field

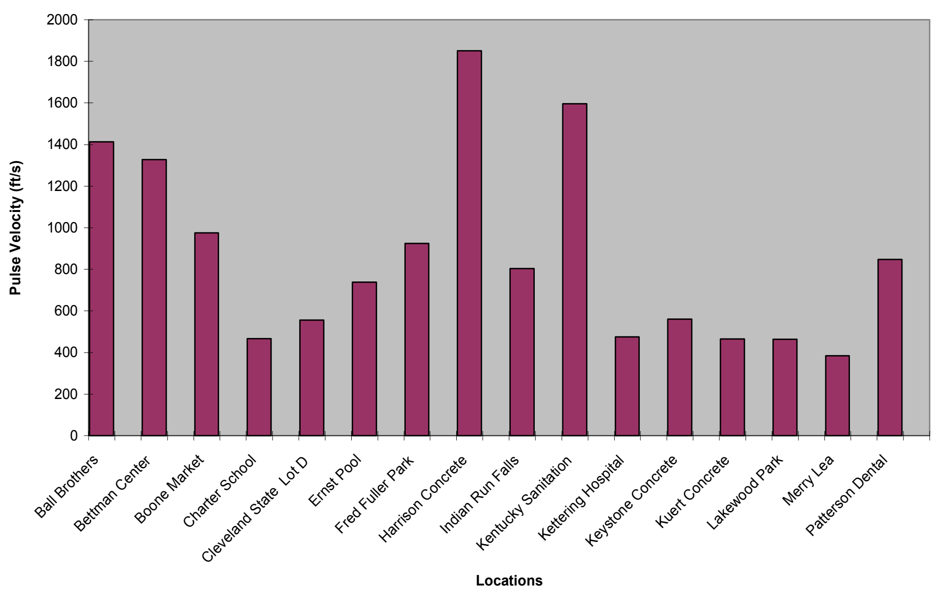

Figure 35: Standard Deviation of Ultrasonic Pulse Velocity in the field

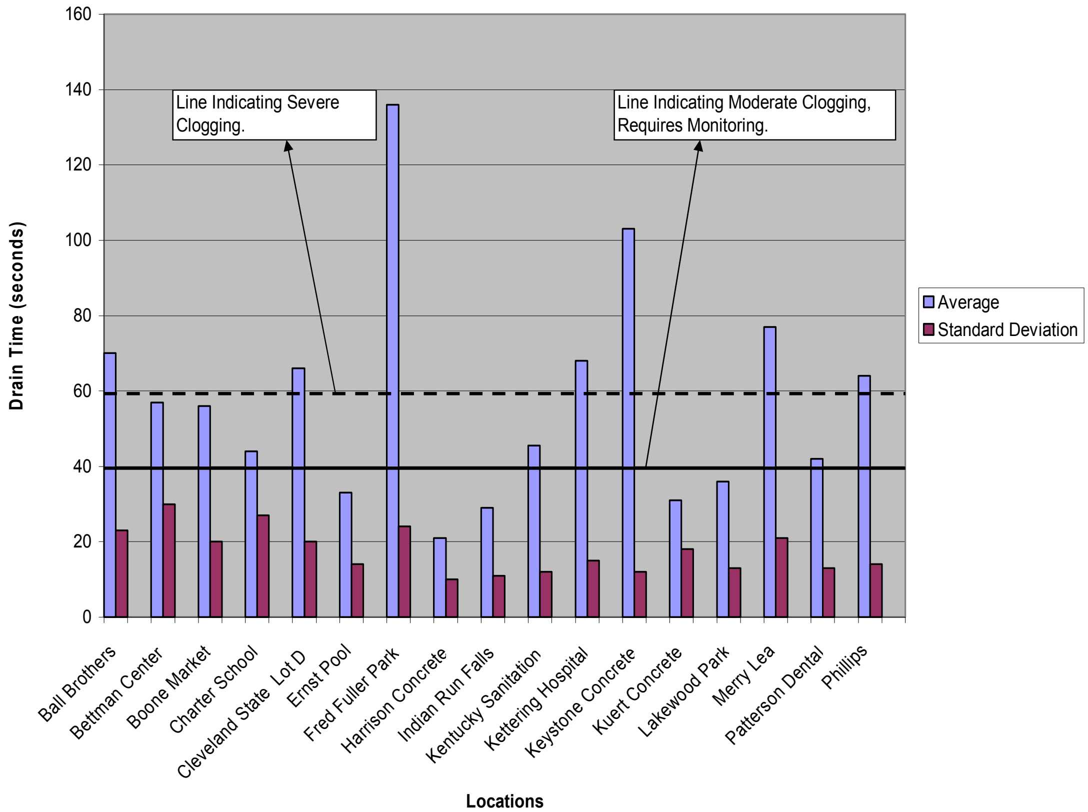

Figure 36: Drain time Results

Laboratory Test Results

Test results from cores and laboratory specimens are shown in Table 10 through Table 17.

Table 10: Direct Transmission Pulse Velocity, Void Ratio, and Strength

LOCATION	UPV (ft/s)				Average			
	Average	S.D.	Max	Min	Void Ratio (%)	Perm. (in/hr)	Comp. Strength (psi)	Tensile Strength (psi)
Phillips	13,300	275	13,900	12,600	13	33	3,400	400
Cleveland State Lot D	12,750	800	13,600	11,100	26	315	1,600	200
CSU Mix Lab	12,200	420	13,100	11,100	19	350	2,600	245
Charter School	10,700	530	12,400	9,300	31	985	1,300	145
Kuert Concrete	11,650	420	12,600	10,900	32	690	1,500	160
Keystone Concrete	13,450	320	14,100	12,400	10	7	5,800	390
Collinwood Concrete	10,800	280	11,400	10,200	32	170	1,000	165

Table 11: Laboratory results for the Phillips Sand and Gravel Company

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Unit Weight (lbs/ft^3)
a1	10	9	13,600	130
i1	90	19	12,600	117
d1	12	15	13,350	122
b1	21	15	12,600	120
Sample	**Compressive Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
a1	3,504	9	13,600	130
g1	3,071	13	13,350	122
f1	2,287	15	13,300	121
e1	3,366	13	13,600	125
j1	4,877	5	13,900	128
Sample	**Tensile Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
h1	367	16	13,350	123
l1	445	14	13,350	126
c1	474	11	13,900	125
k1	306	17	13,100	120

Table 12: Laboratory results for Collinwood Concrete

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Unit Weight (lbs/ft^3)
c1	233	28	11,150	112
h2	128	36	10,600	101
e1	289	34	10,900	105
b2	26	30	10,900	107
Sample	**Compressive Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
c3	1,648	28	11,100	109
g1	1,052	35	10,900	102
f2	617	34	10,200	104
a1	852	33	10,850	105
Sample	**Tensile Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
d2	174	29	11,150	109
a3	151	29	10,600	109
g3	185	32	11,400	106
e3	142	35	10,200	103

Table 13: Laboratory results for Cleveland State University Lot D

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Unit Weight (lbs/ft^3)
b1	260	28	11,100	109
a3	356	29	11,100	98
a1	399	26	11,400	112
a2	238	19	13,600	137
Sample	**Compressive Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
b3	2,325	20	13,400	119
d2	999	28	11,800	110
d3	951	30	11,950	107
f2	2,269	24	13,250	116
Sample	**Tensile Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
b1	155	28	11,100	109
a3	143	29	11,100	98
a1	189	26	11,400	112
a2	300	19	13,600	137
e3	172	31	11,400	107

Table 14: Laboratory results for the Charter School

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Unit Weight (lbs/ft^3)
a2	1,115	34	10,300	104
a1	995	34	10,250	104
c2	797	29	11,200	110
j7	636	29	10,550	110
h9	959	33	10,600	104
b9	1,400	36	9,300	101
Sample	**Compressive Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
e9	564	38	10,200	98
c1	1,852	27	11,500	112
e1	2,830	22	11,700	116
i7	1,108	29	10,000	110
j6	718	33	10,600	105
a4	626	33	10,000	104
Sample	**Tensile Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
e2	258	23	12,400	115
e4	112	31	10,850	107
i5	192	30	11,300	108
i6	109	31	10,650	107
j5	115	29	10,700	110
h4	82	36	10,400	101

Table 15: Laboratory results for Kuert Concrete

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Unit Weight (lbs/ft^3)
e2	548	30	11,800	110
b1	676	32	11,300	107
f3	813	33	11,200	108
d3	718	32	11,400	108
Sample	**Compressive Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
a2	1,993	24	12,600	119
c2	1,339	38	11,900	112
d1	1,153	33	10,900	106
g2	1,577	29	12,500	109
Sample	**Tensile Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
b3	134	34	11,400	105
f1	170	33	11,600	107
h1	177	30	12,000	109
h3	159	33	11,400	106

Table 16: Laboratory results for Keystone Concrete

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Unit Weight (lbs/ft^3)
a3	5	7	13,800	134
b1	7	12	13,300	126
b3	9	14	13,400	123
d2	6	9	14,100	130
Sample	**Compressive Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
a2	5,080	11	13,650	128
b2	8,131	8	13,900	131
c3	4,543	13	13,200	125
d1	5,362	11	13,700	128
Sample	**Tensile Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
a1	421	8	13,500	133
c1	234	11	13,000	127
c2	258	9	12,400	129
d3	370	11	13,400	128
a3	552	7	13,800	134
b1	318	12	13,300	126
b3	386	14	13,400	123
d2	561	9	14,100	130

Table 17 shows results for the 18 samples prepared in the laboratory with the Proctor hammer and the gyratory compactor. The six specimens prepared with the gyratory compactor were numbered one through six. Samples a1, b1, c1, and d1 were compacted with a total of 18 Proctor hammer drops, while samples a2, b2, c2, and d2 were compacted with a total of 36 drops. Samples labeled a3, b3, c3, and d3 were compacted with a total of 54 Proctor hammer drops. A similar void ratio percentage was obtained at 54 drops with the Proctor hammer and 50 gyrations of the gyratory compactor.

Table 17: Laboratory results for the CSU Administration Building Lab Samples

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Unit Weight (lbs/ft^3)
d1	688	24	11,600	115
1	91	16	12,750	126
3	134	19	13,000	123
b1	624	23	11,600	116
a3	175	18	12,200	125
b2	383	19	12,200	121
Sample	**Compressive Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
a1	1,791	23	11,100	117
c2	2,279	19	12,200	122
b3	3,001	16	12,200	126
5	3,008	17	12,450	125
2	3,834	16	12,400	126
a2	2,003	18	11,600	120
Sample	**Tensile Strength (psi)**	**Void Ratio**	**UPV**	**Unit Weight (lbs/ft^3)**
c1	190	19	12,200	120
d2	235	21	11,600	119
c3	291	16	12,200	124
d3	214	17	12,800	124
4	331	17	13,100	125
6	210	17	13,000	125

Comparison of Top and Bottom Results

Several samples were cut in two, and the results between the top and the bottom of the core were compared. Results from field cores are shown in Table 18 through Table 21. In contrast, results from the laboratory specimens made during the CSU Administrative Building parking lot construction are shown in Table 22. Figure 37 compares void ratios for top and bottom samples, and Figure 38 compares hydraulic conductivity for those samples.

Table 18: Top and Bottom Results for Phillips Sand and Gravel Company

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Tensile Strength (psi)	Unit Weight (lbs/ft^3)
i1 top	81	17	13,300	320	118
i1 bott	531	20	11,450	229	117
d1 top	14	14	13,300	258	125
d1 bott	331	20	10,800	186	120
b1 top	24	11	13,200	218	121
b1 bott	398	18	11,100	195	112

Table 19: Top and Bottom Results for Collinwood Concrete

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Tensile Strength (psi)	Unit Weight (lbs/ft^3)
c1 top	169	20	11,200	322	117
c1 bott	448	26	11,350	198	112
h2 top	119	29	9,500	125	105
h2 bott	898	44	7,300	86	86
e1 top	23	21	11,500	173	117
e1 bott	1018	33	8,150	62	103
b2 top	26	14	12,800	187	125
b2 bott	978	25	10,100	165	115

Table 20: Top and Bottom Results for the Charter School

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Tensile Strength (psi)	Unit Weight (lbs/ft^3)
a2 top	525	30	10,000	132	108
a2 bott	1,580	37	9,150	97	98
a1 top	969	32	10,000	130	105
a1 bott	1,364	31	9,600	117	108
c2 top	741	24	10,500	211	116
c2 bott	1,179	31	9,300	133	107
j7 top	697	24	10,150	173	115
j7 bott	1,323	35	8,300	101	102
h9 top	1,253	30	9,300	140	108
h9 bott	1,548	36	8,500	128	101
b9 top	1,394	30	10,100	129	107
b9 bott	1,701	40	8,500	N/A	95

Table 21: Top and Bottom Results for Kuert Concrete

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Tensile Strength (psi)	Unit Weight (lbs/ft^3)
top	1,089	29	9,550	176	112
bott	1,406	26	9,500	112	118
top	640	25	9,600	153	117
bott	N/A	41	9,200	92	95
top	401	14	10,600	218	N/A
bott	1,441	31	10,200	142	109
top	1,029	26	11,200	193	114
bott	921	36	10,000	109	101

Table 22: Top and Bottom Results for the CSU Administration Building Lab Samples

Sample	Hydraulic Conductivity (in/hr)	Void Ratio (%)	UPV	Tensile Strength (psi)	Unit Weight (lbs/ft^3)
b2 top	390	20	12,200	315	120
b2 bott	395	17	12,00	216	124
a3 top	142	21	10,400	255	118
a3 bott	295	13	12,000	351	130
b1 top	605	24	10,600	195	116
b1 bott	650	25	10,200	227	115
3 top	155	16	13,500	355	124
3 bott	171	16	13,750	311	125
d1 top	560	23	10,600	201	115
d1 bott	702	22	10,800	198	118
1 top	76	13	13,400	326	128
1 bott	114	15	13,000	294	126

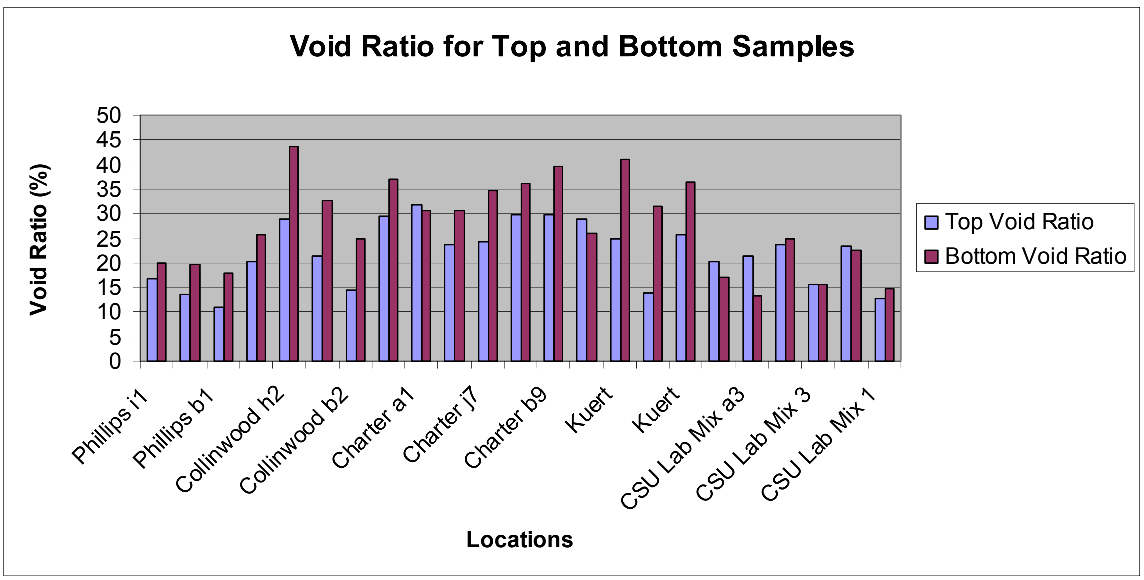

Figure 37: Void Ratios for Top and Bottom Samples

Haselbach and Freeman (2006) found that the void ratio at the top of a pervious concrete pavement was much lower than that at the bottom. The tests results reported in this section confirmed that finding.

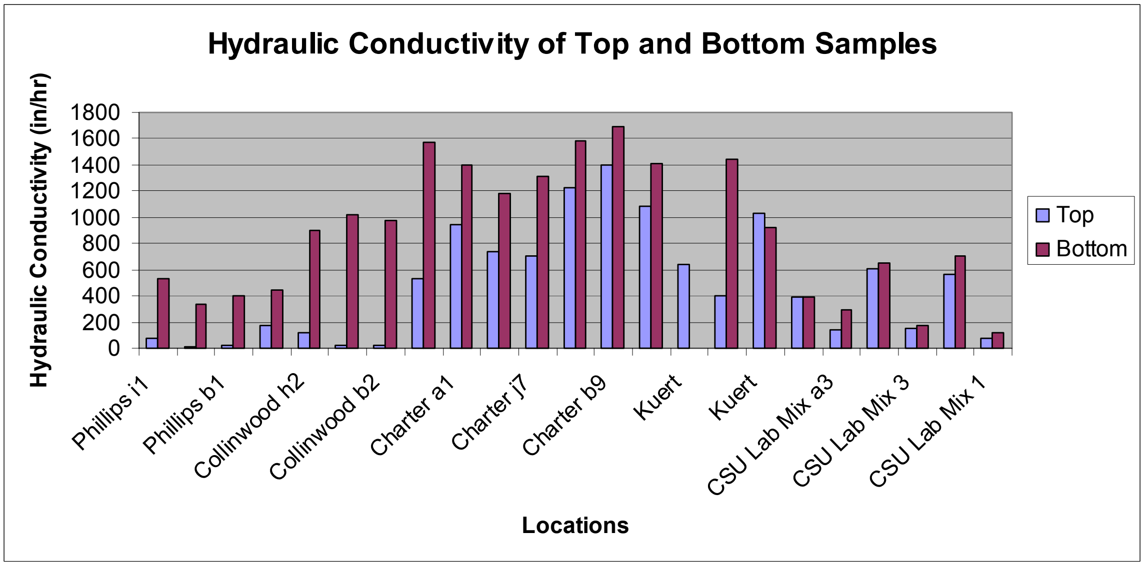

Figure 38: Hydraulic conductivity for the Top and Bottom Samples

Comparison between Field and Laboratory Hydraulic conductivity

The field infiltration/ drain time test developed as part of this research will be more useful if it can be correlated to hydraulic conductivity. Laboratory and field values are shown in Table 23. The bold numbers represent drain time values that were measured in close proximity to the coring locations. At six locations, the drain time was measured prior to coring. The hydraulic conductivity and drain time values are plotted in Figure 39.

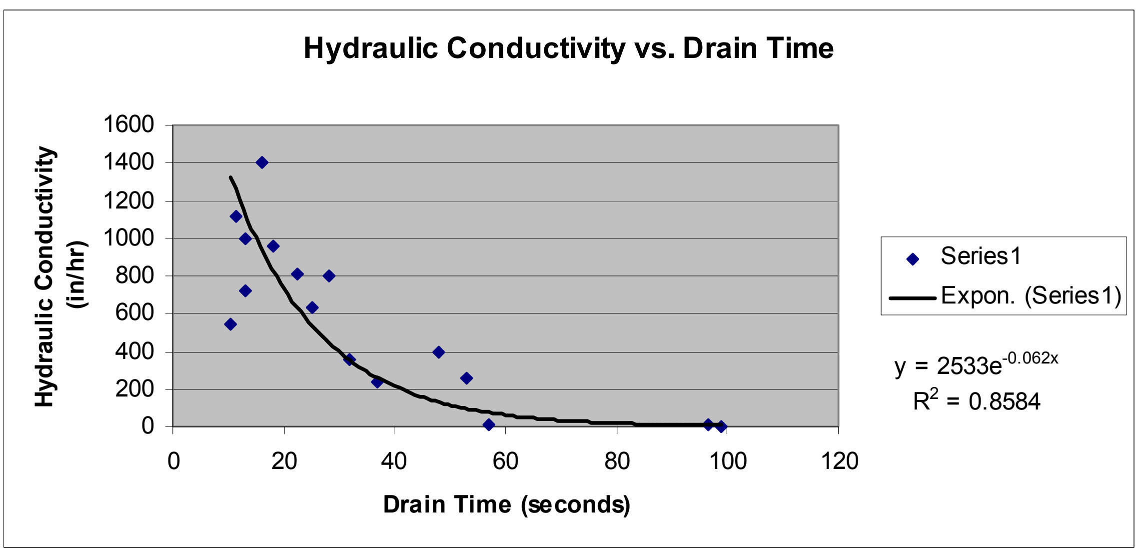

Figure 39: Comparison between Hydraulic Conductivity and Drain Time Values

The laboratory hydraulic conductivity k, in inches per hour, may be estimated from the field infiltration time t:

$$k = 2533 \times e^{-0.062t}$$

The correlation coefficient R^2 was approximately 0.86 for this equation. A similar relationship was developed only using the six data points where the drain time was measured in the same location that the core was extracted. The equation was slightly different, and the correlation coefficient was improved to 0.91.

Figure 39 shows that there is a considerable decrease in infiltration capability with drain times of greater than 40 seconds, and that infiltration capability is very low with times over 60 seconds. This chart may be used to determine whether a PCPC pavement may be considered permeable, or if maintenance is necessary to restore infiltration capability.

Table 23: Lab Hydraulic Conductivity and Drain Time Results

Location	**Sample**	**Lab Hydraulic conductivity (in/hr)**	**Drain time (seconds)**
Phillips	a1	10	N/A
	i1	90	N/A
	d1	11	57
	b1	21	N/A
Cleveland State University	b1	259	**53**
	a3	355	**32**
	a1	398	**48**
	a2	237	**37**
Charter School	a2	1114	11.5
	a1	995	**13**
	c2	797	**28**
	j7	635	25
	h9	959	18
	b9	1399	16
Kuert Concrete	e2	548	**10.5**
	b1	676	**N/A**
	f3	812	**22.5**
	d3	718	**13**
Keystone Concrete	a3	4.8	99
	b1	7.1	N/A
	b3	8.8	N/A
	d2	6.4	**96.5**

Discussion

The subsequent set of figures investigates the correlations between the following relationships:

- Hydraulic conductivity versus void ratio (Figure 40)
- Hydraulic conductivity versus pulse velocity (Figure 41)
- Compressive strength versus void ratio (Figure 42)

- Compressive strength versus pulse velocity (Figure 43)
- Tensile strength versus void ratio (Figure 44)
- Tensile strength versus pulse velocity (Figure 45)

Overall, exponential relationships were found to fit the data best. Correlation coefficients (R^2) ranged from 0.63 to 0.86.

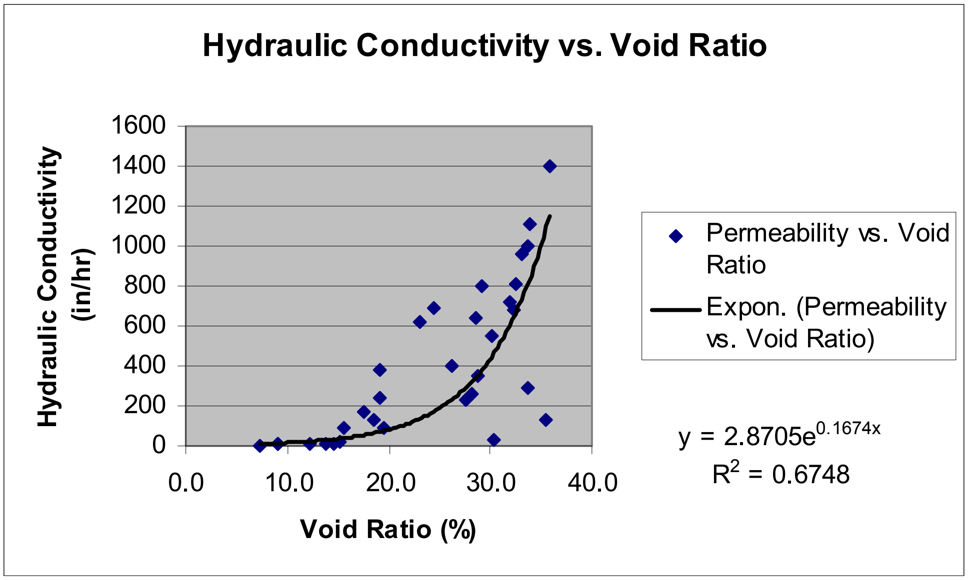

Figure 40: Relationship between Hydraulic conductivity and Void Ratio

As expected, hydraulic conductivity and void ratio are closely related, but there are some discrepancies. This is because the hydraulic conductivity depends on the interconnectivity of the voids, as well as the void ratio.

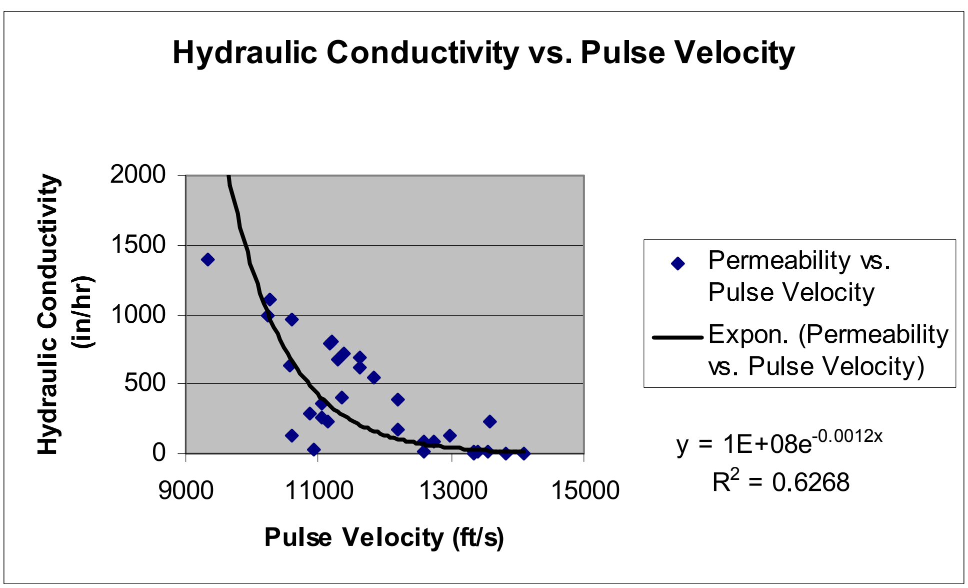

Figure 41: Relationship between Hydraulic conductivity and Pulse Velocity

The relationship between hydraulic conductivity and pulse velocity is the weakest of the six relationships developed. Pulse velocity is a more reliable indicator of strength and modulus of elasticity than of hydraulic conductivity. It can, however, provide a rough prediction.

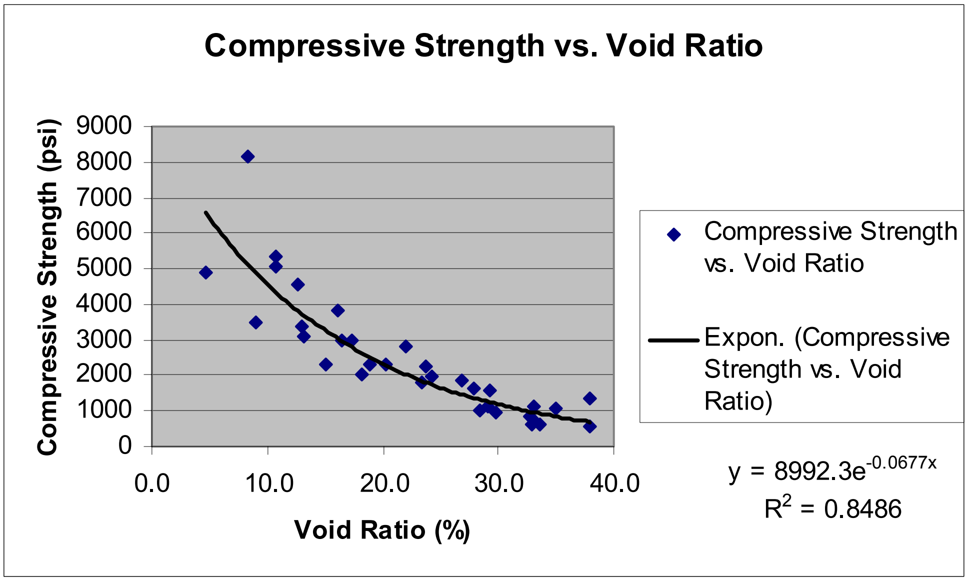

Figure 42: Relationship between Compressive Strength and Void Ratio

The relationship between compressive strength and void ratio has been documented by others, such as Schaefer et al. (2006), and is obviously strong.

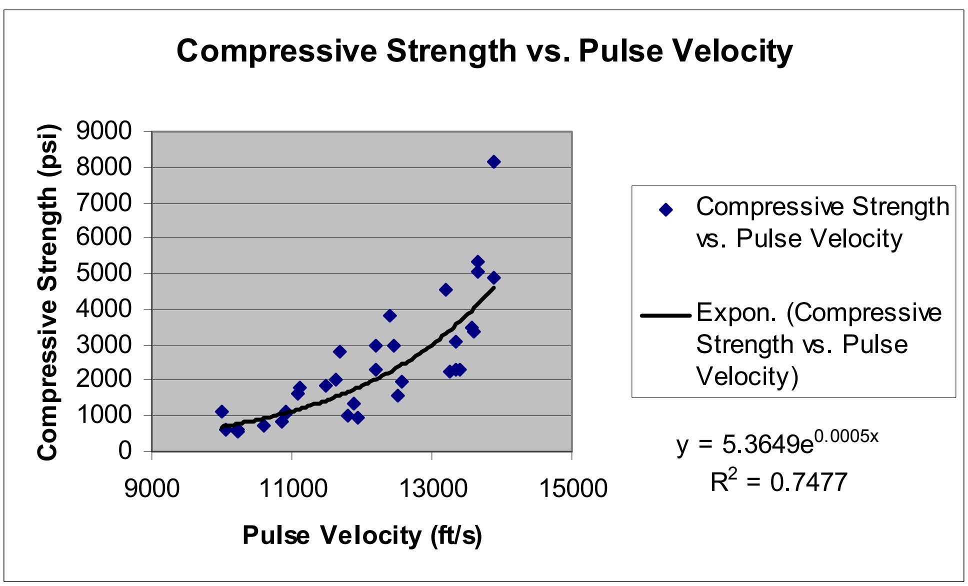

Figure 43: Relationship between Compressive Strength and Pulse Velocity

The relationship between pulse velocity and strength is also strong. The relationship would probably be improved without including one 8,000 psi outlier in the data. Therefore, UPV has potential for reliably predicting pervious concrete strength in the field.

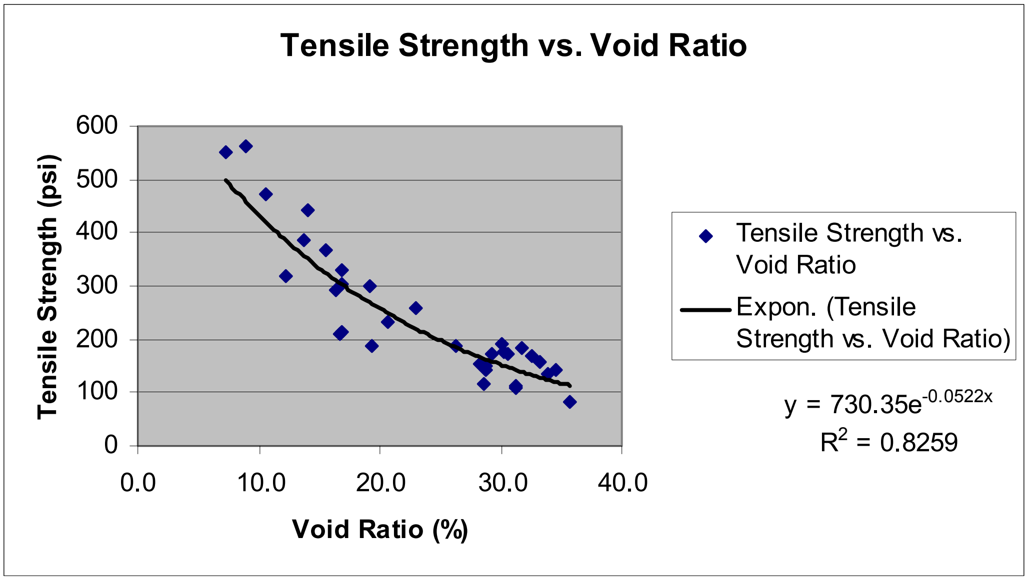

Figure 44: Relationship between Tensile Strength and Void Ratio

The relationship between void ratio and tensile strength is strong, as it is with compressive strength.

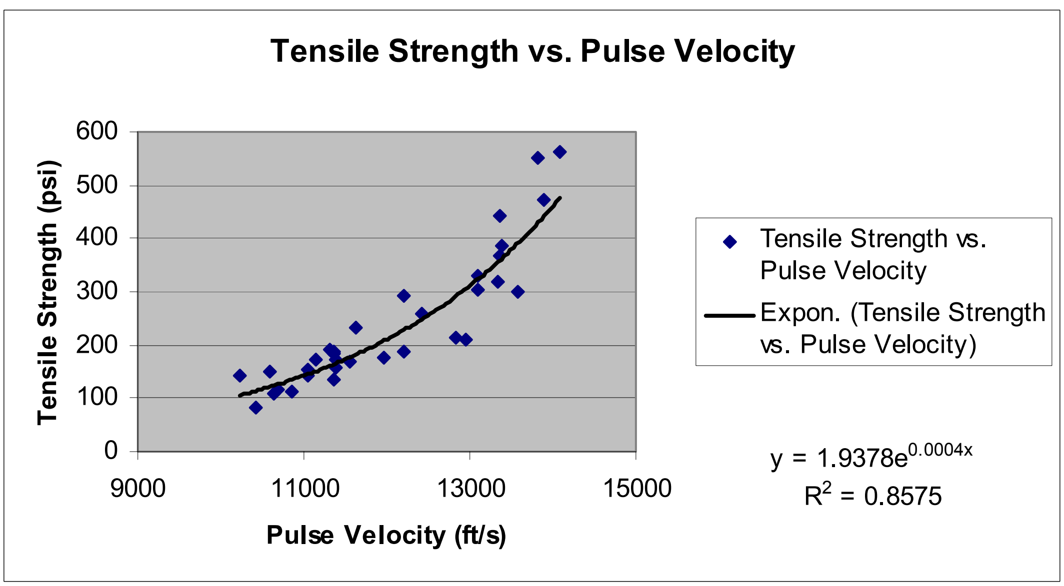

Figure 45: Relationship between Tensile Strength and Pulse Velocity

Results indicated that UPV can be a reliable predictor of tensile strength as well as compressive strength.

Separating mixtures made with the gravel coarse aggregate, and those made with limestone aggregate revealed much stronger relationships developing for the mixtures containing gravels.   These results are provided by Mrkajic (2007).

Effectiveness of Maintenance

The pervious concrete at the CSU Lot D has five parking stalls. The middle stall slightly slopes towards a manhole, and during rainfall water crosses surface of the pervious concrete and flows into the manhole. The research team attempted to restore the infiltration capacity of the middle stall with a 1,500 psi pressure washer. Before performing this maintenance trial, 10 drain time values were obtained in a grid formation. Drain time values before and after maintenance are shown in Figure 46 and Figure 47.

The middle stall was pressure washed for 30 minutes. The average drain time prior to the maintenance was 62 seconds. After maintenance, that average dropped to 40 seconds. The maintenance helped restore some of the infiltration capability, but sheet flow was visible even after the maintenance. Pressure washing of a severely clogged pervious concrete at the CSU Lot D improved the infiltration capability by about 35%.

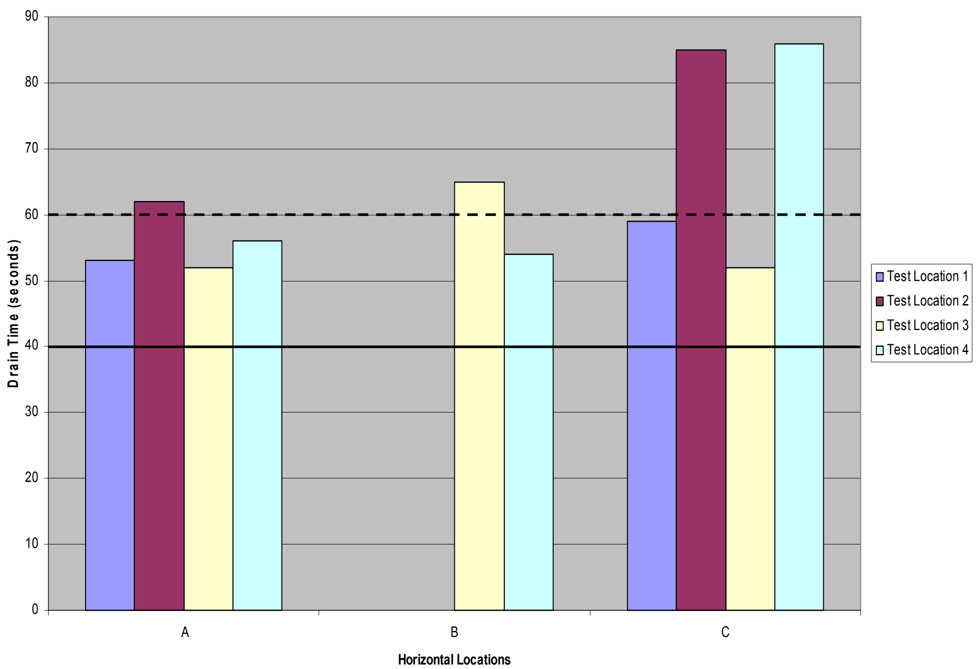

Figure 46: Drain time before Maintenance

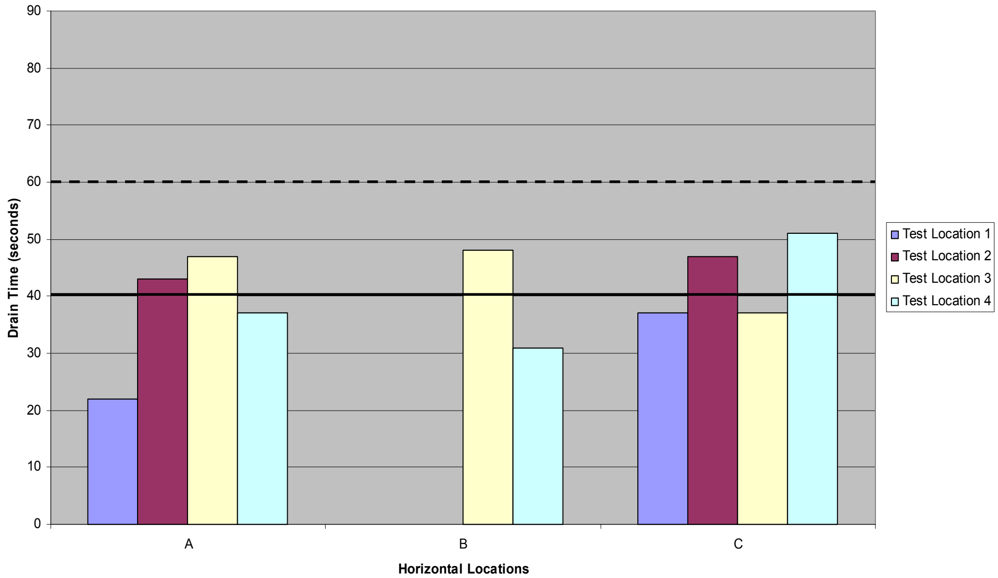

Figure 47: Drain time following Maintenance

CHAPTER 7: SUMMARY AND CONCLUSIONS

Conclusions and recommendations are provided for building freeze-thaw durable PCPC pavements, preventing clogging, restoring infiltration capability, for future field investigation methods, and for future research. Overall, the NRMCA (2004) design recommendations for freeze-thaw environments seem to be validated.

Generally, the PCPC installations evaluated under this research project have performed well in freeze-thaw environments with little maintenance required. No visual indicators of freeze-thaw damage were observed. With the exception of some installations where the pore structure was sealed during construction with wet mixtures or over compaction, nearly all sites showed fair to good infiltration capability based on drain time measurements.

Most of the sites visited do not yet require maintenance. Both vacuuming and pressure washing have worked well to restore infiltration capability. Overly aggressive pressure washing, however, may damage the surface of the pavement.

Because use of PCPC in this region began fairly recently, the sites visited are less than four years old. Although they are performing well now, it would be useful to revisit them periodically in the future. If future visits are made, the results reported in this research will provide a useful baseline for comparing performance.

Designing and Building Freeze-Thaw Durable PCPC Pavements

None of the sites investigated showed any sign of freeze-thaw damage. The damage observed was either due to early age raveling or to structural overload. This was probably because the sites were adequately drained, and therefore the pervious concrete was not saturated when the temperature was below freezing.

In conventional concrete, however, freeze-thaw damage may take many years to become apparent. It eventually results in disintegration. Therefore, in pervious concrete, freeze-thaw damage would be expected to take the form of widespread raveling progressing through the thickness of the pavement. This was not observed at any of the sites visited.

In the laboratory, the relative dynamic modulus determined using a sonometer is used to calculate the durability factor of a concrete specimen. Because UPV works on very similar principles to a sonometer, UPV should be able to detect freeze-thaw damage in the field as a reduction in wave velocity. However, this requires further work.

In addition, this research validated some of the results found in other studies:

- There is a considerable difference between the void ratio at the top and at the bottom of a PCPC pavement. Generally, the top is much better compacted.
- Gravels provide higher strength than crushed limestone.

Preventing Clogging

The most important factor for preserving PCPC infiltration capability is probably initial construction. Wet mixtures or overcompaction can produce an impermeable surface that cannot be restored by maintenance procedures.

Overall site layout and construction sequence also affect the early clogging of PCPC pavements. If the PCPC receives rainwater from a broad area of adjacent parking lot, there will be potential clogging from sediment carried with the water. Loose soil from landscaping or adjacent construction can quickly clog a newly built permeable pavement.

Restoring Infiltration capability

If a pavement which was originally permeable becomes clogged, it is possible to use sweeping or vacuuming to restore infiltration capability. One brief trial showed an improvement in infiltration capability from pressure washing at CSU parking lot D. However, some of the sites visited were still very permeable although no maintenance had yet been performed. A simple test such as the Youngs (2006) test or the drain time test described in this report may be used as a tool to determine when maintenance is required.

Field Investigation Techniques

This research employed a number of field investigation techniques that may be of value to future researchers engaged in similar studies.

Visual Observations

It has been suggested that one of the most powerful and useful investigative tools is the eye connected to the brain of a knowledgeable engineer. Visual observations can identify structural and nonstructural problems in PCPC pavements, and can often identify locations most likely to be clogged.

DrainTtime Testing

The 4 x 8 plastic cylinder mold drain time test has been found to correlate reasonably well to hydraulic conductivity. This test may be used to assess infiltration capability of newly built pavements, or to determine whether maintenance is needed. It would be useful to track results over time, in order to assess the need for and effectiveness of different maintenance treatments.

Ultrasonic Pulse Velocity

Laboratory UPV results, found by direct transmission, correlate very well with hydraulic conductivity and strength of PCPC. Field indirect transmission UPV results have so far been less reliable, but results may be improved with future research.

Testing of Cores

Unfortunately, at this time cores remain the best way to measure thickness, strength, and void ratio of PCPC pavements. In order to avoid the damage and expense of core removal, it would be desirable to develop other test methods. Of course, the new test methods would have to first be calibrated to cores. NDT methods such as UPV show promise, but require further development.

Future Research

The main drawback of the present study has been the relatively recent construction of PCPC pavements in this area. As these pavements are subjected to weather and traffic, the performance trends will become clearer.

For the sites investigated in this project, the test results provided will provide a benchmark for comparison with future test results. More complete data for the individual sites are provided by Miller (2007) and Mrkajic (2007). It is recommended that this study be repeated at 5 and 10 years, to determine the long term performance trends.

As new materials, mixtures, and construction methods are used for PCPC, the methods outlined in this report should be used to document the initial condition after construction. Thus, the long term effect of new technologies on PCPC performance may be assessed.

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