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Advancements in pervious concrete technology

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Advancements in pervious concrete technology

by

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Civil Engineering

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ABSTRACT

Pervious concrete has been used for many years in the southern United States but only recently have stormwater mandates implemented by the United States (U.S.) Environmental Protection Agency (EPA) created interest for more wide-spread installations, especially in freeze-thaw climates. Validation of the freeze-thaw durability of pervious concrete under the most extreme conditions created an opportunity to explore many additional aspects of pervious concrete and to improve durability through additional mixture characterization and new construction practices. While the material components are similar to conventional concrete, the idiosyncratic behavior of pervious concrete requires revaluating material effects and relationships. Many different factors influence the performance of conventional concrete and many different factors also affect pervious concrete, although limited data exist to support observed and expected responses.

The most crucial factors include the specific effect on freeze-thaw durability caused by the coarse aggregate type. Since the volume of paste in a pervious concrete system is much less than traditional concrete and exposure conditions much more severe, aggregate durability criteria must be determined for this specific application. The more extreme exposure conditions also require investigating the effect of air entrainment on the concrete mortar. Air entrainment improves freeze-thaw durability in conventional concrete, but to date has yet to be evaluated in pervious concrete. In addition to mixture properties, construction practices must be modified to suit pervious concrete. While the workability of conventional concrete can be simply checked using a standard slump cone, no method currently exists to determine the workability of pervious concrete. However, workability of pervious concrete influences the ease of placement and density, which also controls the yield and ultimate durability. Determining pervious concrete workability will allow more consistency between placements and help quantify the effect various mixture components have on the fresh mixture behavior. Due to it’s very low water-to-cement ratio (~0.30) curing of pervious concrete is particularly important. Pervious concrete is currently cured under plastic instead of using a conventional curing compound. No research has previously been performed to evaluate the effect various common curing methods have on strength and durability. By studying the important issues, consistency and durability can be improved and baseline values established for future research.

This dissertation includes a selection of papers encompassing a variety of important aspects in pervious concrete research, all to improve pervious concrete durability. The papers include 1) The effect of aggregate type on the freeze-thaw durability of pervious concrete, 2) A novel approach to characterize entrained air content in pervious concrete, 3) Effect of curing regime on pervious concrete abrasion resistance, and 4) Evaluation of pervious concrete workability using gyratory compaction. The results show that freeze-thaw durability of pervious concrete is controlled by the aggregate absorption and specific gravity. Air entrainment can be quantified in pervious concrete and also used to improve workability and freeze-thaw durability. Workability can be characterized by two components, initial workability and resistance to additional compaction. Workability can be determined using a low-pressure gyratory testing apparatus and results show that increased binder amount influences properties more than increased water content. Lastly, for samples cured in the field using different methods, samples cured under plastic had the highest flexural strength and abrasion resistance. Curing compounds also improved strength and abrasion resistance over no curing method.

From the results, highest priority recommendations for future research include development of standardized testing methods and standardized mixture proportioning methods. Strength and durability will be most significantly affected by improving the paste to aggregate bond strength, which will more effectively utilize the coarse aggregate strength. The basic properties established herein along with future research will allow pervious concrete to be utilized not only for parking areas but also successfully on high traffic volume roadways for improved safety and functionality.

CHAPTER 1. INTRODUCTION

Introduction

The socio-economic climate in the United States, and around the world, is changing. Engineers must consider not only the economics of a project, but now more than ever, consider the impact that projects will have on the human and natural environment. Pervious concrete has existed, in one form or another, for many years, but only recently have environmental regulations and stormwater treatment costs allowed its true consideration in engineering designs. Pervious concrete research at Iowa State University (ISU) began in 2004 coinciding with an increase in interest spurred by the United States (U.S.) Environmental Protection Agency (EPA) implementing the National Pollutant Discharge Elimination System (NPDES) Phase II requirements for stormwater improvements to smaller municipalities and construction sites (U.S. Gov. 2004). Consequently, the research findings for cold weather pervious concrete were well-timed as many engineers, both public and private, began to explore the changing world of engineering designs evaluated through an environmental lens. Validation of the freeze-thaw durability of pervious concrete under the most extreme conditions created an opportunity to explore many other aspects of pervious concrete and to improve durability through additional mixture characterization and new construction practices through a comprehensive research project (Schaefer *et al.* 2006). Based on the laboratory results; a fully-instrumented parking lot was constructed at ISU to allow quantification of the benefits provided by a pervious concrete system (Jones 2006). This dissertation includes a selection of papers encompassing a variety of different aspects in pervious concrete research all with the ultimate goal of improving the resulting quality of pervious concrete placements.

Problem Statement

The majority of pervious concrete installations are located in areas of the U.S. which do not experience freeze-thaw cycling and have otherwise benign environmental conditions. Unfortunately, pavement durability failures in these locations, while not widespread, are common. Failure is most often manifested by excessive raveling creating surface rutting and loose particles, which can reduce permeability. The prevailing opinion is that if these pavements can readily fail in warm climates, failure is almost assured in harsh freeze-thaw conditions. Since the field of pervious concrete is characterized by a relatively large number of placements with little to no research defining basic material properties and responses, basic research must first identify significant parameters and establish baseline properties for subsequent testing. Once the general properties are better understood, then long-term durability will be improved. Some general areas which influence long-term durability are:

Important Mixture Proportioning Factors

- Coarse aggregate comprises the largest fraction of material in pervious concrete. The increased exposure conditions caused by the reduced mortar cover may require a more durable aggregate type.
- For similar-sized aggregate particles, a crushed material has more surface area than a rounded particle. Since workability of pervious concrete occurs by mortar lubrication between coarse aggregate particles and by aggregate to aggregate contact, a mixture with high aggregate angularity will have reduced workability compared to a smooth aggregate mixture.
- Pervious concrete consists of aggregate particles covered by mortar joined by small contact areas. Load is transferred through the mortar to the aggregate and to another particle and the strength is significantly influenced by mortar to aggregate bond. Angular aggregate with rough texture has better bond characteristics than smooth aggregate.
- Aggregate gradation must optimize void space to allow for the addition of cement paste, and concrete density to maintain permeability. But also have sufficient strength for the required application. Additional sand creates a thicker mortar layer and higher strength but reduces void space and permeability.
- Similar to aggregate gradation, sufficient cementitious binder must be included to properly coat the aggregate particles and transfer load, but optimize the concrete strength with permeability and workability.

- Concrete performance is often improved by the replacement of cement with supplementary cementitious materials (SCMs). To improve the sustainability component by using waste materials and potentially durability by reducing paste permeability, a blend of SCMs should be used in pervious concrete mixtures.
- Adding water to concrete can improve workability, but reduces performance. A balance must be achieved in pervious concrete between enough water for workability and compaction and too much water and can cause the paste to drain from the aggregate surface.
- Chemical admixtures stabilize the microscopic air system of concrete, improve workability at low water contents, prevent early cement hydration, and improve paste strength and bonding, along with a host of other characteristics. Correct admixture selection and dosing can significantly improve or hinder pervious concrete placement.

Important Concrete Construction Factors

- Workability of pervious concrete controls hardened density and durability. Correct determination of plastic workability is crucial to proper placement.
- Variability in aggregate stockpile moisture, environmental conditions, and batch composition require verification of consistency between concrete batches for the same mixture.
- Once the concrete has been placed, methods are required to determine if the desired engineering properties, such as strength and permeability, were achieved.
- Various compaction and finishing techniques exist and mixture proportions and workability must be adjusted to achieve the design engineering properties.
- The most critical period for pervious concrete is the curing conditions during the first 7-days. Proper hydration creates high strength and durability while poor curing allows the concrete to desiccate, substantially increasing raveling potential.

In order to improve pervious concrete durability, especially for cold weather applications, research must first be performed to understand the effects mixture components have on the material properties and to establish initial baseline values for comparison with future research. Once the mixtures are better understood, test procedures must be developed to verify the mixture design and engineering properties. Also, since various construction practices are available, these practices must be evaluated to determine acceptable methods for particular mixtures and placement situations. Of the preceding components that impact durability, the following were studied further.

Objectives of Factors Selected for Further Study

- The effect of coarse aggregate type on freeze-thaw durability was investigated by obtaining samples from around the U.S. and Canada, and creating pervious concrete using volumetrically the same mixture proportions to account for varying aggregate densities. Aggregate and concrete properties were tested along with freeze-thaw durability testing. The objective was to determine what aggregate properties control freeze-thaw durability and to provide aggregate criteria suggestions for future pervious concrete mixture proportions.
- The effect of air entrainment was evaluated using two aggregate types, two air entraining admixtures, and three dosage rates. Air entrainment was quantified using a RapidAir 457 testing device and for durability by freeze-thaw testing. Objectives were to quantify the level of entrained air, determine the effect on material properties, and to provide suggestions for use of air entrainment in future pervious concrete mixtures.
- While workability controls ease of placement, level of compaction, final density, and ultimate durability, current methods of concrete workability determination do not apply to fresh pervious concrete properties. As a key factor, the objective of the workability study was to develop a workability test for pervious concrete and to evaluate the effects common mixture variables, binder and water content and mixing time, had on the newly developed workability parameters.
- The effect of curing method and mixture composition on durability was evaluated using six curing methods applied to samples of one concrete mixture and of one curing method applied to samples of four different concrete mixtures. Beams were tested for flexural strength and surface abrasion resistance. The objective of the study

was to determine if the standard plastic cure was adequate and if it out performed other curing methods.

Dissertation Organization

This dissertation is organized into seven chapters. Chapter 1 is the introduction and problem statement. Chapter 2 provides a review of pervious concrete literature. Chapter 3 is a report for research sponsored by the Portland Cement Association concerning the aggregate specific effect on the freeze-thaw durability, which will be revised into a submission for the American Concrete Institute (ACI) Materials Journal. Chapter 4 is a paper evaluating the entrained air content and effect on freeze-thaw durability on pervious concrete, published by the Journal of ASTM International. Chapter 5 is a paper discussing the development and verification of a proposed new method to determine workability properties of fresh pervious concrete submitted to the ASCE Journal of Materials in Civil Engineering. Chapter 6 is a paper evaluating various curing methods using concrete strength and surface durability submitted to the ASTM Journal of Testing and Evaluation. Summary and conclusions are provided in Chapter 7.

CHAPTER 2. LITERATURE REVIEW

A thorough literature review of the current state of the art in pervious concrete was provided as part of the author's master's degree thesis in 2006 (Kevern 2006). At that time Portland Cement Pervious Concrete (PCPC) had been utilized in Florida and the southeastern U.S. since the early 1970's for stormwater benefits. U.S. EPA NPDES Phase II stormwater permit requirements were requiring engineers to begin exploring best management practices (BMPs) to meet the stormwater quantity and quality levels. Primary issues of concern were freeze-thaw durability and clogging potential. Limited test installations in hard-wet freeze climates were being constructed in several northern states including Iowa. Pervious concrete had been used in limited applications in Europe and Japan on roadways. Results from Japan and testing at Purdue showed that pervious concrete had the potential for tire noise reduction over a dense-graded pavement.

Mixture proportioning typically consisted of single-sized aggregate with locally selected levels of cementitious binder and water. Water reducing along with air entraining admixtures were also suggested. High durability mixture proportions from Europe found 5 to 10% fine aggregate an optimal amount for strength and durability. Latex-based admixtures had been employed to improve the cement paste tensile strength. Most mixtures in the U.S. had relatively high porosity (15%-35%) and low strength, while European mixtures had lower porosity (15%-20%) and higher strength. Laboratory freeze-thaw testing showed that rapid testing of saturated samples produced 50% faster deterioration than slower testing, while semi-saturated or dry samples had even better performance.

Various studies in Florida and England showed that pervious concrete had an ability to treat stormwater mechanically as well as biologically. Oil dripping from a simulated crankcase was metabolized by soil microbes, while nutrient levels and suspended solids were reduced between 65% and 95%. Although controlled by local conditions, pervious concrete systems easily infiltrated the water quality volume (WQM) of the 2-year rain event and could be designed to store up to a 100-year event.

The following literature review includes a summary of the major advancements, findings, and reports in the field of pervious concrete since May 2006. The recent progression in acceptance and validation of pervious concrete most notably includes the formation of the American Concrete Institute (ACI) committee 522 on pervious concrete, formation of the Association for the Standardization of Testing and Materials (ASTM) subcommittee 09.49 on pervious concrete, several reports of research sponsored by the Ready Mixed Concrete (RMC) research and education foundation, and the Portland Cement Association (PCA) education foundation.

Additional Literature Produced by Researchers at Iowa State University

With research findings and interest generated by the author's master degree thesis, a number of reports, papers, and additional research projects were produced by researchers at ISU. A summary of the references and key findings are provided in Table 1.

In May 2006 the National Ready Mixed Concrete Association (NRMCA) sponsored the Concrete Technology Forum – Focus on Pervious Concrete. The proceedings included four papers from ISU. "Pervious Concrete Construction: Methods and Quality Control," presented a synthesis of compaction and finishing techniques and presented the relationship between compaction and unit weight (Kevern *et al.* 2006). "Development of Mix Proportions for Functional and Durable Pervious Concrete," described the testing of mixtures containing several types and sizes of aggregate along with various admixtures (Wang *et al.* 2006). "The Effect of Compaction Energy on Pervious Concrete Properties," described the strength and unit weight difference of samples placed using two compaction methods (Suleiman *et al.* 2006). "An Overview of Pervious Concrete Applications in Stormwater Management and Pavement Systems," presented the integrated study at ISU to develop PCPC for overlay applications (Schaefer *et al.* 2006).

Site construction and sensor installation along with temperature data produced from the ISU Lot 122 stormwater project throughout the first winter was presented at the Environmental Sensing Symposium hosted by Boise State University. The paper described the construction and sensor installation of the Iowa stormwater project and the preliminary data identified the pervious system as much warmer than the surrounding air temperature even during the winter months, suggesting further research was required to identify the heating mechanism (Schaefer and Kevern 2007).

More complete temperature and soil moisture data from ISU Lot 122 were submitted to the American Society of Civil Engineering (ASCE) for inclusion in the Geo-Congress 2008. The results showed that over the course of the 2007 winter, the pervious concrete pavement and the aggregate base beneath the pervious concrete remained much warmer than the adjacent conventional concrete or the surrounding air temperature. Over the course of the winter there was only a small period of time (10 days) when the soil froze beneath the aggregate, occurring when the air temperature was too cold for precipitation. Whenever melt water was present, the pervious concrete system functioned as an infiltration-based BMP (Kevern and Schaefer 2008).

From the continued research and success of mixture proportioning for freeze-thaw durable concrete, an additional journal article was accepted for publication in the Journal of ASTM International. “Pervious Concrete Mixture Proportions for Improve Freeze-Thaw Durability,” described mixture proportions created with various levels of sand, fibers, and types of fibers. The results showed that sand provided the greatest improvement to freeze-thaw durability with fibers improving mixtures not containing sand (Kevern *et al.* 2008a).

As a follow-up to the 2006 conference, the NRMCA will be hosting the 2008 Concrete Technology Forum – Focus on Sustainable Development, where ISU has three presentations and two papers accepted. “A Synthesis of Pervious Concrete Freeze-Thaw Testing Results,” overviews all of the to-date freeze-thaw testing performed at ISU (Kevern *et al.* 2008b). “A Retrospective Look at the Field Performance of Iowa’s First Pervious Concrete Sections as of Spring 2008,” provides a comparison of initial performance and that after two or three years later (Schaefer *et al.* 2008).

By applying the classification methods described in Chapter 5, a self-consolidating pervious concrete was designed for overlay placement using a slipform paver. A paper describing development of the new concrete will be included in the *Third Annual Conference on the Design and Use of Self-Consolidating Concrete*, hosted by Northwestern University. Mixtures were designed that possessed high workability with equally high required compaction energy. The high workability allowed rapid placement while the high degree of compaction energy allowed the concrete to remain permeable after mechanized compaction (Kevern *et al.* 2008c).

Table 1. Summary of ISU research findings

Reference	Overview of Key Issues	Findings and Conclusions
Kevern *et al.* 2006	A wide variety of construction practices are currently used for pervious concrete placement, yet the effects on hardened material properties are not known. An overview of placement methods is provided and slab samples were placed in the laboratory using different field-based methods.	The density versus porosity relationship is linear for a particular mixture. Fewer passes with a heavy roller produces more uniform compaction, while more passes with a lighter roller densifies the surface layer.
Wang *et al.* 2006	A comprehensive study of mixture proportioning had not been performed which used freeze-thaw durability as a primary criteria. A variety of aggregate types, gradations, and sizes were investigated along with binder amount and admixture dosages.	Approximately 7% fine aggregate by weight of coarse aggregate provided significant increases to strength and durability. Acceptable mixtures should have permeability greater than 0.1 cm/s, compressive strength greater than 20 MPa, and less than 5% mass loss at 300 cycles using the ASTM C666A method.
Suleiman *et al.* 2006	Fresh and hardened concrete properties are controlled by the density produced by a particular compaction method. The effect on material properties was explored using two different compaction energies.	Samples using the same mixture proportions compacted at two different energies, low and high, had very different properties. Strength decreased and permeability and porosity increased. It was expected that the low compaction samples would experience more rapid freeze-thaw deterioration.
Schaefer *et al.* 2006	While the benefits of pervious concrete for stormwater treatment are being research and comparatively well understood, pervious concrete can be beneficial if used for roadway applications.	Two research tracks were proposed, full-depth for stormwater applications and overlay for noise reduction and skid resistance. Both require mixture proportioning and thickness design procedures.
Schaefer and Kevern 2007	A fully instrumented parking lot was constructed at ISU to quantify effects on stormwater of a pervious concrete system.	Sensor installation coordinated with contractor scheduling and weather delays proved difficult. The aggregate layer significantly delayed the frost layer formation beneath the pervious pavement.
Kevern and Schaefer 2008	Temperature data collected from the instrumented lot during the winter, spring, and summer of 2007 was presented.	The cold weather response showed a buffered response of temperature with depth. A frost layer developed underneath the pervious concrete after 32 days of below freezing temperature and thawed within 12 hours of the air temperature rising above 0ºC. In all conditions, mid-layer of the pervious concrete was warmer than the surrounding air temperature.
Kevern *et al.* 2008a	The effects on material properties including freeze-thaw durability was studied using various combinations of fine aggregate and polypropylene fibers.	Fine aggregate reduces porosity and permeability while increasing strength and durability. Fibers follow the same trend except for maintaining or increasing permeability. Fibers increased durability for mixtures without sand, but the best mixture had sand and fibers.

Table 1. Summary of ISU research findings (cont.)

Reference	Overview of Key Issues	Findings and Conclusions
Kevern *et al.* 2008b	Many different mixture variables have been evaluated with respect to freeze-thaw durability. A synthesis of important testing results was provided including a matrix of water-to-cement ratios, compaction levels, SCM replacement levels, and admixture types and dosages.	For mixtures without sand, more water improved compaction and durability. Higher compaction produced better durability. Except for 5% silica fume replacement, SCMs reduced durability. Latex polymers improved workability but generally decreased durability. A more realistic procedure of pre-drying with re-saturating samples produced better freeze-thaw responses.
Schaefer *et al.* 2008	Several pervious concrete locations in Iowa have been installed for two or more winters. A condition survey along with field permeability was presented.	Generally the installations have acceptable durability. Sites with performance issues had marginal curing and excess surface raveling. Communication between the designer and owner about expectations and maintenance was suggested to prevent damage due to ignorance of the pavement characteristics.
Kevern *et al.* 2008c	In order to improve durability, mixture placement must be more consistent. Self-consolidating pervious concrete was developed for use with a slipform paver.	Using workability parameters developed in Chapter 5, mixtures were developed that had high workability for ease of placement but also significant additional compaction energy required to maintain porosity through mechanized placement.

Reports and Activities by the RMC Research & Education Foundation

Before the RMC Research & Education foundation began sponsoring pervious concrete projects, a synthesis was sponsored for Dr. Heather Brown at Middle Tennessee State University to prepare “Pervious Concrete Research Compilation: Past, Present, and Future.” The synthesis contained seven sections: Applications and Case Studies, Construction Techniques, Durability and Maintenance, Hydrological and Environmental Design, Mix Designs, Specifications and Test Methods, and Structural Design and Properties. The document included additional sources of information and the general state of pervious concrete in the United States (Brown 2007). Brief summaries were provided from the proceedings of the 2006 Concrete Technology Forum – Focus on Pervious Concrete, sponsored by the NRMCA.

RMC then released three research reports available on CD-ROM titled, “Construction and Maintenance Assessment of Pervious Concrete Pavements,” “Hydraulic Performance

Assessment of Pervious Concrete Pavements for Stormwater Management Credit," and "Compressive Strength of Pervious Concrete Pavements" from the University of Central Florida.

The construction and maintenance assessment compared field hydraulic performance of sites located in Florida to the laboratory performance as determined by the embedded-single ring infiltrometer. Maintenance was performed using various combinations of pressure washing and surface vacuuming. Results showed that permeability typically increased by 200% when maintenance was performed. One of the major factors controlling permeability and performance was the quality of initial construction and experienced pervious concrete contractors were recommended (Chopra *et al.* 2007a).

The hydraulic performance report focused on the infiltration capacity of core samples extracted from various sites around Florida. Again, the embedded-single ring infiltrometer was used to determine permeability. Laboratory permeability was generally lower than that measured in the field although a recommendation was presented to grant stormwater credit for infiltration for pervious concrete pavement (Wanielista *et al.* 2007).

The study of compressive strength results evaluated core samples previously extracted for permeability testing purposes. Concrete with various mixture proportions was evaluated resulting in average strength of 11.7 MPa (1,700 psi). Raveling of individual concrete pieces was observed at the entrance and exits of various sites leading to the recommendation of limiting pervious concrete installation where repetitive loading occurs. Higher aggregate to cement ratios decreased strength while higher water-to-cement ratios tended to decrease porosity. The recommendation was to limit pervious concrete to lower loading applications (Chopra *et al.* 2007b).

An additional study titled "Portland Cement Pervious Concrete: Field Performance Investigation on Parking Lot and Roadway Pavements," evaluated the field performance of sites installed in cold weather regions including Indiana, Ohio, Kentucky, Pennsylvania, and Colorado. Strength of core samples was correlated to non-destructive ultrasonic pulse velocity testing. *In-situ* permeability was determined using an improvised field permeameter and compared with laboratory testing of core samples. Although the sites were relatively new, four years old or less, none showed signs of freeze-thaw deterioration. Both vacuuming and pressure washing were appropriate methods to maintain and restore permeability. It was recommended that a field investigation be performed in the future to assess long-term performance (Delatte *et al.* 2007).

A study is currently underway at ISU sponsored by the RMC Research & Education Foundation in conjunction with the Federal Highway Administration (FHWA) to evaluate pervious concrete for overlay applications. High durability pervious concrete mixtures are being developed for overlay applications to reduce tire noise and improve skid resistance on high speed roadways.

Reports and Activities by the Portland Cement Association

In 2006, the Portland Cement Association (PCA) education foundation sponsored three fellowships involving pervious concrete, including Chapter 3 of this dissertation. Of the three, "Effect of Pervious Concrete on Potential Environmental Impacts from Animal Production Facilities," has been released on-line. Results showed that pervious concrete provided nutrient reduction when used as a filter for animal waste (Luck and Workman 2007). The third report "Serviceability of Pervious Concrete Pavements," is pending release.

In 2004, the PCA and NRMCA released the comprehensive and often cited "Pervious Concrete Pavements," describing the background and uses for pervious concrete (Tennis *et al.* 2004). Early in 2007, the PCA released a supplemental CD-ROM titled "Pervious Concrete: Hydrological Design and Resources," to assist engineers in section design and estimating the hydrologic impact pervious concrete may have on a new or existing site (Leming *et al.* 2007a). Late in 2007, a companion manual was released for the CD-ROM titled, "Hydrologic Design of Pervious Concrete." The CD-ROM and the manual cover the design process to create a functional pervious concrete system (Lemming *et al.* 2007b).

Reports and Activities by the National Ready Mixed Concrete Association

Motivated by the concrete industry, the NRMCA sponsored the 2006 Concrete Technology Forum – Focus on Pervious Concrete, hosted in Nashville, TN. Over two days, pervious concrete experts from around the country presented papers highlighting new developments, construction techniques, durability and maintenance, and general experiences (NRMCA 2006).

The construction techniques section included two previously mentioned papers by ISU. Additional research was provided from a study at Tennessee Technological University where various gradations of crushed material was impact compacted at six levels. Results showed smooth aggregate produces denser concrete at equal compaction energy. Compressive strength decreased with increased porosity and with increased aggregate gradation coarseness (Crouch *et al.* 2006).

One other study presented freeze-thaw durability results of pervious concrete samples at different moisture conditioning levels. Samples were preconditioned at varying levels of vacuum saturation and then exposed to freeze-thaw testing. When vacuum saturated, pervious concrete had better resistance than conventional concrete at similar conditioning level, however laboratory cured pervious concrete experience more rapid deterioration when tested in moist conditions. Moist samples tested in dry conditions, such as in the field, had the best freeze-thaw durability. The mechanism of deterioration was most often paste debonding from the aggregate resulting in lost particles (Yang *et al.* 2006).

To address the need for educated and experienced pervious concrete contractors, the NRMCA created the Pervious Concrete Contractor Certification course. Participants learn about mixture design and characteristics, tools and equipment, site layout, construction, and troubleshooting. Two levels of certification are possible, the technician level requires the successful completion of the written portion of the certification course, the craftsman level must demonstrate at least 1,500 hours of work experience with pervious concrete and a performance evaluation (NRMCA 2005).

Reports and Activities by the American Concrete Institute

In response to the popularity and interest in pervious concrete, ACI formed the 522 pervious concrete committee. In order to forward the progress of pervious concrete, the ACI 522R-06 committee issued a report to provide a current state-of-practice and identify areas of importance for the technology. The document includes ten chapters covering materials, design, construction, performance, and future research needs (ACI 2006). A brief history of pervious concrete includes the use of pervious concrete as a building material in Europe after World War II. Discussion of current applications focuses on parking areas with mention of roadway uses. Results for basic properties include linear reduction in strength with increased voids and decreased voids with increased compactive effort. Permeability exponentially increases with porosity with a rapid increase above 25%. Only briefly mentioned are mixture proportioning and section design. A construction section includes site preparation and placement procedures, although only one method of compaction is included. Since no standardized testing methods exist, ACI 522R-06 only mentions the need for standard development. The document was produced as a first attempt to briefly acknowledge the current practices; as the field evolves more revisions will be released. The ACI 522 committee will be developing specifications for pervious concrete placement which should be released for public use later in 2008.

Other Pervious Concrete Literature

While the focus of pervious concrete in the U.S. has been for parking areas, significant research and developments around the world have been investigating pervious concrete for higher-volume applications. From the Netherlands, the ModiSlab (Modular, Intelligent, Energy, Slab) consists of a precast concrete panel placed on concrete piles with a two-layer pervious concrete surface for noise reduction and skid resistance. The panels are cast upside-down and consist of a 30 mm (1.18 in.) fine textured surface pervious mixture for noise reduction followed by 40 mm (1.57 in.) of a coarser pervious concrete mixture for water transmission, overlying a precast conventional concrete section. The total thickness of the slab is 380 mm (15 in.). Test results show that the noise level is 6-7 dB quieter than a dense-graded asphalt. A combination of finite element modeling and accelerated load testing determined that the required bond strength between the pervious and conventional layers needed to be 1 MPa (145 lb/in^2) to prevent debonding, while the measured values were 2.4 MPa (345 lb/in^2). Both field testing and accelerated load results have shown excellent durability with little surface raveling (Bax *et al.* 2007).

The Australian Road Network Infrastructure Directorate is exploring the potential of pervious concrete on roadway surfaces. Pervious concrete mixtures and placement techniques were evaluated for wet-on-wet placement for noise reduction and skid resistance. The selected mixtures were latex polymer-modified concrete with 56-day flexural strength between 1.9 MPa and 2.6 MPa (276 psi and 377 psi). Curing the concrete under plastic for 7-days produced the greatest strength. It was observed that the void content increased significantly with increased mixing time, suggesting that a flowable mixture was desired for strength and ease of placement. The best bond strength occurred when the underlying conventional concrete was fresh, less than three hours after initial placement (Vorobieff and Haber 2005).

Summary of Research Available in the Literature

Significant progress concerning all aspects of pervious concrete has been made in recent years. The continued interest and research will ensure better performing and longer lasting pervious concrete pavements. Table 2 presents a summary of the major accomplishments and also continued areas of focus.

Table 2. Summary of the literature and areas of future research

What has been accomplished	What is yet to be accomplished
Research related to mixture proportioning and responses of various components on material properties.	Create a standardized mixture proportioning procedure.
Development of overlay mixture proportions.	Evaluate performance and durability of pervious concrete used as an overlay.
Increased pervious concrete durability and application.	Development of pavement design criteria for parking areas, low volume roads, and overlays.
Investigation into the stormwater benefits provided by pervious concrete.	Determining acceptable stormwater quality and quantity reduction levels for particular site applications for stormwater permitting purposes.
Contractor certification process.	Development of standardized test methods for quality control, quality assurance, and verification of required engineering properties.
Short-term durability evaluation in cold climates.	Longer-term evaluation with an accurate method to determine field permeability.
Research supporting the benefits and durability of pervious concrete.	Creation of an owner’s manual for pervious concrete which clearly defines realistic expectations for maintenance for long-term performance. The manual must include development of a plan both for cleaning schedule and winter maintenance.

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CHAPTER 3. THE EFFECT OF AGGREGATE TYPE ON THE FREEZE-THAW DURABILITY OF PERVIOUS CONCRETE

A report submitted to the Portland Cement Association through the Education Foundation Fellowship program.

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Abstract

Pervious concrete is becoming more common as a stormwater management tool in freeze-thaw climates. One of the main concerns or obstacles preventing more wide-spread application is the aspect of freeze-thaw durability, whether perceived or actual. During previous investigation into the freeze-thaw durability of pervious concrete it has been observed that some aggregates approved for use in conventional concrete experienced premature deterioration when incorporated into pervious concrete (Schaefer *et al.* 2006). This paper describes a series of tests designed to determine the specific role coarse aggregate has on the freeze-thaw durability of pervious concrete using the ASTM C666A procedure. Seventeen different coarse aggregate samples were obtained from locations across the United States and Canada. Concrete mixtures were placed using a mixture proportion previously determined as freeze-thaw durable. The range of aggregate gradations clearly defined a gradation specification and suggestions are made for optimizing the gradation with a small portion of sand. Mixtures with excellent freeze-thaw performance contained either granite or highly durable river gravel. The impact of aggregate angularity on mixture proportions and ultimate yield is also discussed.

Introduction

In recent years stormwater regulations have become more stringent requiring municipalities to provide treatment of stormwater to reduce both the volume of runoff and the concentration of pollutants contained therein. Many different Best Management Practices (BMPs) can be utilized to aid in achieving the new EPA standards and porous pavements, especially Portland Cement Pervious Concrete (PCPC), have shown promising environmental benefits. PCPC reduces the hydrologic peak associated with storm events by increasing the time of concentration and by promoting infiltration underneath the pavement (EPA 2004). Pollutants including hydrocarbons are spread over the large exposed surface area where natural attenuation reduces contaminant levels, where normally pollutants are conveyed directly to nearby surface water via conventional impervious pavement and the stormwater collection system. PCPC has also been shown to reduce pavement noise levels (Olek *et al.* 2003, Bax *et al.* 2007) and prevents the accumulation of water on pavement surfaces where ice may create unsafe surface conditions. PCPC has been used successfully in the southern and western United States (U.S.) for a number of years but the primary obstacle preventing PCPC from being used in the cold regions of the U.S. is the lack of test methods and experimental data verifying the durability of the concrete in freeze-thaw environments (NRMCA 2004).

Recently, research has been performed at Iowa State University (ISU) exploring potential PCPC mixture proportion durability in cold weather applications. The results indicate that PCPC made with single-sized aggregate has high permeability but not adequate strength. Adding a small amount of sand into the mix improved the PCPC strength and freeze-thaw resistance (Kevern *et al.* 2005). However, the ISU research was limited to the use of single-sized aggregates found within a small area of central Iowa. Research has indicated that the freeze-thaw deterioration of PCPC is directly related to the aggregate type (Kevern *et al.* 2006) and Figure 1 shows an example. The average mass loss of a set of samples containing limestone are compared to a set of samples containing river gravel, created using the same mixture proportions. Both aggregates were approved for standard Iowa Department of Transportation concrete mixtures, but the additional exposure level of aggregate in pervious concrete suggested a more durable aggregate may be required. In order to promote further use of PCPC in the U.S., the behavior of a wider variety of aggregates must be studied.

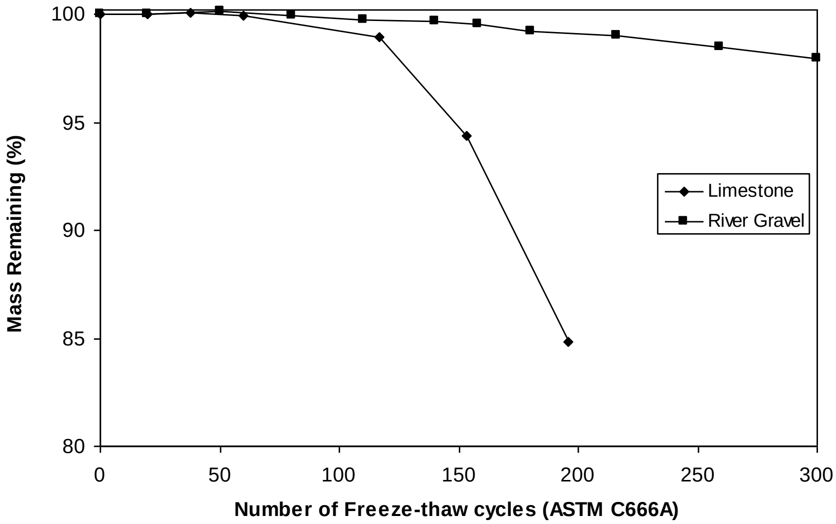

Figure 1. Freeze-thaw performance of PCPC made with two different aggregates, a 3/8" single sized limestone and a #4 river gravel and sand (Kevern *et al.* 2005)

Although, no consensus has been reached concerning an appropriate test method for evaluating PCPC freezing-thawing resistance. ASTM C 666A was performed since the saturated state represented the worst possible scenario for pavement, with the greatest potential for accelerated deterioration. Also, the effect of aggregate on PCPC freeze-thaw durability may be significantly different from that of conventional concrete because the thickness of cement paste surrounding the aggregate is much smaller becoming saturated much more quickly leading to premature deterioration. This may lead to the determination that certain aggregates approved for traditional concrete will not be suitable for pervious concrete.

Background

The Role of Aggregate in the Freeze-Thaw Behavior of Conventional Concrete

Aggregate, comprising 60% to 75% volume of concrete, plays an important role in concrete performance (Kosmatka *et al.* 2002). Besides influencing concrete workability and mechanical properties, aggregate strength, pore structure, size, and gradation also significantly affect concrete strength. Durable aggregates are required for long-term concrete performance.

When the aggregate particles become saturated and the water freezes, hydraulic pressure increases, and if the aggregate pores do not allow water to rapidly move to unsaturated portions of the aggregate, hydraulic pressure exceeds aggregate strength causing cracking and deterioration. Another aspect of freeze-thaw durability is premature deterioration caused by movement of deicer chemicals into the concrete paste matrix. Water carries salt solutions into the concrete and when drying occurs the salt crystallizes in the concrete or aggregate creating excess pressure and damaging the concrete structure from within (Kosmatka *et al.* 2002). Generally, smaller aggregates are more freeze-thaw durable than larger aggregates of the same material by reducing the length water must travel to exit the aggregate and relieving pressure (Mehta and Monteiro 1993). In certain aggregate types deicer salts damage the chemical structure of the aggregate causing deterioration. The various mechanisms of freeze-thaw deterioration are manifested by durability (D) cracking, which is the most common distress caused by non-freeze-thaw resistant aggregate. Concrete deteriorates from the saturated edges across the slab often forming the shape of a capital letter D (Taylor *et al.* 2006).

Features and Requirements of Aggregate Used in Pervious Concrete

In conventional concrete the cement paste surrounds the aggregate particles and completely occupies the entire volume between the aggregates (Kosmatka *et al.* 2002) and permeability is primarily controlled by the cement paste. In pervious concrete, ideally, the cement paste completely coats the aggregate particles but without occupying too much volume between the particles, allowing rapid water movement. Pervious concrete has two levels of permeability where, macro-scale voids control stormwater infiltration and micro-scale voids control the concrete durability. For aggregate freeze-thaw deterioration in conventional concrete, water must saturate the concrete by exposed surfaces or edges, penetrating through the large volume of cement paste. Oppositely, aggregate in pervious concrete is surrounded by a very thin (~1mm) layer of cement paste which may become saturated relatively quickly as water infiltrates through the pavement. While sections in cold climates are designed to prevent storing water in the pervious concrete layer, the paste may actually become saturated when water movement occurs through the pavement, trapping moisture inside the coarse aggregate.

While aggregate has much the same role in pervious as conventional concrete, certain idiosyncrasies of pervious require additional aggregate considerations. Considering that pervious concrete transfers forces through cement paste coated aggregates by aggregate-to-aggregate contact and the paste contact area connecting the particles, the important aspects of the system are:

- A volume of cement paste is required to completely coat all of the aggregate particles with enough paste thickness to provide intraparticle contact area and load transfer.
- Sufficient paste/aggregate bond strength is required to prevent debonding during load transfer. Cement paste must be workable enough to completely coat the aggregate particles and lubricate the mixture to achieve the design concrete density but, have minimized paste permeability to help prevent aggregate saturation, most often achieved through very low water-to-cement ratios.
- Aggregate should be durable enough for extreme exposure conditions.

Overview of Pervious Concrete Freeze-Thaw Behavior

Recently a number of publications, reports, synthesis, and thesis have been released that provide an excellent summary of the current state-of-practice in the field of pervious concrete research. A complete literature survey, up to 2004, was included in the Master's thesis of Kevern (2006) and Schaefer *et al.* (2006) and updates provided in the Ph.D. dissertation (Kevern 2008). To prevent unnecessary duplication, the following literature review will only include significant contributions to the field of pervious concrete related to freeze-thaw durability.

The first documented investigations into the freeze-thaw durability of PCPC were performed in Belgium and Japan. Beeldens *et al.* developed a polymer-modified pervious concrete for highway pavements (Beeldens *et al.* 1997). The best performing mixture contained a polymer-to-cement ratio of 15% and a sand-to-coarse aggregate ratio of 7%, producing 32 MPa (4,650 psi) compressive strength and 5.7 MPa (825 psi) flexural strength at a porosity of 25%. Significant improvements to freeze-thaw durability and deicing resistance occurred at polymer-to-cement ratios around 10% due to the more continuous polymer film formation (Beeldens *et al.* 2001). Tamai and Yoshida presented "Durability of Porous Concrete," to the sixth CANMET/ACI international conference. It was concluded that freeze-thaw resistance was proportional to the amount of binder. Also, silica fume and air-entraining improved the freeze-thaw durability of PCPC (Tamai and Yoshida 2003).

The National Ready Mixed Concrete Association (NRMCA) published a report titled “Freeze-Thaw Resistance of Pervious Concrete,” which indicated that PCPC had poor freeze-thaw resistance when fully saturated and suggested that the ASTM C666A test procedure was overly severe and not indicative of actual field conditions. The document provides a representative listing of pervious concrete installations in the U.S., including some in hard wet freeze zones installed as early as 1985. The NRMCA concluded at that time, caution should be taken when installing pervious concrete in freeze-thaw conditions due to the limited experience (NRMCA 2004).

The interest in concrete by the ready-mixed concrete community led the NRMCA to hold the 2006 Concrete Technology Forum – Focus on Pervious Concrete in Nashville, TN. Numerous presentations detailed all aspects of pervious concrete with several including freeze-thaw durability. Yang *et al.* (2006) concluded that saturation state played an important role in the freeze-thaw durability and vacuum saturated pervious concrete samples displayed better freeze-thaw resistance than similarly prepared conventional concrete. Partially saturated PCPC frozen and thawed in air to simulate field conditions showed high durability, while the majority of freeze-thaw deterioration occurred in the cement paste. The Ohio Ready Mixed Concrete Association presented a summary of pervious concrete sites in the Northeast, which commonly experience hard wet freeze conditions. Again, most installations were only a few years old, none had experienced freeze-thaw deterioration (Bass 2006).

Most recently the RMC research & education foundation released a report titled “Portland Cement Pervious Concrete Field Performance Investigation on Parking Lot and Roadway Pavements,” which documents field observations and non-destructive test results from pervious concrete sites in Ohio, Kentucky, Colorado, Indiana, and Pennsylvania. The sites had been in place a maximum of four years and the results showed that the installations had good freeze-thaw performance with little clogging and required maintenance. Any durability issues were associated with early-age raveling or structural overload (Delatte *et al.* 2007).

Starting in late 2004, Iowa State University (ISU) through sponsorship by the Iowa Ready Mixed Concrete Association (IRMCA) and Iowa Concrete Paving Association (ICPA) began investigating the potential application of pervious concrete. The objective was to evaluate currently utilized mixtures with ASTM C666A, fully saturated freeze-thaw procedure, and to develop mixtures suitable for use in northern climates. Results of the initial study are presented in Kevern 2005, Schaefer *et al.* 2006, and Kevern 2006. A mass loss of 15% was used to represent a terminal serviceability level as determined by visual analysis. Mixes that contained sand, latex, or both had better freeze-thaw resistance than baseline mixes containing only single-sized aggregate.

Through continued sponsorship by the Federal Highway Administration (FHWA) and the RMC research & education foundation, researchers at ISU are currently developing PCPC for slip-form overlay applications for noise mitigation. Two recent papers have been published in the journal of ASTM International. "Pervious Concrete Mixture Proportions for Improved Freeze-Thaw Durability," concluded that sand and short polypropylene fibers significantly improved freeze-thaw durability (Kevern *et al.* 2008-1). Another paper utilizing an automated air determination device concluded that air entrainment does occur in pervious concrete and increased air entrainment improved compaction and freeze-thaw durability (Kevern *et al.* 2008-2).

A synthesis paper on the freeze-thaw testing performed at ISU has been included in the NRMCA 2008 Concrete Technology Forum – Focus on Sustainable Development. Durability was improved by optimizing the ratio of cement to aggregate for particular aggregate gradations and including the previously mentioned additional fine aggregate and fibers. Freeze-thaw durability increased with density for the same mixture proportions. Increased water-to-cement ratio improved workability and consequently density, improving freeze-thaw durability for mixtures without additional sand. Binary mixtures including various replacement rates of fly ash and silica fume showed decreased freeze-thaw durability with replacement rate, while ternary mixtures including slag improved tensile strength and durability. Latex-based admixtures improved workability and strength but had poor freeze-thaw performance utilizing the standard ASTM C666A procedure. Freeze-thaw durability improved by drying the samples completely after curing and then resaturating before testing to allow formation of the polymer film (Kevern *et al.* 2008-3).

The body of knowledge concerning the freeze-thaw durability of pervious concrete is building. Research most often reports the effects of mixture proportions or admixtures on pervious concrete. Since aggregate comprises the largest fraction of PCPC, the following study was designed to identify the specific coarse aggregate effect on the freeze-thaw durability of pervious concrete.

Scope of the Present Study

In the present study seventeen PCPC coarse aggregate samples, collected from areas across the U.S., were characterized. Gradation, shape, absorption, unit weights, and voids of the aggregates were analyzed. Compressive strength development with time, splitting cylinder tensile strength, permeability, porosity, and freeze-thaw durability of concrete made with these aggregates were measured. Relationships among the aggregate properties and the PCPC properties were examined. The results allowed establishment of some practical requirements/criteria for accepting aggregate properties for use in pervious concrete, such as gradation.

Experimental Work

Source Locations

In order to obtain a cross-section of the available aggregates used in pervious concrete, material was obtained from state and national associations along with various industry representatives that have experience with pervious concrete. The request was for aggregate that had been used in pervious concrete or with the potential for use in pervious concrete. No requirements were set for aggregate composition or gradation. Since pervious concrete has been used since the 1970’s in the southeastern U.S., aggregate was obtained from Florida and Georgia. Other than one aggregate from San Diego, the remaining types came from regions that routinely experience freeze-thaw activity. The aggregate types and source locations are shown in Table 3.

A majority of the aggregate fell into three main types, granite, river gravel, and limestone. The angularity was visually classified as angular, round, or a combination which included three aggregates classified as semi-angular. An example of the visual classification is shown by Figure 2.

Table 3. Aggregate sources

Location	Type	Designation	Shape Classification
Maine, Eliot	Granite	(ME)Gr	Angular
Minnesota, Minneapolis	Granite	(MN)Gr	Angular
New Hampshire, Wilton	Granite	(NH)Gr	Angular
Georgia, Adel	Granite	(GA)Gr	Semi-angular
Indiana, Evansville	River Gravel	(IN)RG	Round
Indiana, Vincennes	River Gravel	(IN)RG2	Round
New York, Painted Post	River Gravel	(NY)cRG	Angular
Iowa, Ames	River Gravel	(IA)RG	Round
Washington, Seattle	River Gravel	(WA)RG	Round
Florida, Miami	Limestone	(FL)LS	Semi-angular
Iowa, Ames	Limestone	(IA)LS	Angular
Indiana, Evansville	Limestone	(IN)LS	Angular
Indiana, South Bend	Limestone	(IN)LS2	Angular
Tennessee, Knoxville	Limestone	(TN)LS	Angular
California, San Diego	Conglomerate	(CA)C	Angular
South Dakota, Sioux Falls	Quartzite	(SD)Qtz	Angular
British Columbia, Sechelt	Sechelt	(BC)S	Semi-angular

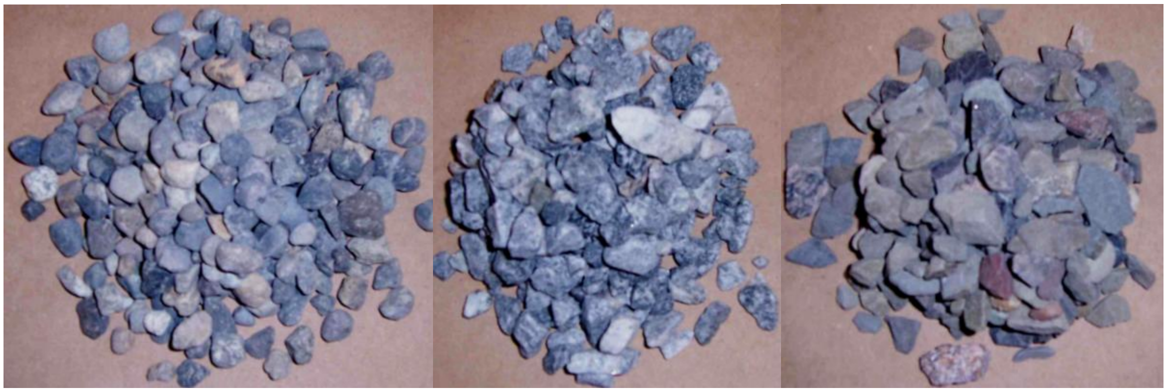

Figure 2. Examples of round (WA RG), semi angular (GA GR), and angular (NY RG) aggregate angularity

Sample Preparation and Test Methods

The aggregate material properties were evaluated using ASTM C33 for particle size analysis and ASTM C127 for absorption and specific gravity. The dry-rodded unit weight (DRUW) was determined according to ASTM C29. To assist defining the aggregate angularity, the unrodded unit weight (URUW) was determined by filling a 7 L (0.25 ft^3)

container used for DRUW but, without providing any compaction. Aggregate abrasion resistance was evaluated using the micro-deval device according to ASTM D6928. Where, 1500 g (3.3 lb) of material was saturated and then abraded with 5,000 g (11 lb) of 9.5 mm diameter stainless steel balls in water by a device rotating at 100 rpm for 2 minutes. After abrasion, the material was washed over a 1.18 mm (No. 16) sieve and then oven dried to determine mass remaining.

Concrete was prepared using a rotating-drum mixer. First, to the aggregate in the mixer, 2/3rds of the water and the air entraining agent (AEA) was added and mixed until foam was observed. Then the cement and water with high-range water reducer (HRWR) were added. Finally, the concrete was mixed for three minutes, covered and allowed to rest for three minutes, and then mixed for an additional two minutes before casting. All specimens were placed by lightly rodding 25 times in three layers to ensure uniform compaction in each lift. In addition to rodding, the samples were placed on a vibration table for three to five seconds after rodding each layer to ensure the layers properly meshed together, since the rodding was performed to evenly distribute the porosity and not to penetrate the underlying layer. This procedure was designed to uniformly compact the specimens without consolidation. The samples were demolded after 24 hours, placed in a humidity chamber at >98% relative humidity, and cured according to ASTM C192.

Compressive strength testing was performed at 7, 21, and 28-days according to ASTM C39. Splitting tensile testing was performed at 28-days according to ASTM C496. Both used cylinders of 100 mm (4 in.) in diameter and 200 mm (8 in.) in length.

The pervious concrete porosity was determined by taking the difference in weight between samples oven dry and submerged under water, using Equation 1 and the proposed standard procedure developed by Montes *et al.* (2005).

$$P = [1 - (\frac{W_2 - W_1}{\rho_w \mathrm{Vol}})]100(\%) \qquad \textbf{(1)}$$

Where:

P = total porosity, %.
W_1 = weight under water, kg.
W_2 = oven dry weight, kg.
Vol = volume of sample, cm^3.
ρ_w = density of water @ 21°C, kg/cm^3

Permeability was determined using a falling head permeability test apparatus. A flexible sealing gum was used around the top perimeter of a sample to prevent water leakage along the sides of a sample. The samples were then confined in a latex membrane and sealed in a rubber sleeve which was surrounded by adjustable hose clamps. The average coefficient of permeability (k) was determined using Equation 2, which follows Darcy's law and assumes laminar flow.

$$k = \frac{aL}{At} LN\left(\frac{h_1}{h_2}\right) \qquad \textbf{(2)}$$

Where:

k = coefficient of permeability, cm/s.
a = cross sectional area of the standpipe, cm^2.
L = length of sample, cm.
A = cross sectional area of specimen, cm^2.
t = time in seconds from h_1 to h_2.
h_1 = initial water level, cm.
h_2 = final water level, cm.

Mixtures were further investigated by freeze-thaw resistance using ASTM C666, procedure A, in which samples were frozen and thawed in the saturated condition (Figure 3). The durability factors were determined using the standard 60% cutoff for relative dynamic modulus (RDM) as specified in ASTM C215, Standard Test Method for Fundamental Transverse Resonant Frequency of Concrete Specimens. Also, a less sensitive approach determined freeze-thaw durability using the aggregate soundness requirements from ASTM C33. When using a magnesium sulfate solution the allowable aggregate mass loss is 18%, and 12% is allowed for sodium sulfate solutions. Averaging the two values, the test was completed when a sample reached 300 cycles or 15% mass loss. Durability response was tested every 20 to 30 cycles. The durability factors were calculated using equation 3.

$$DF = \frac{PN}{M} \qquad \textbf{(3)}$$

Where:

DF = durability factor of the test specimen
P = relative dynamic modulus of elasticity or relative mass, at N cycles, %.
N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less, 60% RDM, 85% mass remaining, or 300 cycles.

M = specified number of cycles at which the exposure is to be terminated, 300 cycles.

Figure 3. Freeze-thaw apparatus

The surface abrasion resistance was determined according to ASTM C944, in which a constant load of 98 N (22 lbs) was applied through rotary cutter dressing wheels in contact with the sample surface for two minutes. The diameter of the circular abraded area is 81 mm (3.25 in.). The beams were first cleaned with a stiff-bristled brush and vacuumed on all sides to remove any loose particles. After each abrasion test, the beams were again brushed clean and vacuumed to remove loose debris. The mass loss between trials was recorded and a total of six abrasion tests were performed on each set of beams. Figure 4 shows the abrasion device with a shaft-mounted container for load calibration and abrasion head cutting device.

Mixture Proportions

The pervious concrete mixture proportions were selected based on proportions previously determined as freeze-thaw durable (Schaefer *et al.* 2006). The original mixture contained river gravel, a small portion of additional concrete sand, Type II cement, air entraining agent, and water reducer to allow placement at water-to-cement (*w/c*) of 0.27. The baseline mixture proportions are shown in Table 4, the coarse aggregate mass for all other placements were adjusted to maintain the volumetric mixture proportions and produce a

Design Void Content (DVC) of 18.7%. The coarse aggregate was brought to saturated-surface-dry (SSD) condition before batching.

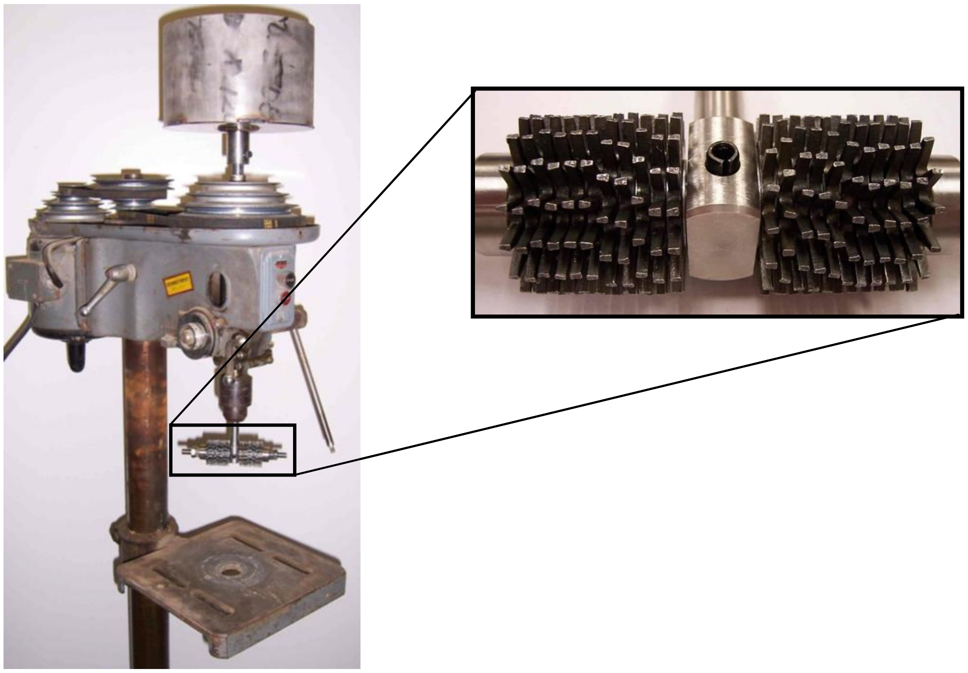

Figure 4. Surface abrasion device

Table 4. Baseline mixture proportions

Material	**Amount**	**Volume**
	kg/m^3 (pcf)	(%)
Type I/II Cement	340 (21)	10.9
Coarse Agg.	1,530 (95)	58.2
Fine Agg.	80 (5)	2.9
Water (0.27)	90 (6)	9.3
AEA, mL/kg (oz/cwt)	1.4 (2.2)	-
WR, mL/kg (oz/cwt)	2.8 (4.3)	-
Voids	-	18.7

Results and Discussion

Aggregate Properties

The aggregate properties are shown in Table 5. Specific gravity values ranged from 2.35 for the calcareous limestone from Miami to 2.71 for the limestone from Tennessee. The micro-deval abrasion resistance ranged from 3.1% for river gravel from Evansville, IN to 33.0% for limestone from Ames, IA. Ignoring the two limestone samples with significantly higher abrasion responses (Miami, FL and Ames, IA), there was no trend between aggregate abrasion and either specific gravity or absorption.

Table 5. Aggregate properties

Aggregate	Specific Gravity	Absorption	Abrasion Resistance	DRUW	Rodded Voids	URUW	Unrodded Voids
		(%)	(%)	kg/m^3(pcf)	(%)	kg/m^3(pcf)	(%)
(ME)Gr	2.57	1.1	8.7	1,460 (91)	43	1,340 (84)	48
(MN)Gr	2.65	0.6	7.4	1,460 (91)	45	1,320 (82)	50
(NH)Gr	2.66	1.0	10.3	1,490 (93)	44	1,330 (83)	50
(GA)Gr	2.66	0.5	11.5	1,500 (93)	44	1,460 (91)	45
(IN)RG	2.52	1.7	3.1	1,570 (98)	38	1,500 (94)	41
(IN)RG2	2.55	2.3	8.8	1,580 (99)	38	1,530 (95)	40
(NY)cRG	2.59	1.6	16.0	1,490 (93)	42	1,300 (81)	50
(IA)RG	2.62	1.7	14.4	1,640 (102)	37	1,480 (93)	42
(WA)RG	2.65	1.0	4.1	1,700 (106)	36	1,540 (96)	42
(FL)LS	2.35	3.8	22.4	1,360 (85)	42	1,210 (76)	49
(IA)LS	2.45	3.9	33.0	1,390 (87)	43	1,290 (80)	47
(IN)LS	2.63	1.4	13.2	1,460 (91)	44	1,360 (85)	48
(IN)LS2	2.64	1.9	10.6	1,440 (90)	46	1,340 (84)	49
(TN)LS	2.71	0.8	8.5	1,560 (98)	42	1,410 (88)	48
(CA)C	2.57	1.2	5.8	1,440 (90)	44	1,300 (81)	49
(SD)Qtz	2.62	0.5	8.8	1,570 (98)	40	1,390 (87)	47
(BC)S	2.67	0.8	6.1	1,610 (100)	40	1,430 (89)	47
Avg.	2.59	1.5	11.3	1,510 (94)	40	1,380 (86)	47

As shown by Figure 5, most of the aggregate had absorption ranging from 0.5% to 2.3% and had corresponding specific gravity values from 2.52 to 2.71. However, two limestone samples had low specific gravity (≤2.45) and high absorption rates (≥3.8%). One of these samples came from Miami, FL where freeze-thaw is not of a concern, while the other was produced in central Iowa. Since the aggregate properties are significantly different than the other aggregates, the appropriateness of these two limestone types in pervious concrete was initially questionable.

The relationship between DRUW and URUW can be used to describe the effect aggregate angularity may have on the concrete mixture workability. Round aggregate will have an URUW closer to its DRUW, due to the self-compacting nature of the round material. While the surface friction of the angular particles will naturally create a more open structure and cause a larger difference between the URUW and DRUW values. The relationship between URUW and DRUW is shown in Figure 6 with a strong linear relationship between the compaction states.

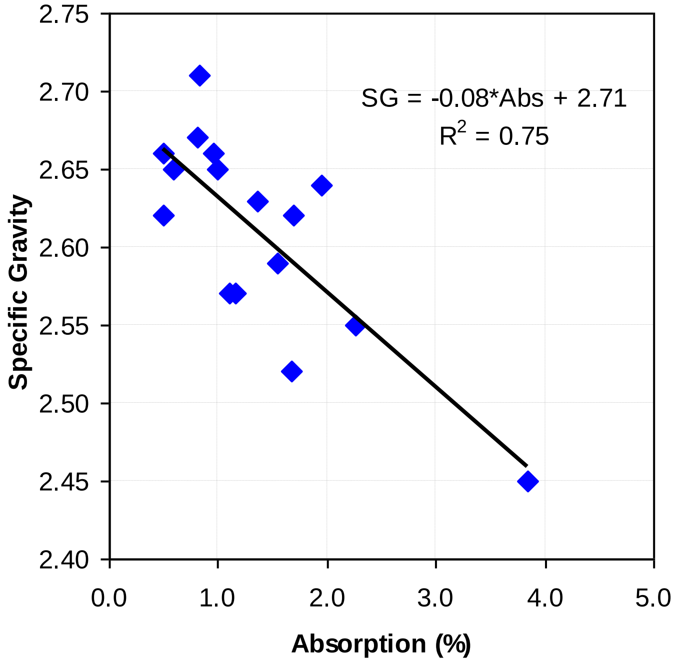

Figure 5. Relationship between aggregate density and absorption

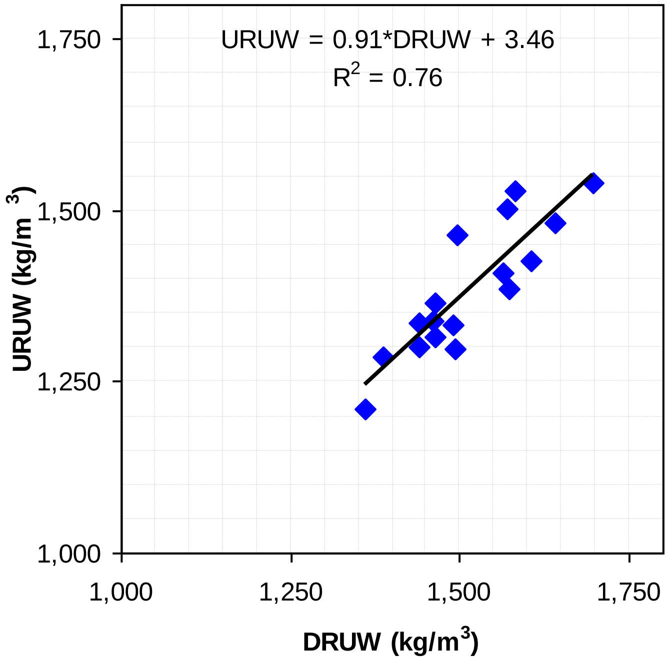

Figure 6. Relationship between aggregate compaction states

The as-received aggregate gradations are shown in Figure 7. Common of all of the gradations were a majority of the particles between the 9.5 mm (3/8 in.) and 4.75 mm (No. 4) sieves. The coarsest sample was defined by the South Dakota quartzite which had 5.4% passing the 4.75 mm (No. 4) sieve and 4.6% passing the 2.36 mm (No. 8) sieve. The lower gradation represents the limestone from central Iowa which is a commonly available gradation used as an intermediate aggregate for asphalt mixtures, with 44.4% passing the 4.75 mm (No. 4) sieve and 13.1% passing the 2.36 mm (No. 8) sieve. Samples located near the coarse and fine gradation extremes were mechanically produced crushed material, while the rounded natural gradations fell in the center of the reported gradations.

In pervious concrete the fine aggregate fraction increases the cement paste volume and viscosity, allowing a thicker paste layer on the coarse aggregate and ultimately greater contact area between particles. The greater contact area produces higher strength and lower porosity than samples with lower amounts of small-sized particles (Wang *et al.* 2006).

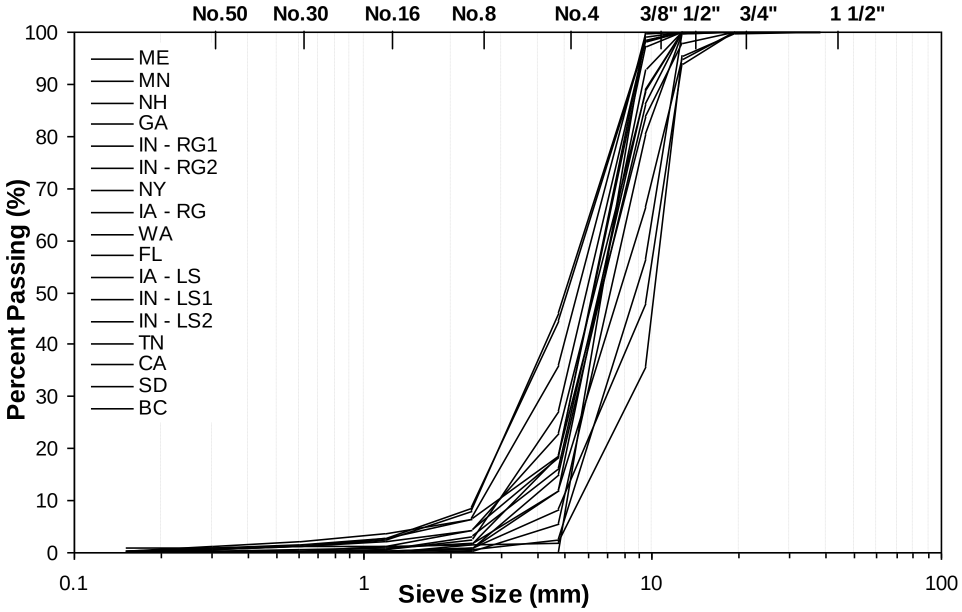

Figure 7. Aggregate gradations

Observing the common gradations and the material property behavior from the sand addition, material that functions as coarse aggregate (i.e. load bearing individual pieces) includes all particles retained above the 2.36 mm (No.8) sieve, while material that functions as fine aggregate (i.e. increases the volume of the cement paste, mortar) includes all particles passing the 2.36 mm (No.8) sieve. So, according to ASTM C33 gradation requirements for fine aggregate, up to 10% of the fine aggregate fraction may actually contribute to the coarse aggregate composition when used in pervious concrete.

Previous research has shown that an additional 5% to 7% fine aggregate added to the coarse aggregate gradation optimizes the mixture producing the greatest strength and durability responses (Schaefer *et al.* 2006). When the optimized sand content is combined with the cross section of U.S. aggregates, a clear a gradation criteria is produced as shown in Figure 8. The suggested grading requirements for pervious concrete are provided in Table 6. The most critical location for optimizing the aggregate gradation involves sand addition controlled by the amount passing the 2.36 mm (No.8) sieve.

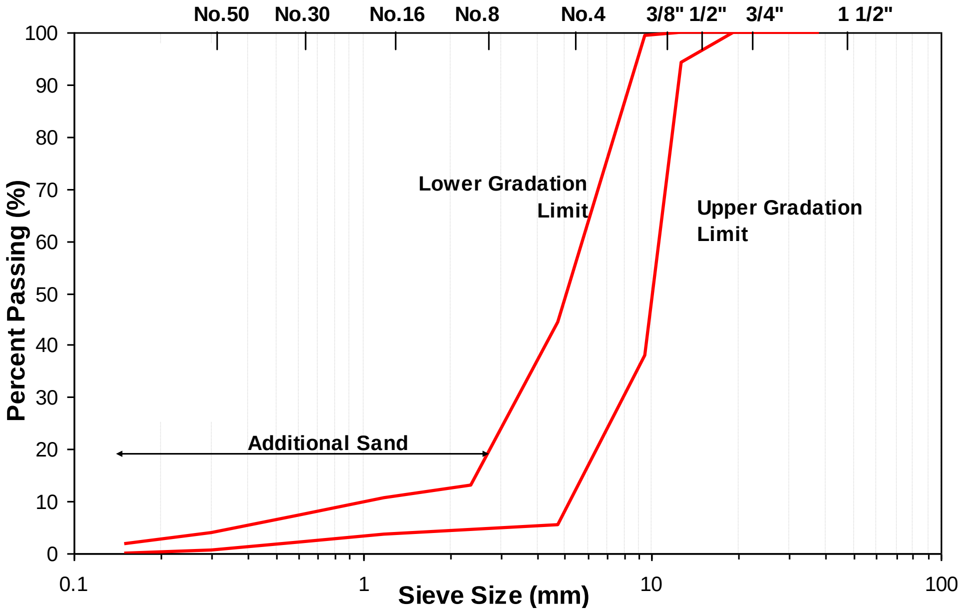

Figure 8. Aggregate gradation limits

Table 6. Pervious concrete aggregate gradation limits

Sieve Size		Gradation Limits	
mm	ID	Fine	Coarse
38.1	1 1/2"	100.0	100.0
19.1	3/4"	100.0	100.0
12.7	1/2"	100.0	94.3
9.5	3/8"	99.3	38.1
4.75	#4	44.4	5.4
2.36	#8	13.1	4.6
1.18	#16	10.6	3.6
0.6	#30	7.3	2.1
0.3	#50	4.0	0.5
0.15	#100	1.8	0.0

Concrete Material Properties

The concrete testing results are shown in Table 7, sorted by aggregate type. Washington river gravel had the maximum compressive strength of 28.5 MPa (3,750 psi) corresponding to the lowest porosity of 15.1%. Florida limestone had the lowest compressive strength of 7.7 MPA (1,110 psi) at 21.9% porosity, which was not the highest. While the design porosity was 18.7%, the measured values ranged from 15.1% to 30.0%, with an average of 21.1%.

Table 7. Concrete properties

Aggregate	**Porosity** (%)	**Compressive Strength**			**Splitting Tensile Strength** MPa (psi)	**Permeability**	
		7-day MPa (psi)	21-day MPa (psi)	28-day MPa (psi)		75 mm (3 in.) cm/s (in./hr)	100 mm (4 in.) cm/s (in./hr)
(ME)Gr	22.0	16.1 (2,340)	17.8 (2,580)	18.9 (2,740)	2.05 (295)	0.14 (198)	0.49 (694)
(MN)Gr	18.5	11.6 (1,680)	15.6 (2,270)	16.0 (2,330)	1.85 (270)	0.23 (326)	0.41 (581)
(NH)Gr	19.5	9.6 (1,400)	15.1 (2,190)	15.6 (2,270)	2.05 (300)	0.13 (184)	0.36 (510)
(GA)Gr	15.2	9.0 (1,300)	11.0 (1,590)	11.0 (1,600)	1.85 (265)	0.10 (142)	0.33 (468)
(IN)RG	16.2	17.5 (2,540)	17.6 (2,560)	20.4 (2,960)	2.95 (425)	0.11 (162)	0.24 (340)
(IN)RG2	19.3	16.6 (2,410)	21.2 (3,080)	22.7 (3,300)	2.45 (355)	0.16 (227)	0.37 (524)
(NY)cRG	30.0	13.1 (1,910)	14.5 (2,100)	15.4 (2,240)	1.85 (270)	0.62 (879)	0.98 (1,389)
(IA)RG	21.2	16.5 (2,390)	19.0 (2,750)	23.0 (3,340)	2.30 (335)	0.07 (99)	0.06 (85)
(WA)RG	15.1	23.4 (3,400)	25.1 (3,640)	25.8 (3,750)	3.00 (435)	0.00 (0)	0.06 (85)
(FL)LS	21.9	6.0 (870)	6.5 (940)	7.7 (1,110)	0.85 (125)	0.11 (156)	0.16 (227)
(IA)LS	25.9	8.9 (1,270)	11.5 (1,670)	12.0 (1,740)	1.45 (215)	0.31 (439)	0.44 (624)
(IN)LS	20.9	16.4 (2,380)	17.0 (2,470)	20.3 (2,950)	2.55 (370)	0.25 (354)	0.57 (808)
(IN)LS2	26.9	17.7 (2,570)	18.0 (2,610)	19.3 (2,800)	2.60 (380)	0.54 (765)	0.88 (1,247)
(TN)LS	21.8	15.2 (2,200)	19.4 (2,820)	20.6 (2,990)	2.00 (290)	0.31 (439)	0.43 (609)
(CA)C	25.2	15.5 (2,250)	16.4 (2,380)	19.1 (2,770)	2.25 (325)	0.31 (439)	1.04 (1,474)
(SD)Qtz	21.6	14.5 (2,110)	15.7 (2,280)	17.5 (2,540)	2.00 (295)	0.32 (454)	0.58 (822)
(BC)S	17.6	13.4 (1,940)	18.2 (2,650)	18.9 (2,740)	1.75 (255)	0.05 (71)	0.38 (539)

The results of the splitting tensile compared to compressive strength are shown in Figure 9. Splitting tensile strength values ranged from 0.85 MPa (125 psi) to 3.00 MPa (435 psi). The trend was similar to that assumed for traditional concrete with tensile strength 10% of the compressive strength values, values ranged from 9% to 14% for all of the samples.

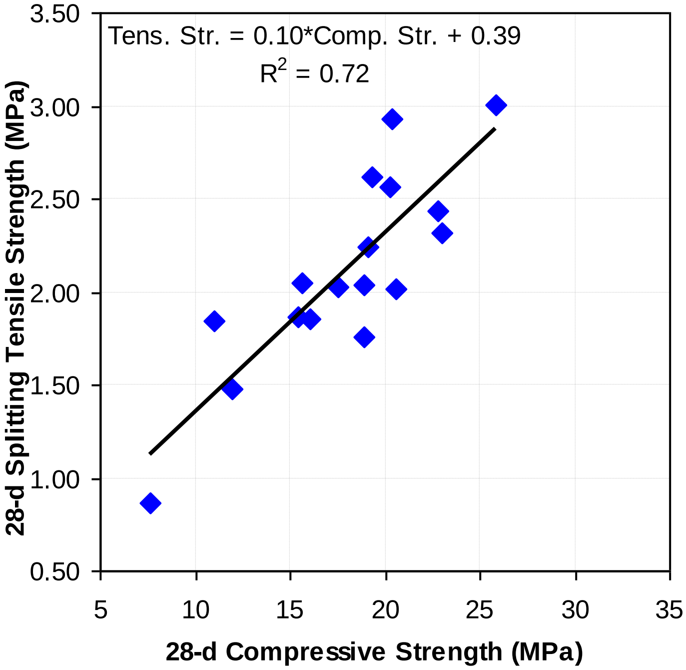

Figure 9. Relationship between splitting tensile and compressive strength

The permeability values ranged from 0 cm/s (0 in/hr) to 0.62 cm/s (879 in/hr) for the 75 mm (3 in.) diameter samples and the range increased from 0.06 cm/s (85 in/hr) to 1.04 cm/s (1,474 in/hr) for the 100 mm (4 in.) diameter samples. Figure 10 shows the permeability relationship, where the trendline is plotted along with the line of equality. Since the 100 mm (4 in.) diameter samples are always equal to, and in most cases, greater than the values determined for the 75 mm (3 in.) diameter samples, it will be necessary to establish the representative elementary volume for pervious concrete to allow comparisons between permeability values determined for different samples and laboratories.

In order to use concrete unit weight as quality control criteria for pervious concrete, the effect of various mixture components on the fresh concrete compaction characteristics must be understood. The relationship between the concrete unit weight and the aggregate natural compaction state (URUW) is shown in Figure 11. For the volumetric mixture proportions used in this study, URUW controls the resulting concrete unit weight ($R^2 = 0.91$).

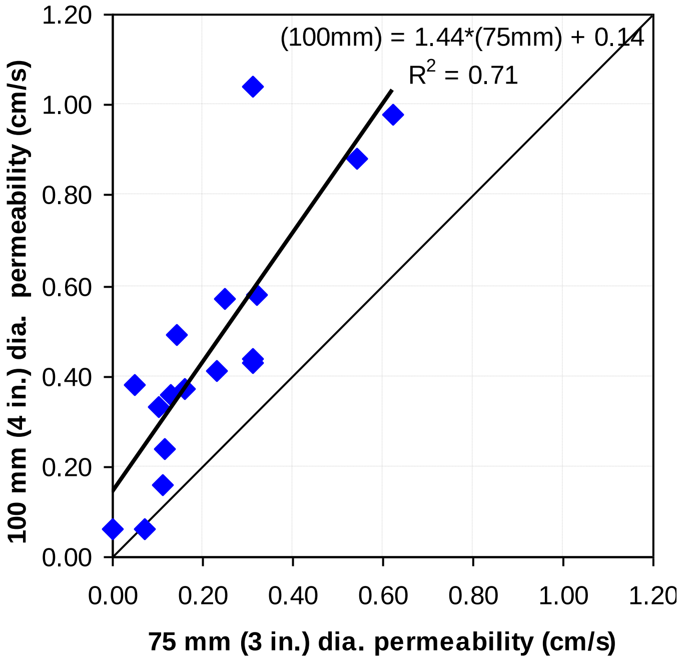

Figure 10. Effect on permeability of sample size

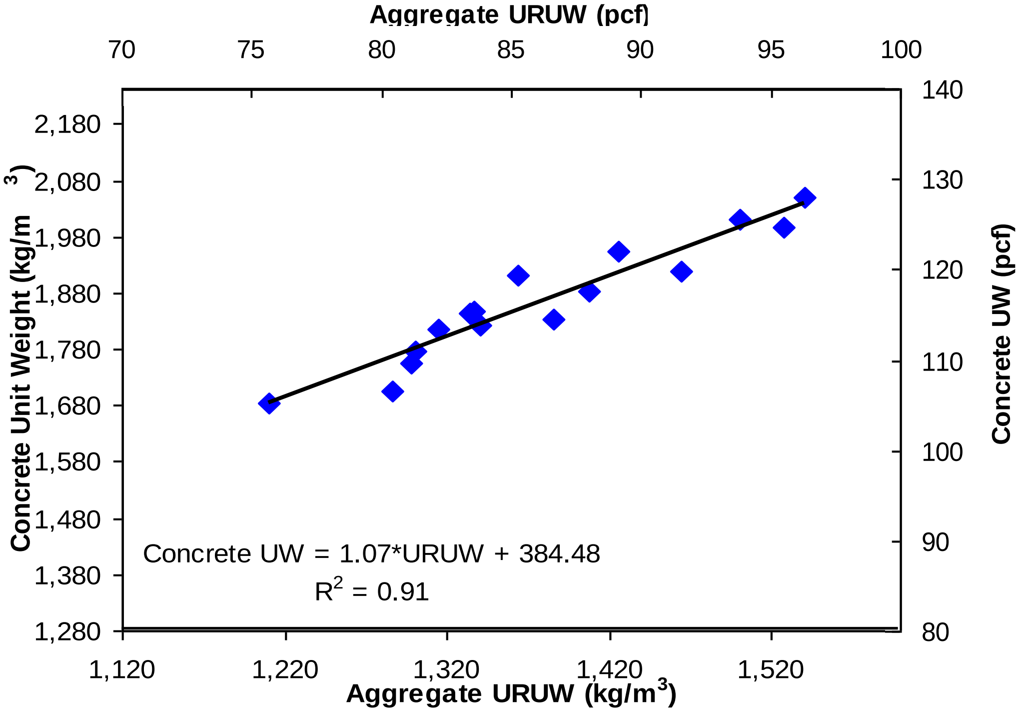

Figure 11. Relationship between concrete unit weight and aggregate natural state

The relationship between the DVC (porosity) and the actual measured values for the particular aggregate types are shown in Figure 12. Round or semi-angular coarse aggregate particles produced concrete near or below the DVC, while the angular aggregate particles tended to have porosity values higher than the DVC. As expected, the angular aggregate mixtures required more compaction energy to achieve the DVC than the relatively self-consolidating mixtures containing rounded aggregate.

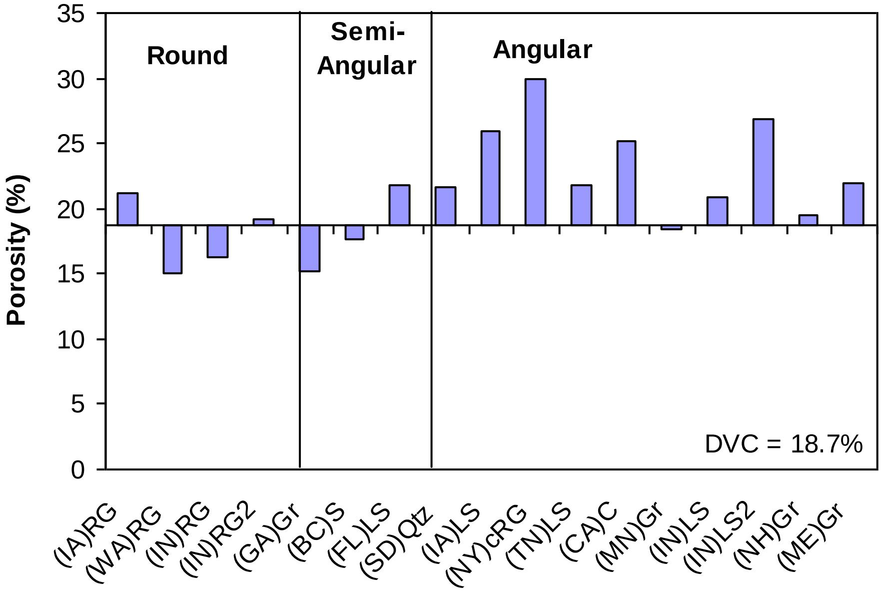

Figure 12. Deviation from design porosity due to aggregate angularity

Freeze-Thaw Results

The results of the freeze-thaw testing are shown in Table 6. The original test limits were taken as 60% relative dynamic modulus (RDM) or 85% mass remaining, durability factors (DF) were also determined for 95%, 97%, and 99% mass remaining criteria. The granite specimens had the best freeze-thaw durability with all four granite sources achieving greater than 60% DF (RDM) and 85% DF (mass). The poorest freeze-thaw response occurred in river gravel specimens from Indiana, which was not expected since the samples had acceptable compressive and tensile strength values, 20.4 MPa (2,960 psi) and 2.95 MPa (425 psi), respectively. Generally samples with higher strength have exhibited greater freeze-thaw durability, comparing samples with the same mixture proportions indicated that other factors also impact freeze-thaw durability.

Table 8. Freeze-thaw testing results

Aggregate	DF (RDM)	Durability Factor (% mass remaining)				FT Evaluation
	60%	85%	95%	97%	99%	
(ME)Gr	77	99	99	99	99	Accept.
(MN)Gr	85	99	99	99	96	Accept.
(NH)Gr	64	99	99	99	99	Accept.
(GA)Gr	87	98	98	98	57	Accept.
(IN)RG	3	17	13	12	9	Unaccept.
(IN)RG2	3	12	8	5	2	Unaccept.
(NY)cRG	32	87	76	68	45	Unaccept.
(IA)RG	22	66	55	47	23	Unaccept.
(WA)RG	96	98	98	98	47	Accept.
(FL)LS	8	22	21	16	10	Unaccept.
(IA)LS	20	58	56	53	45	Unaccept.
(IN)LS	19	60	51	45	23	Unaccept.
(IN)LS2	7	40	37	30	16	Unaccept.
(TN)LS	37	95	95	81	62	Accept.
(CA)C	68	95	95	90	14	Accept.
(SD)Qtz	50	97	97	96	53	Accept.
(BC)S	85	98	98	98	67	Accept.

The relationship between RDM and relative mass durability factors is shown in Figure 13. Once the samples reached 37% durability factor using RDM, the mass response produced a durability factor of 95% or greater. Additional mass loss criteria were also evaluated to determine if the 85% mass remaining cutoff was appropriate. The mass loss durability factors for 85% along with 95%, 97%, and 99% versus the 60% RDM criteria are shown in Figure 14. There is a similar trend for the 85%, 95%, and 97% mass cutoff criteria of freeze-thaw durability by the mass loss criteria achieved for samples with RDM of 37% or greater. The 99% durability factor for mass loss did not show any trend due to the variability in particles lost from the surface of the freeze-thaw beams which did not represent the structural soundness of the beams. For the remainder of this report, samples that surpassed 37% RDM had acceptable freeze-thaw durability and those below, unacceptable.

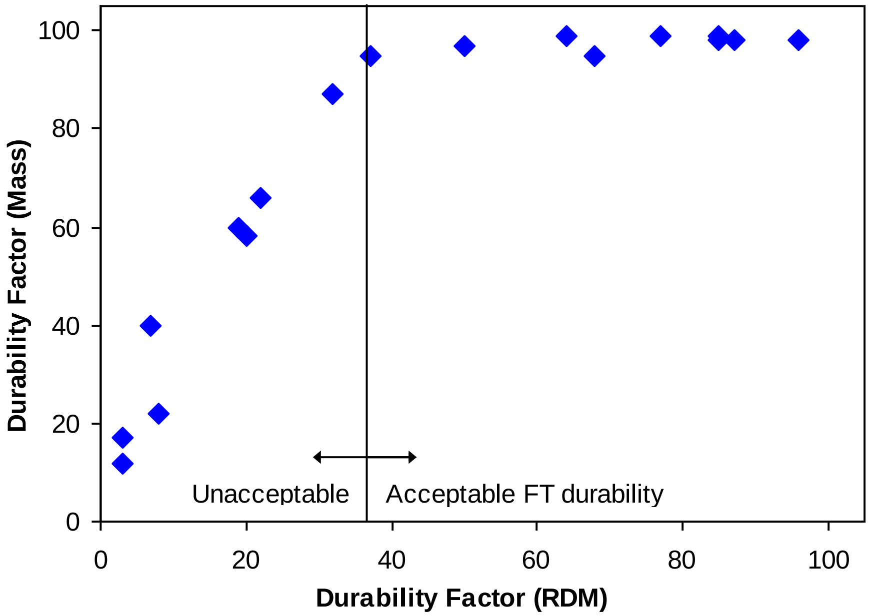

Figure 13. Relationship between freeze-thaw durability factors

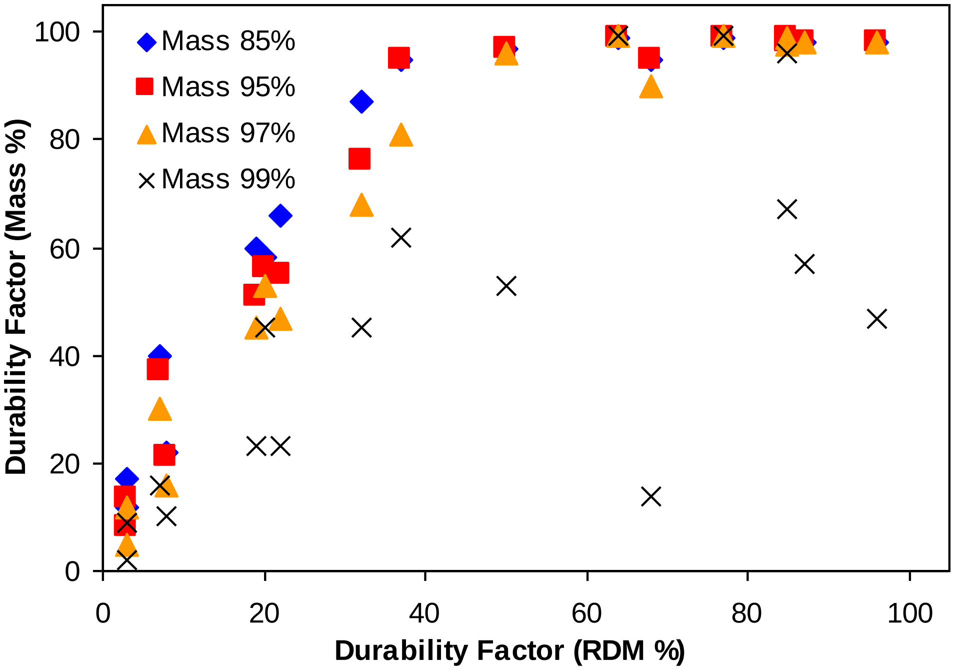

Figure 14. Durability factors with different criteria

In previous studies the relationship has been increased freeze-thaw durability with higher concrete unit weight, for mixtures containing the same aggregate (Kevern 2006). The relationship between durability factor, concrete density, and aggregate specific gravity using the RDM criteria are shown in Figure 15. For this study, there was not a trend of higher freeze-thaw durability with increased concrete density or aggregate specific gravity.

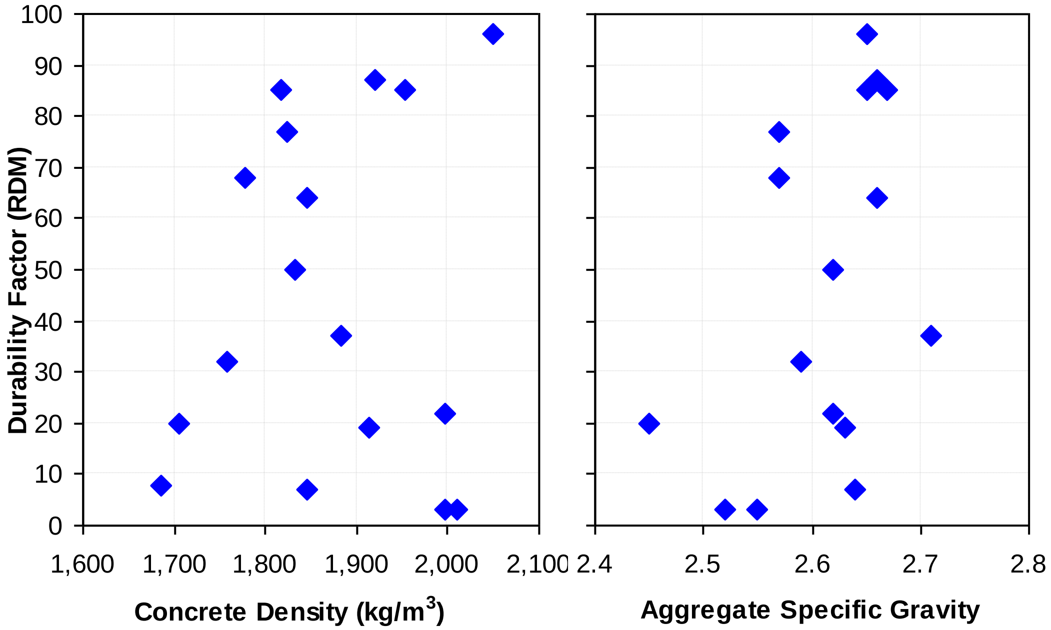

Figure 15. Relationship between concrete and aggregate densities and freeze-thaw response

Excluding the two limestone samples with very high absorption values, there was a good trend of increased freeze-thaw durability with decreased aggregate absorption (Figure 16). Generally, aggregate with absorption less than 1.5% had acceptable freeze-thaw durability.

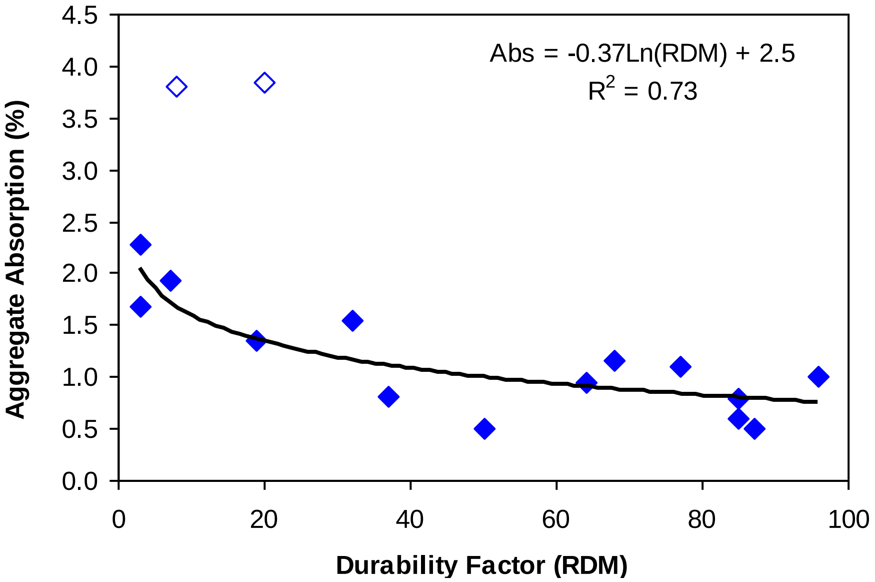

Figure 16. Effect of aggregate absorption on freeze-thaw durability

Table 9 presents the average aggregate and concrete properties of the mixtures which had acceptable and unacceptable freeze-thaw durability. Properties that were significantly different between the freeze-thaw responses are underlined. Those properties which had the greatest influence were aggregate absorption and abrasion resistance with a small effect observed of specific gravity. No property of the concrete correlated to freeze-thaw response. At least for this particular set of mixture proportions, which have been previously determined as freeze-thaw durable, the aggregate, not the concrete, controlled the ultimate freeze-thaw durability.

Table 9. Acceptance properties of freeze-thaw samples

	FT Response		
Aggregate	**accep.**	**unaccep.**	**w/o outliers**
SG	2.64	2.57	2.59
Abs (%)	0.82	2.27	1.75
DRUW (kg/m^3)	1,530	1,490	1,530
URUW (kg/m^3)	1,390	1,360	1,410
Abrasion (%)	7.9	15.2	11.0
Concrete			
UW (kg/m^3)	1,880	1,860	
Porosity	19.6	22.8	
k, 100mm (cm/s)	0.45	0.46	
Compressive Strength (MPa)	18.2	17.6	
Tensile Strength (MPa)	2.1	2.1	

The results of freeze-thaw testing are shown in Figure 17. through Figure 21 for the range of responses. For the river gravel and quartzite mixtures (Figure 17. and Figure 18), mass loss occurred by the separation of paste from the aggregate surface and the occasional splitting of a surface aggregate piece. The lowest acceptable freeze-thaw response (Figure 19) deteriorated in a similar mechanism to the previous samples, although more aggregate was lost from the surface. Unacceptable freeze-thaw deterioration occurred by deterioration of the aggregate causing a loss of cement paste contact between particles and a large amount of aggregate raveling (Figure 20 and Figure 21). When the aggregate was not freeze-thaw durable, expansion of the water inside the aggregate particles or in the paste caused the thin outer cement paste shell to become detached. This mechanism occurred throughout the sample, reinforcing the difference in freeze-thaw behavior between pervious and conventional concrete. The thin layer of cement paste coating the aggregate had limited ability to prevent the migration of water into the coarse aggregate. Consequently, the observation of durability cracking and freeze-thaw deterioration may occur much more quickly and severely in pervious concrete compared to traditional concrete produced with the same aggregate.

(a) Before testing **(b) After 300 cycles**

Figure 17. Washington river gravel freeze-thaw results, DF=98 mass, DF=96 RDM

(a) Before testing **(b) After 300 cycles**

Figure 18. South Dakota quartzite freeze-thaw results, DF=97 mass, DF=50 RDM

(a) Before testing **(b) After 300 cycles**

Figure 19. Tennessee limestone freeze-thaw results, DF=95 mass, DF=37 RDM

(a) Before testing **(b) After 206 cycles**

Figure 20. Iowa limestone freeze-thaw results, DF=58 mass, DF=20 RDM

(a) Before testing **(b) After 41 cycles**

Figure 21. Indiana river gravel freeze-thaw results, DF=12 mass, DF=3 RDM

Conclusions and Recommendations

The following conclusions and recommendations are made from the present study:

- Aggregate absorption has the greatest effect on the freeze-thaw durability of pervious concrete. The average absorption for mixtures with acceptable freeze-thaw durability was 0.82%. Mixtures with acceptable freeze-thaw durability also had higher aggregate specific gravities (avg. 2.64) and abrasion resistance (avg. 7.9%).

- The Unrodded Unit Weight (URUW) or natural state of the aggregate controlled the resulting concrete unit weight.
- Mixtures that contained angular aggregate tended to have porosity greater than the Design Void Content (DVC), while rounded or semi-angular aggregate were near to or below the DVC.
- The freeze-thaw durability results showed that mixtures which have Durability Factors (DF) >37% using the 60% Relative Dynamic Modulus (RDM) criteria have acceptable freeze-thaw durability. Using mass remaining as a freeze-thaw durability criteria, 85% mass remaining criteria produced the same durability response as 97% mass remaining when compared to RDM 60% criteria.
- For the concrete produced with the same mixture proportions, the concrete properties were not able to be correlated to freeze-thaw performance.
- The cross-section of aggregate from the United States had a narrow range of utilized gradations. By the addition of known beneficial quantities of fine aggregate, a clearly defined aggregate grading requirement was produced.
- It is suggested that aggregate for high durability mixtures (i.e. heavy traffic loading or hard wet freeze environments) should have specific gravity greater than 2.5, absorption less than 2.5%, abrasion mass loss less than 15%, and have a combined gradation close to the lower gradation limit.

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CHAPTER 4. A NOVEL APPROACH TO CHARACTERIZE ENTRAINED AIR CONTENT IN PERVIOUS CONCRETE

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Abstract

The current pervious concrete placed in cold climates generally contains air entrainment but, unlike traditional concrete, the evaluation of entrained air is not performed. This paper presents results from a study that characterized the entrained air voids in pervious concrete using a RapidAir system. The RapidAir system is an automatic device that determines the air void properties of hardened concrete according to ASTM C457. Two types of aggregates, crushed limestone and rounded river gravel (pea gravel), and two types of air entraining agents (AEA), natural and synthetic were used. The air entrainment dosage rates varied from zero to double the manufacturer's recommended dosage. Compressive strength, tensile strength, and freeze-thaw durability (ASTM C666A) of the pervious concrete were tested. The results show that use of air entrainment improves workability of pervious concrete, thus reducing the overall porosity and increasing unit weight of the pervious concrete. The strength and freeze-thaw durability also increases with the level of entrained air in pervious concrete. (160 words)

Keywords: Pervious concrete, freeze-thaw durability, freeze-thaw resistance, air entrainment, air content testing

Introduction

As Portland Cement Pervious Concrete (PCPC) becomes a more popular stormwater management tool, the number of installations in cold climates increases. It is widely accepted that air entrainment increases the freeze-thaw durability of traditional concrete [1]. The microscopic air void system can provide spaces in the concrete to accommodate expansive materials, such as water that is expelled from ice formation, thus reducing hydraulic and osmotic pressures. PCPC has a more complicated void system than traditional concrete, containing not only the small-sized entrapped and entrained air in the paste or mortar but also porosity, the larger-sized interconnected void space between the paste-coated aggregate particles. While air content is a standard property of traditional concrete, no method is currently used to characterize the air voids in pervious concrete.

Due to the large porosity in pervious concrete, commonly used methods of concrete air measurement, such as pressure or volumetric air meters, do not provide useful data for pervious concrete. Although, the National Ready Mixed Concrete Association (NRMCA) suggests air entraining pervious concrete at a standard dosage rates used to produce concrete curb mixtures, no study has properly approved whether or not air entrainment is necessary for pervious concrete [2].

The RapidAir system is a relatively new device that automatically determines entrained air properties using ASTM C457-98 [3]. Sample cross sections are stained black and then the voids are filled with a white material, such as zinc paste. The contrast allows the device to distinguish between air voids and the hardened matrix of either paste or aggregate. Recent studies have shown that the RapidAir has a high degree of multi-lab reproducibility and has less variation than the ASTM C457 manual technique [4].

In the present paper, the air structure of pervious concrete was determined using the RapidAir system. The test results provide insight into whether or not the use of Air Entraining Agents (AEA) in pervious concrete is necessary and if the dosage rates of AEA used were sufficient to impact durability.

Material Properties and Mixture Proportions

Two types of coarse aggregate were included in the study, crushed limestone and rounded-river gravel (pea gravel). The basic properties and gradations of the aggregates are shown in Table 10. The limestone has previously been shown to exhibit poor freeze-thaw durability in the ASTM C666A test therefore, the study of freeze-thaw resistance of the concrete produced with the limestone is not included in the present paper [5].

Table 10. Coarse aggregate properties

	Aggregate Type	
Property	**Limestone**	**Pea Gravel**
Specific Gravity	2.45	2.62
DRUW - kg/m^3 (lb/ft^3)	1,390 (87)	1,640 (102)
Voids in the aggregate (%)	43	37
Absorption (%)	3.9	1.7
Micro Deval Abrasion (%)	36.4	14.4
Sieve	**Percent Passing**	
19.0 mm (3/4 in.)	100.0	100.0
12.5 mm (1/2 in.)	99.9	99.8
9.5 mm (3/8 in.)	88.5	99.7
4.75 mm (No.4)	22.9	21.8
2.36 mm (No.8)	4.3	1.2

The mixture proportions of the pervious concrete studied are shown in Table 11. The fine aggregate is standard concrete river sand with a specific gravity of 2.62 and a fineness modulus of 2.9. The cement is a Type II, marketed as a Type I/II, with a specific gravity of 3.15 and a Blaine fineness of 384 m^2/kg. A polycarboxylate-based High-Range Water Reducer (HRWR) was used for all mixtures. The natural AEA (N) was a vinsol resin type, and the synthetic AEA (S) was olefin based. A total of ten mixtures were studied.

Table 11. Mixture Proportions

	Coarse Aggregate	**Fine Aggregate**	**Cement**		**HRWR**	**AEA**	
Mixture	kg/m^3 (lb/ft^3)	kg/m^3 (lb/ft^3)	kg/m^3 (lb/ft^3)	**w/c**	mL/kg (oz/cwt)	Type	mL/kg (oz/cwt)
Pea Gravel (PG)	1,525 (2,570)	80 (130)	345 (580)	0.27	2.75 (4.25)	N, S	0, 1.4, 2.8 (0.0, 2.2, 4.3)
Limestone (LS)	1,425 (2,400)	80 (130)	345 (580)	0.27	2.75 (4.25)	N, S	0, 1.4, 2.8 (0.0, 2.2, 4.3)

Sample Preparation

Concrete was mixed using a rotating-drum mixer by dry mixing a small amount of cement (about 5%) with the aggregate until the aggregate particles were completely coated (about one minute). Next, 2/3rds of the water and the AEA were added and mixed until foam was observed. Then the remaining cement and water (with HRWR) were added. Finally, the concrete was mixed for three minutes, covered and allowed to rest for three minutes, and then mixed for an additional two minutes before casting. All specimens were placed by lightly rodding 25 times in three layers to ensure uniform compaction in each lift. The samples were placed on a vibration table for up to five seconds after rodding each layer. After 24 hours the samples were demolded and placed in a fog room at 98% relative humidity and cured according to ASTM C192-02 [6].

Cylinder specimens 100 mm (4 in.) in diameter and 200 mm (8 in.) in length were used for RapidAir testing. The top and bottom 50 mm (2 in.) of the hardened concrete cylinders were removed using a concrete slab saw. Two more cuts were then made vertically to produce a specimen with dimensions of 100 mm (4 in.) by 100 mm (4 in.) by 19 mm (0.75 in.). The specimen represents a vertical section taken from the center of the cylinder. The samples were then wet-sanded with progressively finer grit paper, finishing with six μm grit.

Samples were treated according to the manufacture's recommendations [3]. The polished samples were coated with a broad-tipped black marker. After the ink had completely dried, the samples were placed into an 80ºC oven for two hours. Then, the samples were removed and coated with a white paste comprised of petroleum jelly and zinc oxide and allowed to cool. The extra paste was removed by dragging an angled razor blade across the surface until all of the paste was removed from the aggregate and cement paste areas. If porous areas of the aggregates contained any white paste, they were individually colored with a fine-tip black marker [3].

Once a specimen was prepared, the RapidAir device was used to scan across the sample using a video frame width of 748 pixels. Up to ten probe lines per frame can be used to distinguish between the black and white sections. A white-level threshold adjustment further refines the image before air void determination.

Testing Procedures

The porosity of the pervious concrete was determined using Archimedes principle by taking the difference in weight between oven-dry and saturated submerged specimens using the procedure developed by Montes *et al.* [7]. The average values of triplicate testing results on 100 mm (4 in.) by 200 mm (8 in.) samples are reported in this paper.

Compressive strength testing was performed according to ASTM C39-01 [8]. Splitting tensile testing was performed according to ASTM C496-96 [9].

The water permeability of the specimens was determined using the falling head permeability test apparatus. A flexible sealing gum was used around the top perimeter of a sample to prevent water leakage along the sides of a sample. The samples were then confined in a latex membrane and sealed in a rubber sleeve which was surrounded by adjustable hose clamps. The test was performed using several water heights which represented values that a pavement may experience [10]. The average coefficient of permeability (k) was then determined following Darcy's law and assuming laminar flow. Reported permeability values represent an average of triplicate testing results on 100 mm (4 in.) diameter by 75 mm (3 in.) samples removed from the center of a 100 mm (4 in.) by 200 mm (8 in.) cylinder.

Freeze-thaw resistance was tested using ASTM C666-97, procedure A, in which samples were frozen and thawed in the saturated condition [11].

Values determined from the RapidAir device (Figure 22) are reported according to ASTM C-457-98 [12]. Five traverse lines per frame were used to distinguish between the black sections (aggregate or paste) and the white portions (compacted, entrapped, or entrained air). The threshold values were 120 for the pea gravel mixtures and 104 for the limestone mixtures. From previous studies it has been determined that threshold values are not very sensitive to some changes and ultimately the threshold used for testing is best determined by experience according to specific conditions [4].

Figure 22. RapidAir device

Results and Discussion

General properties of the concrete studied are shown in Table 12. The unit weight increased from 1,920 kg/m^3 (120 lb/ft^3) to 2,070 kg/m^3 (129 lb/ft^3) and the porosity decreased from 27% to 15% for the pea gravel mixtures having air entrainment from zero to double the recommended dosage. As air entrainment occurs the volume of paste or mortar increases.

The increased volume of paste may reduce the space between the aggregate particles and/or more completely coat the aggregate particles improving the concrete workability and causing better compaction, thus reducing the porosity and increasing the concrete unit weight. With the increased unit weight and reduced porosity, the compressive strength increased from 16.1 MPa (2,340 psi) to 24.4 MPa (3,530 psi), the splitting tensile increased strength from 1.95 MPa (280 psi) to 2.85 MPa (410 psi) and permeability decreased from 3,492 cm/hr (1,375 in./hr) for the highest porosity sample to 72 cm/hr (28 in./hr) for the lowest porosity sample.

Table 12. Concrete testing results

Mixture	Porosity (%)	Unit Weight kg/m^3 (lb/ft^3)	28-day Compressive Strength MPa (psi)	28-day Splitting Tensile Strength MPa (psi)	Permeability cm/hr (in/hr)
PG	27.0	1,920 (120)	16.1 (2,340)	1.95 (280)	3,492 (1,375)
PG-N1	23.0	1,980 (124)	23.0 (3,340)	2.30 (340)	1,116 (439)
PG-N2	20.7	1,990 (124)	24.4 (3,530)	2.85 (410)	720 (283)
PG-S1	21.2	2,000 (125)	23.0 (3,340)	2.30 (335)	216 (85)
PG-S2	15.3	2,070 (129)	23.8 (3,450)	2.40 (345)	72 (28)
LS	32.6	1,720 (108)	15.1 (2,190)	1.60 (230)	3,672 (1,446)
LS-N1	31.7	1,710 (107)	13.9 (2,020)	1.40 (205)	2,844 (1,120)
LS-N2	31.1	1,740 (109)	11.3 (1,650)	1.30 (185)	2,664 (1,049)
LS-S1	25.9	1,710 (107)	12.0 (1,740)	1.50 (215)	1,584 (624)
LS-S2	24.7	1,720 (107)	9.6 (1,390)	1.70 (245)	900 (354)

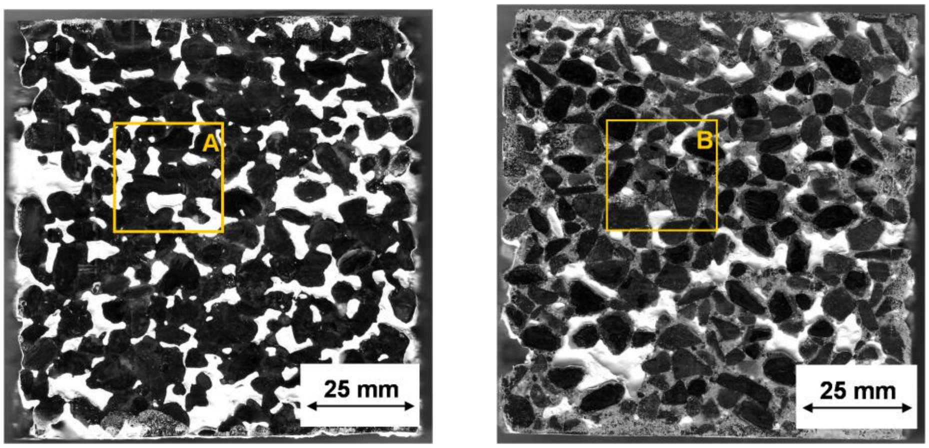
The unit weight values for the angular crushed limestone mixtures were less variable than the pea gravel mixtures and ranged from 1,710 kg/m^3 (107 lb/ft^3) to 1,740 kg/m^3 (109 lb/ft^3). The highest and lowest unit weight values did not coincide with lowest and highest porosity as did the pea gravel mixtures, although the variability in unit weight values was relatively low 30 kg/m^3 (2 lb/ft^3). The porosity values ranged from 32.6% for the mixture without air entrainment, to 24.7% for the mixture with double dosage synthetic air entrainer. It is possible that for the case of the limestone aggregate, the reduction in porosity occurred primarily because the increased paste volume resulting from the air entrainment filled the voids between the aggregate particles. Permeability ranged from 3,672 cm/hr (1,446 in./hr) for the highest porosity mixture to 900 cm/hr (354 in./hr) for the lowest porosity mixture. The air entrainment produced increased workability/compactibility for both mixtures but the effect was more pronounced in the pea gravel aggregate.

The following trends can be observed from the concrete testing results (Table 12), which are consistent with previously observed trends [5].

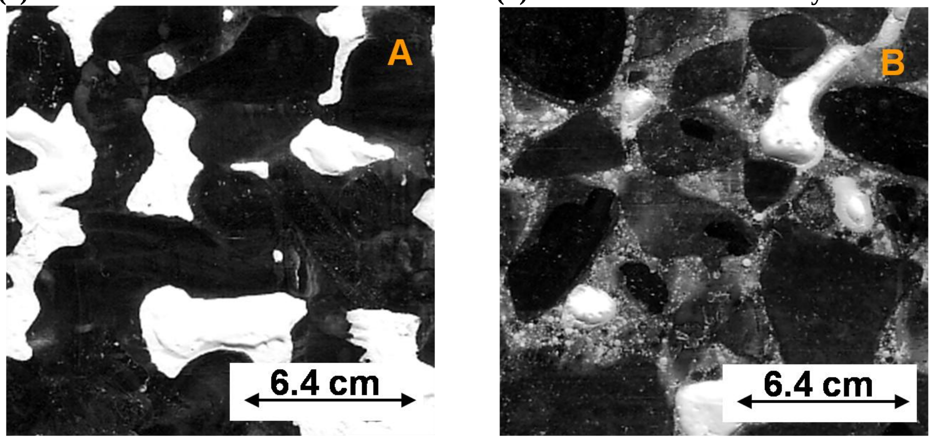
1. Addition of AEA decreases concrete porosity, thus increasing unit weight.
2. As concrete porosity decreases, the concrete unit weight increases, compressive strength, and tensile strength increase, while permeability decreases.

The void structure of two limestone samples prepared for RapidAir testing are shown in Figure 23, (a) a sample containing no air entrainment and (b) a sample containing the highest amount of entrained air produced from the double dosage of the synthetic air entrainer. The boxes represent further magnified areas. It was observed that Figure 2(c), no AEA, appears much darker than Figure 2(d), the paste with entrained air. During sample preparation, zinc paste fills in the entrained air void space resulting in a grayish coloration in the picture of the paste while, the pure white areas are the entrapped air or water-permeable voids (porosity).

In the RapidAir testing, each sample was rotated 90º between trials to determine the consistency of the measurements. Table 13 shows the variation in results produced for the pea gravel mixture with double dosage of the natural AEA. The rapidair device reports entrained air up to 4 mm in size so then the total air as measured by the rapidair includes air voids 4mm and smaller (Total Air <4mm).



(a) Limestone with no AEA **(b) Limestone with double synthetic AEA**



(c) Area A in Figure 2(a) **(d) Area B in Figure 2(b)**

Figure 23. Images of typical pervious concrete samples

Table 13. Variation of RapidAir tests for a typical sample

	Total Air (<4mm)			**Entrained Air (< 1mm)**		
PG-N2	Air (%)	SpF (mm)	SSA (mm^{-1})	Air (%)	SpF (mm)	SSA (mm^{-1})
1 (0°)	16.53	0.054	22.47	7.04	0.057	50.09
2 (90°)	15.51	0.051	25.39	6.66	0.053	56.80
3 (180°)	15.21	0.050	26.70	8.89	0.051	44.23
4 (270°)	16.15	0.053	23.54	6.76	0.056	53.47
Average	15.85	0.052	24.53	7.34	0.054	51.15
Std dev.	0.60	0.002	1.89	1.05	0.003	5.36

SpF-Spacing Factor, SSA-Specific Surface Area

The air void characteristics are shown in Table 14. As previously mentioned, for concrete made with rounded pea gravel aggregate, increased air entrainment results in more paste and in increased workability, decreasing porosity. The synthetic AEA at the single dosage produced similar amounts of entrained air as the natural AEA at double dosage. The levels of entrained air in the limestone ranged from 2.3% (without AEA) to 14.4% (with double dosage of synthetic AEA) and the levels of entrained air in the pea gravel mixtures ranged from 2.7% to 8.6%. The air void spacing factor decreased with increased air entrainment. It is generally accepted that smaller spacing factor produces better freeze-thaw protection of the paste however, all of the samples tested had values lower than the suggested limit of 0.2mm [13]. A few larger air voids (> 1mm) caused the substantial increase in air volume between that measured as entrained air and the total air less than four mm. The larger voids but did not significantly impact the spacing factor, although the average specific surface area decreased.

Table 14. Air void characteristics

	Porosity	**Average of RA Analysis Entrained Air (< 1mm)**			**Average of RA Analysis Total Air (< 4mm)**		
Mixture	(%)	Air (%)	SpF (mm)	SSA (mm^{-1})	Air (%)	SpF (mm)	SSA (mm^{-1})
PG	27.0	2.7	0.143	2.75	18.3	0.153	7.31
PG-N1	23.0	6.7	0.065	47.81	18.6	0.062	18.19
PG-N2	20.7	7.3	0.054	51.15	15.9	0.052	24.53
PG-S1	21.2	7.8	0.068	49.58	11.8	0.066	22.30
PG-S2	15.3	8.6	0.055	43.79	16.8	0.052	23.36
LS	32.6	2.3	0.115	52.52	11.7	0.149	11.82
LS-N1	31.7	4.3	0.074	60.76	13.2	0.073	21.46
LS-N2	31.1	6.8	0.047	65.45	18.5	0.045	25.21
LS-S1	25.9	6.7	0.063	48.72	15.6	0.060	22.04
LS-S2	24.7	14.4	0.034	41.84	26.1	0.033	24.20

SpF- Spacing Factor, SSA- Specific Surface Area

The air content for the pea gravel mixtures is shown in Figure 24 for measure porosity and total air and entrained air measured by the RapidAir device. The porosity decreased with increased level of air entrainment caused by the additional workability added to the cement mortar by the entrained air. The level of entrained air and porosity were similar between PG-N2 and PG-S1. The porosity represents an average of the water-permeable void space measured by the water displacement method, while the RapidAir values represent the measured air less than 4 mm. The porosity values were higher than total air for all mixtures except for the highest level of air entrainment (PG-S2) which had a porosity of 15.3% and total RapidAir voids of 16.8%. The difference between the porosity measurement and total RapidAir measurement is 1.5%, which is smaller than the 2.2% variation due to the testing method for the porosity determination [7]. As more air entrainment occurs, workability increases, and the samples become more compacted. The compacted samples generally have smaller pores, thus making more of the porosity void space included in the RapidAir measurements.

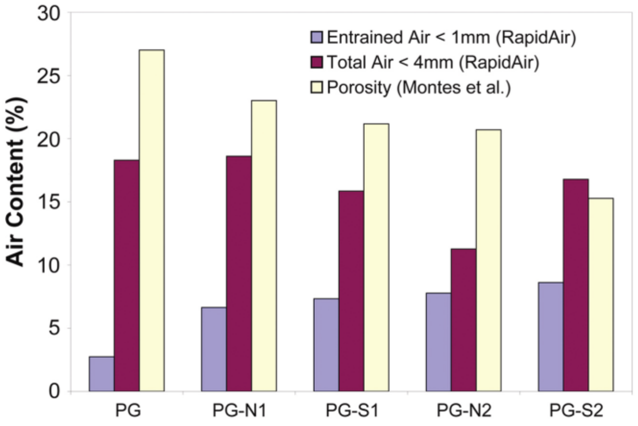


Figure 24. Total air and entrained air for pea gravel aggregate

The air void size distribution for the pea gravel mixtures are shown in Figure 25. The highest occurrence of entrained air was in the range of 0.02 to 0.03 mm. A majority of the entrained air was sized between 0.01 and 0.1 mm. The natural AEA produced higher amounts of the smaller (0.02 to 0.05 mm) voids, while the synthetic AEA produced higher amounts of the medium-sized (0.05 to 0.10 mm) voids. The samples with no AEA had the lowest level of entrained air.

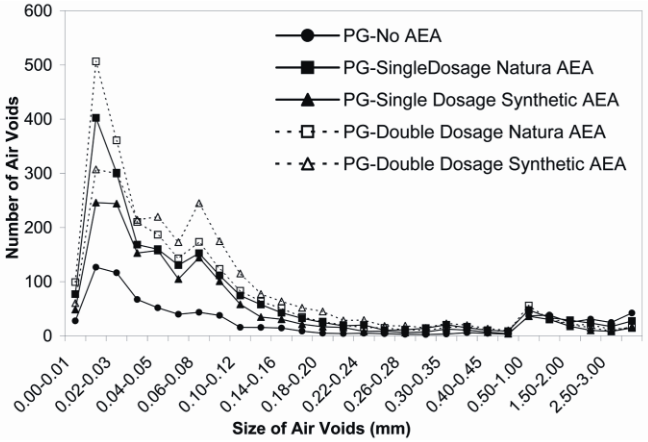


Figure 25. Air void distribution in the pea gravel mixtures

The cumulative distribution of entrained air in the pea gravel mixtures is shown in Figure 26. The delineation between entrained air and porosity can clearly be observed between void size less than one mm and those greater. The samples with no air entrainment had the least volume of entrained air. Samples with double dosage of natural AEA (PG-N2) and single dosage of synthetic AEA (PG-S1) had similar levels of air entrainment. The highest dosage of the synthetic AEA had the highest level of entrained air.

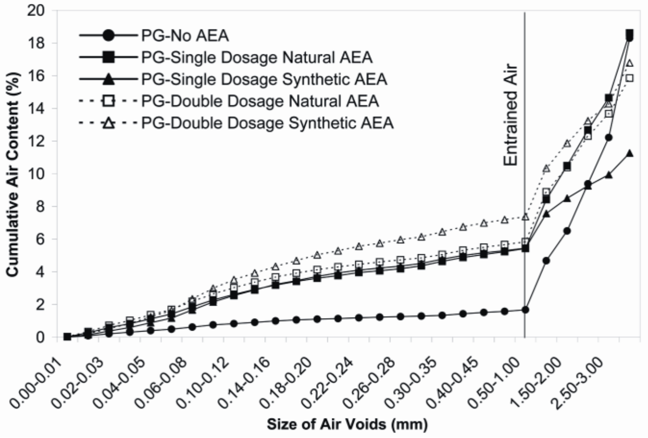


Figure 26. Cumulative air content of pea gravel mixtures

The air contents for the limestone mixtures are shown in Figure 27 for measured porosity and total air and entrained air determined by the RapidAir device. Differently, for concrete made with the angular limestone aggregate, the total air content measured by the RapidAir system (< 4mm) increased with air entrainment. It is possible that due to the rough surface texture of the limestone aggregate, the improvement in concrete workability due to the air entrainment might also be less effective than that which occurred in the concrete made with rounded pea gravel. The porosity generally decreased with increased entrained air, but not as significantly as the pea gravel due to the ability of the crushed material to resist compaction through aggregate friction. Similar to the pea gravel mixtures, the porosity was higher than the RapidAir total for all mixtures except that with the highest amount of air entrainment (LS-S2). The testing error of the measured porosity (24.7%) was within that of the RapidAir device (26.1%) for LS-S2).

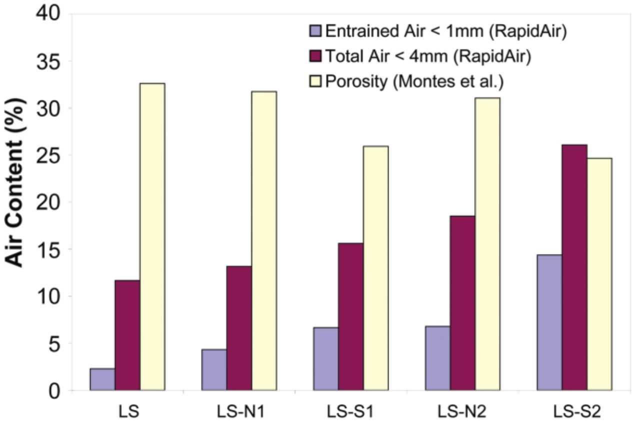


Figure 27. Total air and entrained air for limestone aggregate

The air void size distribution for the limestone mixtures are shown in Figure 28. Significantly higher amounts of air voids were generated at both the double AEA additional levels, particularly in the small (0.01 to 0.03 mm) range. The synthetic AEA had higher amounts of the small voids at the double dosage and the amounts of small-sized voids were similar at the recommended dosage rate.

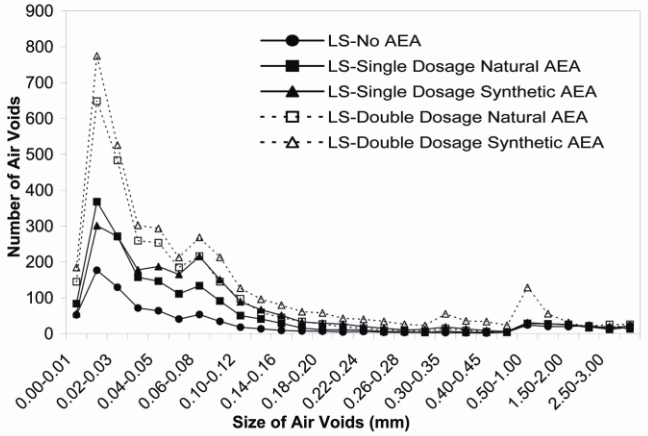


Figure 28. Air void distribution in the limestone mixtures

The cumulative volume of entrained air for the limestone mixtures is shown in Figure 29. The rapid increase in measured air above the 1 mm size again provides segregation between entrained air and porosity. Samples with the double dosage of synthetic AEA (LS-S2) had the highest amount of entrained air, while the lack of AEA (LS) had the lowest amount of entrained air. Similar to the pea gravel mixtures, the single dosage of synthetic AEA (LS-S1) produced equal volume of entrained air as the higher dosage of the natural AEA (LS-N2).

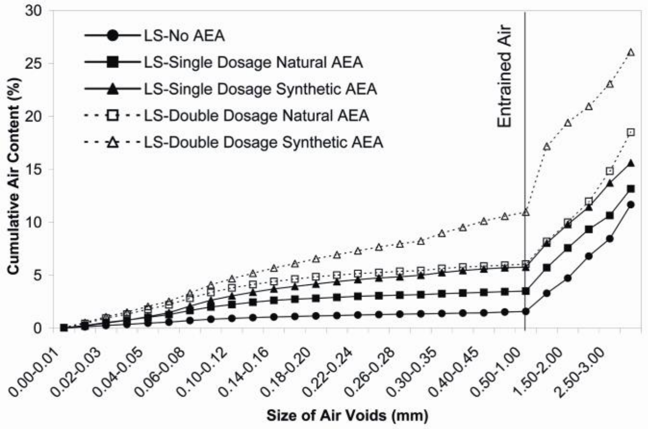


Figure 29. Cumulative air content of limestone mixtures

Freeze-thaw test results for the pea gravel concrete are shown in Figure 30. As mentioned before, the freeze-thaw test results of the limestone concrete are not presented here since the limestone aggregate is not freeze-thaw durable using the ASTM C666A procedure. The pea gravel has been previously shown freeze-thaw durable [5]. The only mixture which completed the duration of 300 cycles had the greatest amount of entrained air (8.6%), lowest porosity (15.3%), and highest unit weight (2,060 kg/m^3), PG-S2. Poorest freeze-thaw durability, failure at 99 cycles, occurred in the mixture without AEA (PG), which had the lowest amount of entrained air (2.7%), highest porosity (27%), and lowest unit weight (1,920 kg/m^3). The air entrainment, porosity, and unit weight were similar between PG-N2 and PG-S1, consequently those mixtures had similar freeze thaw durability failing at 229 cycles.

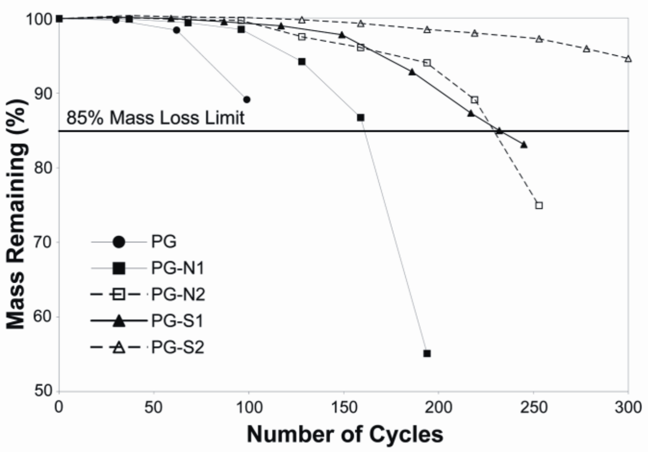


Figure 30. Freeze-thaw durability of the pea gravel mixtures

Conclusions

From this study the following conclusions can be made:

1. Air entrainment increased the paste volume and improved workability of pervious concrete, thus reducing overall porosity and increasing density. The effect of air entrainment on porosity and workability is more pronounced for concrete made with the rounded pea gravel aggregate than that in concrete made with the angular crushed limestone.
2. Concrete having lower porosity and consequently higher unit weight, displayed higher strength, better freeze-thaw resistance, and lower permeability.
3. The RapidAir test results indicated that even without air entrainment pervious concrete still had spacing factor values less than 0.2 mm (200 μm). This implies that it is the improved density resulting from air entrainment which enhanced freeze-thaw resistance.
4. The recommended dosage of synthetic air entrainer produced equivalent contents of entrained air as the double recommended dosage of the natural air entrainer. Synthetic air entrainer produced higher amounts of air entrainment that the natural air entrainer at a given dosage. The entrained air void structure of pervious concrete can be characterized using the RapidAir device.

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CHAPTER 5. EVALUATION OF PERVIOUS CONCRETE WORKABILITY USING GYRATORY COMPACTION

A paper submitted to the *ASCE Journal of Materials in Civil Engineering*.

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Abstract:

The increased use of Portland Cement Pervious Concrete (PCPC) across the United States (U.S.) has prompted various entities to begin the process of standardized test techniques. A major issue with placing PCPC is the inconsistencies in workability between batches, countered by tempering the mixture at the job site, which is subjective to human interpretation. Determining workability of pervious concrete will allow consistent placement between batches and will allow mixtures to be designed for particular compaction methods. Slump loss and the effect of admixtures on workability and placing time will be quantified and the overall placement quality will improve. This paper describes research performed to allow unbiased sample preparation and workability determination using gyratory compaction. The effect of binder content and water to cement ratio were studied along with the plastic concrete behavior with increased mixing time to simulate field conditions. The results show that gyratory compaction is able to produce PCPC specimens to design void content or unit weight. Observation of the compaction curve defines both the initial concrete workability but also the resistance of the mixture to further compaction and values are presented for acceptable ranges. (187 words)

CE Database Subject Headings: Concrete, Concrete Construction, Concrete Pavements, Concrete Technology, Porous Pavements, Permeability, Porous Materials, Stormwater Management, Best Management Practice, Compaction

Introduction

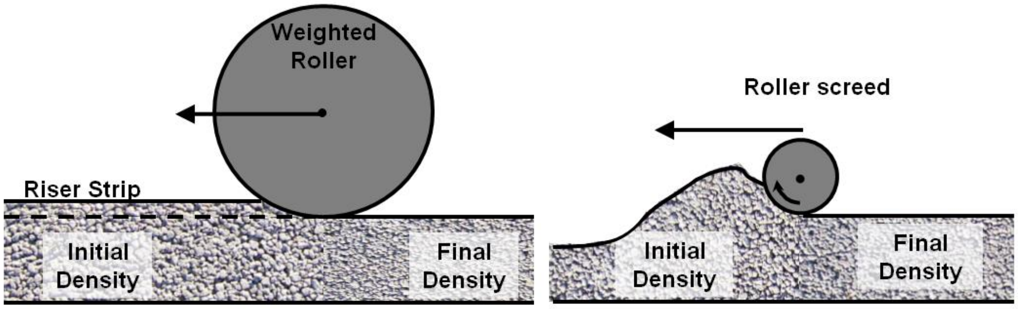
Portland Cement Pervious Concrete (PCPC) mixture designs that have excellent performance in the lab may stiffen during transport resulting in poor compaction, requiring additional water at the project. Addition of water at the job site increases water-to-cement ratio (*w/c*), reducing the concrete strength and durability. Many practitioners of pervious concrete have experienced instances when principles from traditional concrete are applied to pervious, resulting in a less-than optimal final product. To date, determining the workability of pervious concrete has been considered an art form, since the conventional slump test does not provide useful information for such stiff concrete. The current method is to evaluate the concrete ability to form a ball with the plastic pervious concrete (Tennis *et al.* 2004). This method is impossible to specify due to the lack of quantifiable values such as the force to compact by hand. A more scientific method of workability determination is required if PCPC is to progress to large-scale parking areas and surface overlays.

Pervious concrete is designed to transport stormwater into the underlying layers through a series of interconnected voids, while providing the designed load-carrying capacity, typically for parking areas. The interconnected voids are produced from a balance between aggregate gradation and binder content. In the concrete mixture design, the objective is to provide a sufficient amount of voids to infiltrate the designed stormwater intensity. There is a direct relationship between voids and compressive strength, where lower voids produce more intraparticle contact and consequently higher load-carrying capacities (Schaefer *et al.* 2006). The void content (porosity) of the plastic and hardened pervious concrete can be determined from the unit weight. Determination of plastic workability becomes paramount since the required parameters (permeability and strength) are based on unit weight, which is achieved through proper placement. A highly workable mixture requires less compaction energy to achieve higher unit weight than a stiff mixture. By quantifying pervious concrete workability, mixtures can be designed to produce certain void contents using specified compaction methods and the workability can be verified and adjusted accordingly before placement.

In the present study, a modified Superpave Gyratory Compactor (SGC) test method is employed to characterize the workability of pervious concrete. In this test, pervious concrete samples were produced using a SGC that allows for simulating various field compaction conditions. Workability of the concrete is then defined by the unit weight to number of gyration relation curve. A matrix of concrete mixtures that consists of various water-to-binder ratios (*w/*b) and cement contents were tested. The effect of mixing time on concrete workability was also evaluated so as to identify “slump loss” of field concrete. The results show the SGC is able to produce consistent pervious concrete specimens and the output of the test method well quantifies the workability and compactibility of pervious concrete. The discussion includes a range of suggested values to allow design and verification of production pervious concrete workability.

Field Compaction Methods and Requirements for Pervious Concrete Workability

There are two basic methods of pervious concrete placement/compaction currently employed in the United States (U.S.): 1) riser strip method and 2) roller-screed method.
The riser strip method is commonly used in the southern U.S. and involves riser strips placed above the forms. Concrete is roughly finished to the riser height, and then the risers are removed, and a weighed roller is used to compact to final height (Figure 31a).



(a) (b)

Figure 31. Compaction of pervious concrete

In the roller-screed method, which is gaining a more wide-spread use, an electrically or hydraulically driven roller-screed is used to accomplish both the compaction and finishing steps. As shown in Figure 31b, the steel tube screed rotates opposite to the direction of placement. Roller-screeds can either be filled with sand or water, commonly 30 kg/m (20 plf) or 18 kg/m (12 plf), respectively. The compaction pressure applied to the fresh concrete is a function of the weight of the roller and the contact area between the roller and the pavement. At a low level of compaction, the roller to concrete contact area is large, and decreases with the level of compaction. Figure 32 shows a typical contact pattern between a weighted roller and the pavement. During the initial pass the contact area is large (circumference, C/8) and decreases for subsequent passes (C/16 to C/32), which produce low compaction pressure during the initial pass and increase compaction pressure for later passes.

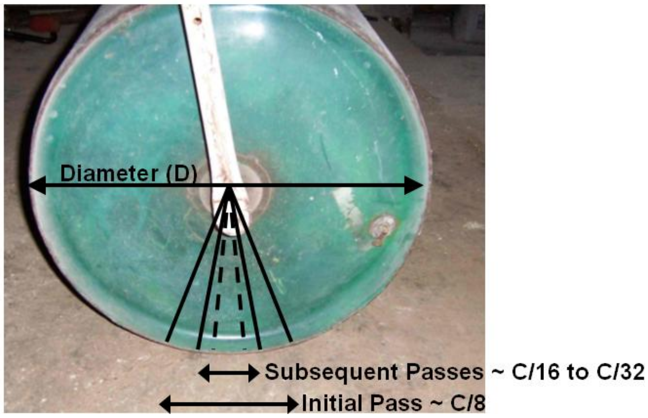


Figure 32. Roller contact area

To appropriately determine compaction energy, the contact area must be considered. The contact pressure for two common cases for a roller-screed and a typical weighted lawn-roller are shown in Table 15. Compaction pressures range from 2.9 kPa (0.4 psi) for the water-filled roller-screed during the initial pass, to 40 kPa (5.8 psi) for the weighted roller during later passes. For comparison, the pressure exerted by a 90.7 kg (200 lb) person is about 11.7 kPa (1.7 psi). Since the compaction applied to the field pervious concrete pavement is low, modification of the SGC commonly used for conventional asphalt concrete pavement is required so as to produce compaction response to more closely simulate field conditions.

Table 15. Range of roller compaction pressure

Roller Type	Diameter	Linear Weight	Pressure C/8	Pressure C/16	Pressure C/32
	cm (in.)	kg/m (lb/ft)	kPa (psi)	kPa (psi)	kPa (psi)
Weighted w/water	46 (18)	182 (122)	9.7 (1.4)	20.0 (2.9)	40.0 (5.8)
Screed w/water	15 (6)	18 (12)	2.9 (0.4)	5.9 (0.85)	11.7 (1.7)
Screed w/sand	15 (6)	30 (20)	4.9 (0.7)	9.7 (1.4)	19.5 (2.8)

It is well-understood that gyratory compactors better simulate the type of compaction utilized by the asphalt industry, primarily steel drum and pneumatic compaction (AI 2001). Since pervious concrete is loosely placed and then finished/compacted with either a weighted drum or roller-screed, the use of a gyratory compactor is appropriate to simulate field conditions. Normal conditions for Superpave asphalt design require a 600 kPa (87 psi) load for laboratory compaction to simulate field compaction. For this study, a gyratory compactor was modified to achieve compactive effort of 60 kPa (8.7 psi), within a tolerance of 2 kPa (0.3 psi), for 150mm (6 in.) diameter samples.

Gyratory Test Method Development

Determination of Appropriate Compaction Pressure

A simple baseline pervious mixture was selected to determine if the lowest amount of compaction energy (60 kPa), provided by the available SGC, was capable for producing the Design Void Content (DVC) as determined by the absolute volume mixture proportions. The baseline mixture contained single-sized 4.75mm (No. 4) river gravel, Type II Portland cement, and a water to cement ratio of 0.27. Using the mixture proportions shown in Table 16, the DVC was determined as 20% at 1,990 kg/m^3 (125 pcf).

Table 16. Baseline mixture proportions

Material	**Specific Gravity**	**Amount** kg/m^3 (pcf)	**Volume** %
River Gravel	2.60	1,570 (98)	60.6
Type II Cement	3.15	330 (21)	10.5
Water (0.27)	1.00	90 (6)	8.9
DVC		0	20.0

In order to determine the pressure required for producing DVC of 20% at 100 gyrations, the baseline mixture (Table 16) was compacted in 150 mm (6 in.) diameter molds using 60 kPa, 120 kPa, 180 kPa, and 240 kPa. The ratio of the unit weight at N gyrations to the unit weight at the DVC is defined as the apparent Degree of Compaction (DoC). The test results show that the baseline mixture with 60 kPa produced 100.2% DoC at 19.84% voids, 120 kPa 100.5% DoC at 19.61% voids, 180 kPa 101.3% DoC at 19.02% voids, and 240 kPa 101.6% DoC at 18.70% voids. Since the compaction pressure applied in the field is less than 60 kPa (Table 1), the lowest pressure of 60kPa, slightly higher than the pressure (57 kPa) capably provided by the available SGC, was selected for the subsequent design compaction level.

Determination of the Maximum Number of Gyrations

Previous research using gyratory compaction on roller-compacted concrete (RCC) has shown that 100 gyrations is sufficient to obtain uniform and complete compaction (Amer *et al.* 2003). Figure 33 shows the gyratory response of the baseline pervious samples compacted at 60 kPa for 20, 50, and 100 gyrations and Figure 34 shows the height difference of the samples. At 100 gyrations, the change in slope of the compaction curve is was small, nearing the maximum asymptote. Consequently, 100 gyrations were selected as the upper limit for compaction of the pervious specimens.

Samples produced from the SGC have a uniform level of compaction across the specimens, eliminating the variability created when samples are produced using some type of rodding or jigging procedure.

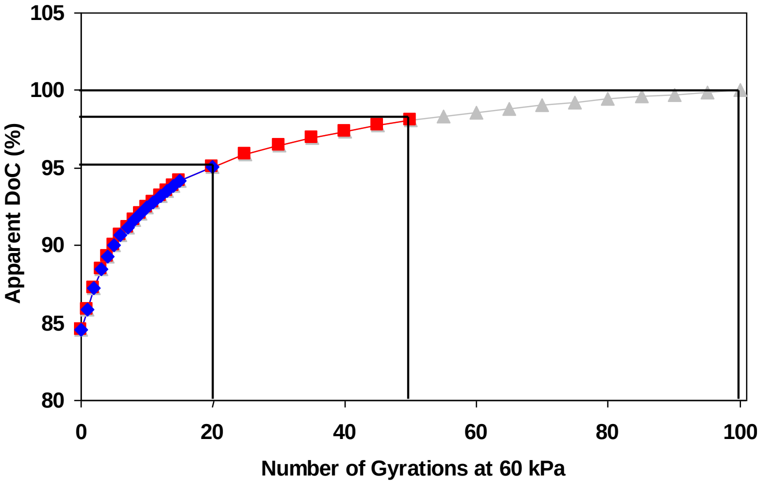


Figure 33. Degree of compaction curve of the baseline mixture


20 gyr, h=138 mm 50 gyr, h=133mm 100 gyr, h=128mm

Figure 34. Samples compacted at different gyrations

Determination of Workability Using the Gyratory Compaction Curve

The compaction curve produced by the SGC (see Figure 35) has two distinct portions; 1) the initial phase characterized by a steep slope where excess air voids are removed under the initial, short-term compaction and 2) the final phase characterized by a small change in slope resulting from particle re-arrangement under further applied compaction. The initial phase is dependent primarily on intrinsic workability of a particular mixture or the self-compacting ability. The final phase is controlled by the resistance of a particular mixture to additional compaction energy. Since the goal of pervious concrete placement is a design *in-situ* void content (DVC) and unit weight, the same outcome can be achieved by either a highly workable mixture or additional compaction energy. A very fluid mixture design may require little to no compaction after discharge, but a stiff mixture design may require compaction with a weighted roller. Both mixtures result in the same voids, although achieved by two different mechanisms, requiring the consideration of both components of the compaction curve.

In the asphalt industry the initial compaction level is calculated between six and eight gyrations, depending on the design traffic level (Stakston and Bahia 2003). The point of maximum curvature was determined as the boundary between workability and compactibility. When the point of maximum curvature was determined for the initial project variables, the inflection point occurred between seven and nine gyrations with the most occurring at eight gyrations (Table 17). For pervious concrete specimens, the compaction at eight gyrations is slightly greater than 90% of DVC. Consequently, eight gyrations was selected to define initial workability for pervious concrete.

Table 17. Determination of maximum curvature

binder/aggregate	w/c	Inflection point
21	0.25	8
21	0.27	8
21	0.29	8
21	0.31	7
10	0.27	8
15	0.27	8
19	0.27	9
21	0.27	8
23	0.27	8
25	0.27	9
	avg	8.10
	std dev	0.57

The unit weight and DoC at zero gyrations were observed to have a large degree of variability resulting from the placement of the samples in the gyratory mold. Beginning at the first gyration, the compaction curve was controlled by the sample placement in the mold. In order to eliminate this variability, workability was defined after the first gyration. The area under the compaction curve from one to eight gyrations is termed the Workability Energy Index (WEI) and defines the inherent workability from little additional compaction, as shown in Figure 35. The final portion of the curve, representing compactibility, is defined as the area under the compaction curve from eight gyrations to the DVC or 100 gyrations, whichever occurs first, to the compaction level achieved at eight gyrations. This value is termed the Compaction Densification Index (CDI) and indicates the practical amount of additional energy required to bring the mixture to the DVC, as shown in Figure 35. The combination of WEI and CDI is termed the placeability of a pervious concrete mixture.

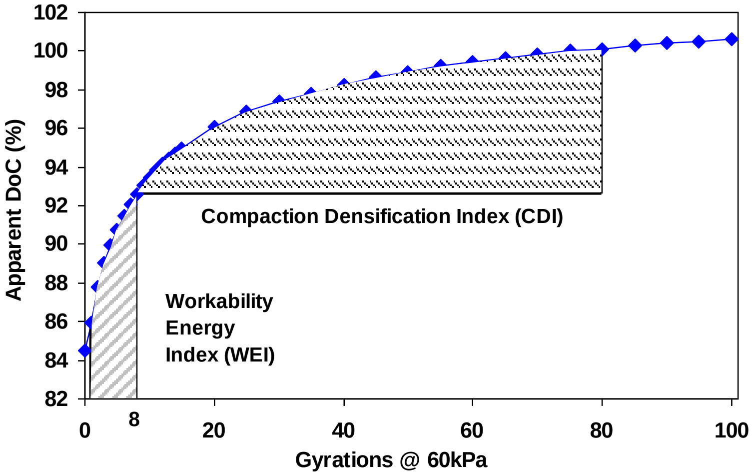


Figure 35. Definition of the workability index parameters

Evaluation of Gyratory Compaction on Pervious Concrete Specimens

The relationship between unit weight and void ratio for pervious concrete is well understood (Schaefer *et al.* 2006, Kevern 2006). The SGC has the ability to provide plastic workability properties through the compaction output curve, in addition to producing unbiased hardened samples for quality control purposes. Samples produced using the baseline mixture, while determining appropriate pressure and number of gyrations, were tested for hardened unit weight, voids, and splitting tensile strength at 7-day according to ASTM C496 (1996). Voids were tested according to the procedure developed by Montes *et al.* (2005). Unit weight of fresh concrete, or the plastic unit weight, was determined from the SGC compaction curve and then used to calculate voids. The properties of samples produced from the baseline mixture are shown in Table 18. The void ratios ranged from 19% to 30%, with up to a 6% difference between the plastic voids and those determined from oven-dry samples.

Table 18. Gyratory-compacted sample properties (baseline mixture)

Gyrations	**Pressure**	**Measured Plastic Unit Weight**	**Calculated Plastic Voids**	**Measured Oven Dry Unit Weight**	**Measured Oven Dry Voids**	**7-day Splitting Tensile Strength**
	kPa (psi)	kg/m^3 (pcf)	(%)	kg/m^3 (pcf)	(%)	MPa(psi)
100	60 (8.7)	2,000 (125)	19.9	1,940 (121)	25.1	1.80 (260)
100	120 (17.4)	2,020 (126)	19.0	1,940 (121)	25.1	1.85 (265)
100	180 (26.1)	2,010 (125)	19.5	1,960 (122)	21.3	1.90 (275)
100	240(34.8)	2,030 (127)	18.7	1,970 (123)	23.9	1.75 (255)
4	60 (8.7)	1,750 (109)	30.0	1,690 (106)	36.5	1.00 (145)
20	60 (8.7)	1,880 (117)	24.6	1,830 (114)	29.9	1.15 (170)
25	60 (8.7)	1,870 (117)	25.1	1,800 (113)	31.2	1.35 (200)
50	60 (8.7)	1,940 (121)	22.0	1,900 (118)	26.3	1.85 (270)
150	60 (8.7)	1,990 (124)	20.4	1,940 (121)	24.5	1.50 (215)

The relationship between voids and unit weight is shown in Figure 36 for both the plastic values calculated from the SGC and the measured oven dry values. As previously observed, the reduction in unit weight with increased voids is linear for samples of different compaction levels produced from the same mixture. The plastic unit weight was always higher, corresponding in lower voids, than that of the same samples tested in the oven dry state. The difference between calculated and measured voids decreased with increased compaction level.

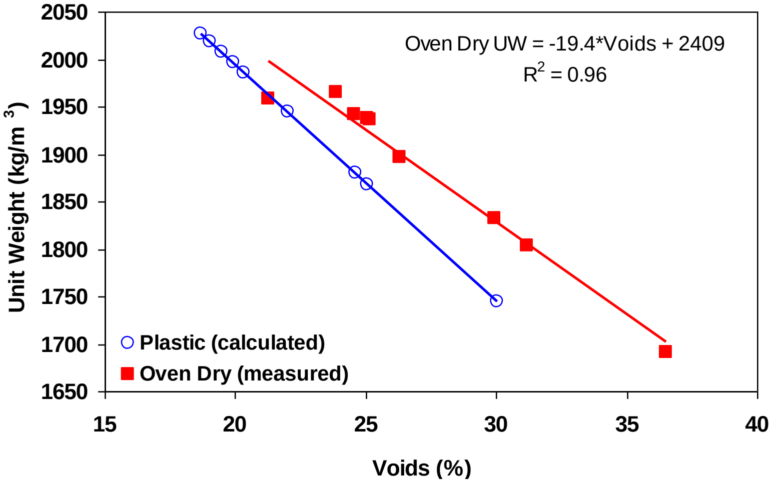


Figure 36. Relationship between voids and unit weight of pervious concrete samples made with gyratory compaction

Samples produced in the SGC have a diameter of 150mm (6 inches), which requires coring to produce compressive strength samples with the correct height to diameter aspect ratio. The relationship between splitting tensile strength and compressive strength for pervious concrete is between 12% and 15% of the compressive strength (Schaefer *et al.* 2006). Since the determination of splitting tensile strength allows for any diameter and length specimen, splitting tensile strength was selected to report strength. The samples were tested at 7-days and the relationship between voids and tensile strength is shown in Figure 37. The trendline has an R^2 of 0.77 with the expected outcome of lower strength with increased voids.

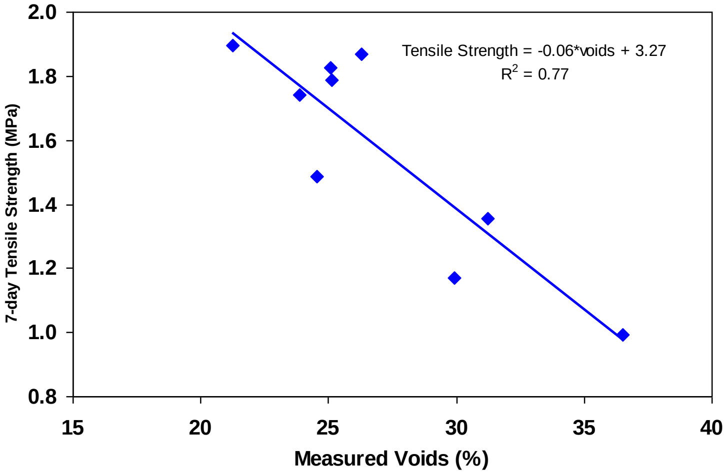


Figure 37. Relationship between voids and splitting tensile strength

Factors that Influence Pervious Concrete Workability

The key factors in pervious concrete mixture design are the aggregate gradation, binder-to-aggregate ratio (b/a), and water-to-cementitious binder (*w/b)* ratio. In addition to the basic mixture design components, admixtures are often used to enhance workability and to extend the placing window. The mixture proportions used to evaluate gyratory workability all had a DVC of 20% and aggregate, binder, and water contents were adjusted accordingly. To evaluate the validity of the WEI and CDI indices, a variety of common pervious concrete mixture proportions were tested. Table 19 lists the project variables used to characterize workability behavior with time, effect of binder content, and water to cement ratio.

Table 19. Project variables

Variables					
Additional Mixing Time (min.)	0	15	30		
Binder Content (%)	10	19	21	23	25
w/b	0.25	0.27	0.29	0.31	

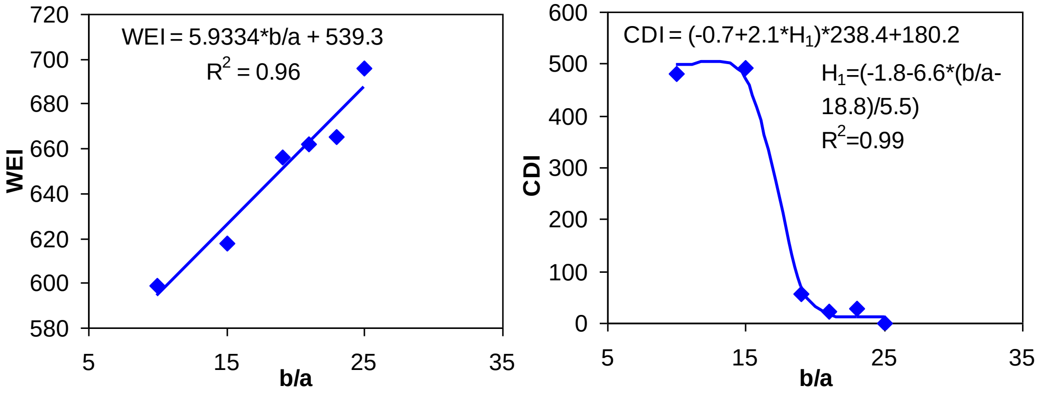
Effect of Binder Content

Pervious concrete binder connects the aggregate pieces and transfer load throughout the pavement. Too little binder provides insufficient connected area for the required concrete strength and durability. On the other hand, too much binder fills in the concrete voids and does not allow the required permeability. The effect of the binder content on workability was evaluated using a mixture with a fixed *w/b* of 0.27. Table 20 provides the average workability and compactibility results for the various binder contents.

Table 20. Gyratory results for pervious concrete with different binder contents

w/b	b/a (%)	WEI	CDI
0.27	10	599	482
	15	618	492
	19	656	56
	21	662	24
	23	665	27
	25	696	0

Figure 8 shows the relationship between workability (Figure 38a), compactibility (Figure 38b), and binder content. Each point in the figure represents the average of three tests. The workability (WEI) increased linearly with increased binder and additional required compaction energy (CDI) decreased with increased binder content. In pervious concrete, the sufficiently wetted cementitious paste provides lubrication between the aggregate particles. While the workability continued to increase with increased binder content, there was a sudden drop in required compaction energy when enough cement paste was present to separate the aggregate particles and to provide lubrication, between b/a (0.15 to 0.19).



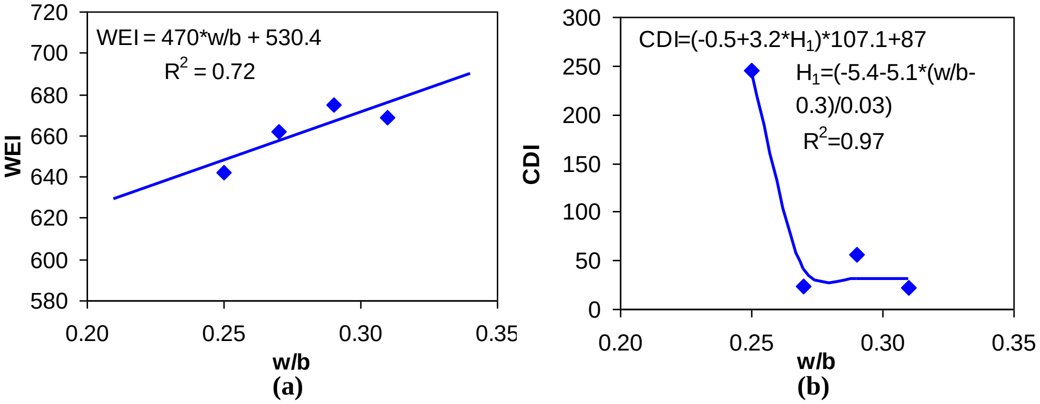
(a) (b)

Figure 38. Effect of binder-to-aggregate ratio on workability index parameters

The mixtures with b/a of 10% (WEI = 599) and 15% (WEI = 618) were similar to the mixtures commonly observed in the field. Any mixture having a further decrease in workability (WEI<600) would require remediation or rejection. Once the b/a increased to 19% (WEI = 656), the workability had increased to a point where the mixture achieved DVC easily and especially for the 25% b/a (WEI = 696), which may result in self-consolidating concrete. The effect on compactibility was even more pronounced than WEI. The lower binder mixtures, b/a of 10% (CDI = 482) and 15% (CDI = 492), resisted compaction and required substantial compaction energy to achieve DVC. Again, once the b/a increased to 19% (CDI = 56), the required compaction energy decreased and when b/a = 25%, no additional energy was required. The results suggest that a minimum WEI of 600 and CDI of 450 may be appropriate for pervious concrete to have acceptable workability.

Effect of water-to-binder ratio

When pervious concrete arrives at a job site the workability is "evaluated" and if too dry, up to a half a gallon per cubic yard of water is added at a time to improve workability (NRMCA 2005). It is understood that more water generally improves workability, in either traditional or pervious concrete, but reduces overall performance (Kosmatka *et al.* 2002). Pervious concrete is produced in a very small window of water contents (approximately 0.27-0.33). Too dry and the paste does not have enough cohesion to coat and join the aggregate particles together, while too wet and the paste drains away from the aggregate and clogs the water-carrying pores. The effect of water-to-binder ratio on the narrow range used for pervious concrete is shown in Figure 39. Each point in the figure represents the average of three tests. The workability (WEI) generally increased with increased *w/b* and required compaction energy (CDI) decreased with increased *w/b* with a large decrease in CDI between 0.25 and 0.27. Similarly to the compactibility trend shown in the previous figure, a significant drop in required compaction energy occurred when the paste became sufficiently wetted and began lubricating the aggregate particles, between *w/b* (0.25 and 0.27). Visually, concrete at w/c = 0.25 was cement powder-coated aggregate particles and would not be considered concrete. While concrete at w/c=0.27 was cement paste-coated particles and had the consistency associated with pervious concrete.



(a) **(b)**

Figure 39. Effect of w/b on workability and compactibility

Since the mixtures were placed with typical *w/b* contents, the measured workability was high (WEI >600). The compactibility for all mixtures was less than CDI = 450 and typical for pervious concrete mixtures in the field, although the *w/b* = 0.25 had significantly higher CDI. Comparing the effect on workability of b/a and *w/b*, the WEI is influenced more significantly by binder content than by *w/b*. Workability increased with either increased binder or water content but, the required compaction energy dropped significantly when enough paste (cement and water) was present.

Effect of Mixing Time

The large amount of exposed surface area makes pervious concrete especially susceptible to "slump loss" with time. The effect of mixing time on placeability of pervious concrete has not been previously studied. Typical specifications allow concrete to be placed up to 90 minutes after batching or 150 revolutions in the ready mixed truck (ASTM C94 2003). Highly workable pervious concrete mixtures produced in the lab are rarely comparable with the actual production. Therefore, the effect of mixing time on pervious concrete placeability was evaluated in the present study. Figure 40 shows the decrease in workability caused by additional mixing time for one example mixture #4RG-B19 and 0.27 *w/b*, where T=1 indicates the sample was tested immediately after approximate 10 minute initial mixing, T=2 after 5-10 minutes waiting for the first sample to test and 15 minutes of additional mixing (about 30 minutes total mix time), and T=3 after an additional 15 minutes of mixing following sample T=2 testing (about one hour total mix time). It was observed that the DoC of the tested mixture at any given gyration decreased with mixing time (from T=1 to

T=3), indicating stiffening of the pervious concrete mixture. The initial slope was similar for a particular mixture observed at different mixing times.

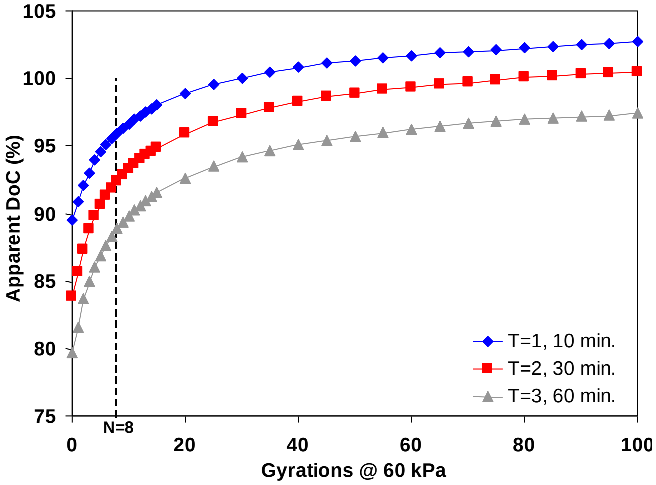


Figure 40. Effect of mixing time on workability of baseline mixture

The placeability for the various mixing times is shown in Figure 41. The initial case shows a highly workable mixture requiring little additional compaction to achieve DVC. After 30 minutes total time (T=2), the workability decreased and required compaction energy significantly increased. At one hour of total time (T=3) it was observed that the mixture had passed a placeability window and would be subject to rejection. The paste had lost the required metallic sheen and had started forming paste balls and leaving bare aggregate.

The large difference in workability and compactibility caused by time makes consistent placement of pervious concrete using a fixed compaction method difficult. A certain compaction and finishing method which produces DVC at T=1 will result in unacceptably high voids and low unit weight if applied to the same mixture at T=3. The effect on placeability of the maximum and minimum b/a and *w/b* caused by mixing time is shown in Figure 41. The effect on workability caused by mixing time was similar for all mixtures tested in either of the previous two phases. A relatively uniform decrease in workability occurred with increased mixing time. Required compaction energy increased regularly with mixing time for different binder contents with fixed water content. At a low *w/b* (0.25) and fixed cement content (0.21), the CDI increased when the mixing time increased from T=1 to T=2 but leveled off after T=2. At a high *w/b* (0.31), compactibility of the mixture remained low (CDI<100) for the periods of T=1 and T=2 but substantially increased at T=3, and at the later time there was no difference in compactibility between the lowest and highest *w/b* samples.

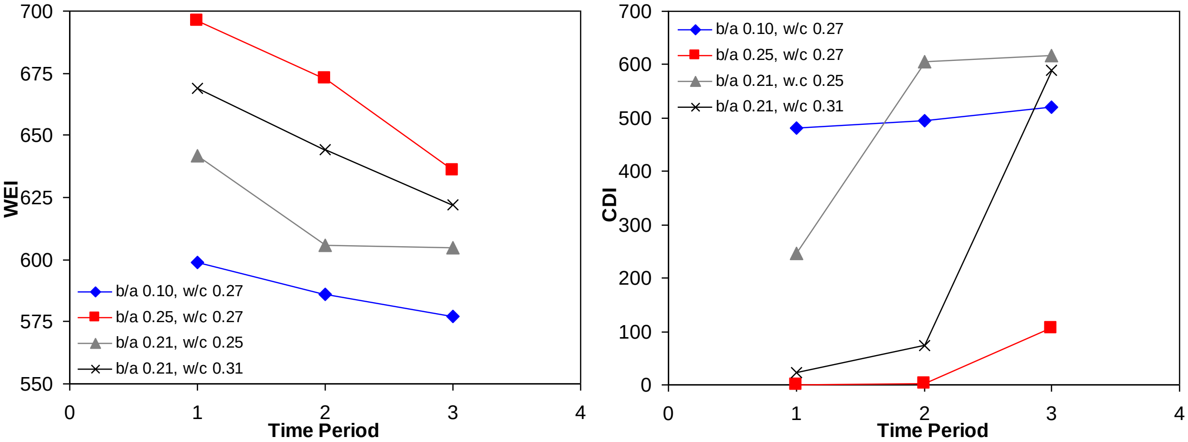


Figure 41. Effect on placeability of mixing time

The common reaction to improve placeability of pervious concrete is to increase the water content. Increased water content provides greater workability for all time periods although, does not provide increased compactibility at later times. To increase placeability at later ages, it is more beneficial to increase the binder content rather than water content.

Classification of Pervious Concrete Placeability

The identification of desired placeability parameters will allow pervious concrete mixtures to be designed better, taking into account compaction energy versus desired voids, and achieve quality control in the field. Based on the SGC test results discussed previously, guidelines for evaluating pervious concrete workability and compactibility are proposed in Table 21. Following the guidelines, mixtures can be designed and required to meet placeability requirements, increasing the consistency and quality of pervious concrete placements.

Table 21. Range of pervious concrete gyratory values

Workability (WEI)	
Explanation	**Range**
Highly Workable	> 640
Acceptable Workability	640>WEI>600
Poor Workability	WEI<600
Compactibility (CDI)	
Explanation	**Range**
Self-Consolidating	CDI<50
Normal Compaction Effort Required	50<CDI<450
Considerable Additional Compaction Effort Required	CDI>450

Conclusions and Recommendations

From this study the following conclusions can be made:

1. The gyratory compaction allows consistent placement of pervious concrete samples to designed void contents, which removes the variability caused by existing pervious concrete placement methods used in the lab and field.
2. The gyratory compaction curve defines workability (WEI) in the initial portion to eight gyrations and compactibility (CDI) from eight gyrations to the DVC or 100 gyrations.
3. The workability (WEI) generally increased with increased *w/b* and required compaction energy (CDI) decreased with increased *w/b*.
4. To increase concrete placeability, it is more beneficial to increase the binder content rather than the *w/b*.
5. The effect of mixing time on placeability shows a significant decrease in workability causing a corresponding decrease in compactibility.
6. Guidelines are developed to assist designing pervious concrete mixtures for specific compaction methods and to allow quantification of placeability.

Future Research

The determination of placeability indices for pervious concrete will allow quantification of the effects of various admixtures on pervious concrete behavior. Specifically, the ability of specialized admixtures to maintain mixture consistency over a typical period of time will be measured and compared. The effect of various cementitious materials on the workability and aggregate angularity and mixture improvement from sand addition will be known. By designing a mixture for a specific void content and unit weight produced by a given compaction method at a known mixing time, the problems associated with inconsistent highly-variable pervious concrete mixtures can be eliminated. A greater level of QA/QC ability will allow pervious concrete to better transition from nitch markets to mainstream applications.

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CHAPTER 6. EFFECT OF CURING REGIME ON PERVIOUS CONCRETE ABRASION RESISTANCE

A paper submitted to the *ASTM Journal of Testing and Evaluation*

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Abstract

The current method of curing pervious concrete is to cover with plastic for 7-days although, no studies have been performed to determine if that is sufficient or even required. This paper presents results of combinations of four different pervious concrete mixtures cured using six common curing methods. The surface abrasion of the concrete was tested using a rotary cutter device according to ASTM C944. The results show that a majority of the concrete abrasion resistance was improved with surface-applied curing compounds, although the surfaces covered with plastic sheets produced the lowest abrasion levels. A majority of the curing regimes also produced higher flexural strength than the control concrete. There was no significant difference observed in the strength between curing under plastic sheets for 7-days or 28-days. Of the surface-applied curing compounds, the best abrasion resistance and highest strength concrete was that applied with soybean oil. The best abrasion resistance and highest strength overall was the mixture containing fly ash and cured under plastic for 28-days.

Introduction

The recent increases in the requirements for stormwater management have moved many previously under-utilized best management practices to the forefront. Pervious pavements have been used in the Southern United States for many years but only in the last few years has the demand and research knowledge allowed successful commercial installations in Northern climates. The freeze-thaw durability of Portland Cement Pervious Concrete (PCPC) has been studied in the laboratory and the findings show that this aspect may not be as much of a concern as initially believed. When pervious concrete is applied to pavements in areas which undergo freeze-thaw, durability also refers to the surface abrasion resistance against snow clearing operations. If pervious concrete is to progress from parking lot applications to low-volume and potentially high-volume applications, the pavement must be resistant to all aspects of cold weather maintenance.

Concrete curing is required to maintain sufficient moisture to allow cement hydration and concrete microstructure development (Wang *et al.* 2006). Also, curing has been shown to impact concrete durability as well as concrete strength (ACI 2000). Many techniques exist to control moisture loss in traditional concrete, although most are not appropriate for pervious concrete. Because of the high porosity of pervious concrete, rapid loss of moisture from the fresh concrete due to evaporation can occur. Since the water-to-cement ratio (w/c) of the concrete is generally low, loss of moisture can result in rapid desiccation, low strength, and excessive surface raveling. Thus, curing is especially important for pervious concrete, because unlike traditional concrete, the bottom of the slab is exposed to air as well as the surface. On the other hand, protecting the surface with even a small measure, may provide enough protection to allow proper curing throughout. For PCPC, water misting or fogging washes the cement paste from the coated aggregate particles. Due to potential surface damage of the fresh concrete, wet burlap can not be applied until final set has been reached which results in excess surface desiccation. Liquid membrane-forming compounds prevent surface moisture loss but do nothing to prevent evaporation from within pervious concrete. Curing compounds are designed to prevent moisture loss from the surface of freshly placed concrete which presents an obstacle for proper pervious concrete curing.

The current method of curing PCPC involves covering the fresh concrete with plastic sheets and allowing the pavement to cure for 7-days before removal of the plastic. In most cases the plastic sheets must be rolled onto a pipe for rapid application after placement and aggregate or sand bags must be used to seal the edges and prevent wind from ballooning under the plastic and drying the surface. Covering with plastic is the preferred method to cure pervious concrete but can be problematic and has not been compared with other standard methods. This study evaluated the effect of nine different curing methods or curing materials on pervious concrete properties, including flexural strength and surface abrasion resistance.

Testing Procedures

Flexural strength was determined using modulus of rupture of the beams tested at 28-days according to ASTM C78 (2002). Once the samples were tested for modulus of rupture the fractured pieces were tested for surface abrasion. Surface abrasion was determined according to ASTM C944 (1999), in which a constant load of 98 N (22 lbs) is applied through rotary cutter dressing wheels in contact with the sample surface for two minutes. The diameter of the circular abraded area is 80 mm (3.25 in.). The beams were first cleaned with a stiff-bristled brush and vacuumed on all sides to remove any loose materials. After each abrasion test, the beams were again brushed clean and vacuumed to remove loose debris. The mass loss between trials was recorded and a total of six abrasion tests were performed on each set of beams. Figure 42 shows the abrasion device with the shaft-mounted container for load calibration and abrasion head cutting device. The physical result of an abrasion test is shown in Figure 43 for a beam cured with the standard white-pigment curing compound. The left portion of the sample had not undergone testing while the tested portion is the exposed aggregate circular section on the right. The Abrasion Index (AI) was taken as the ratio of the average abraded mass loss for a particular sample divided by the average for the control mixture with no curing method.

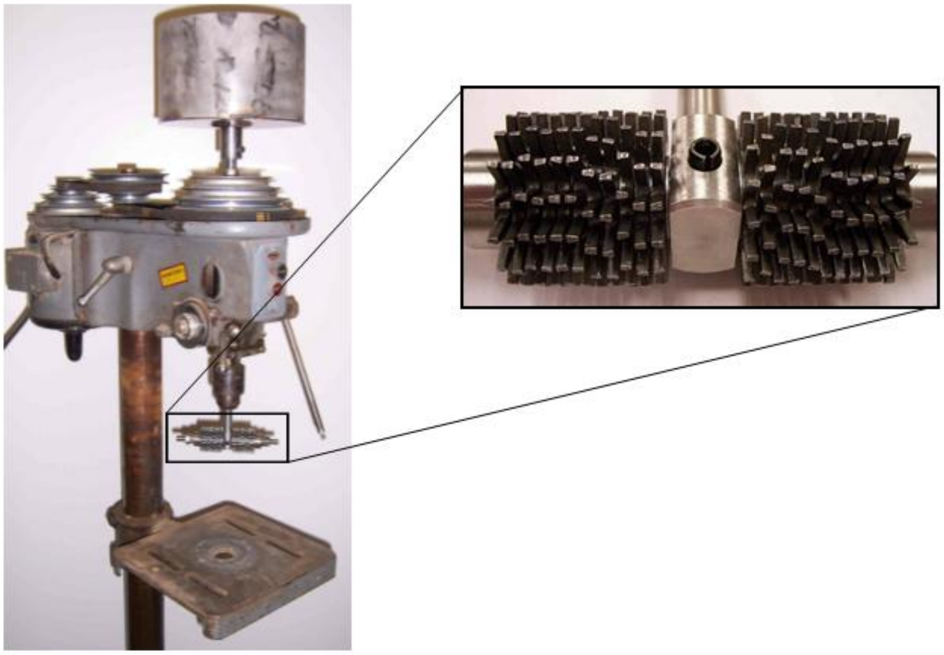

Figure 42. **Abrasion apparatus and cutting head**

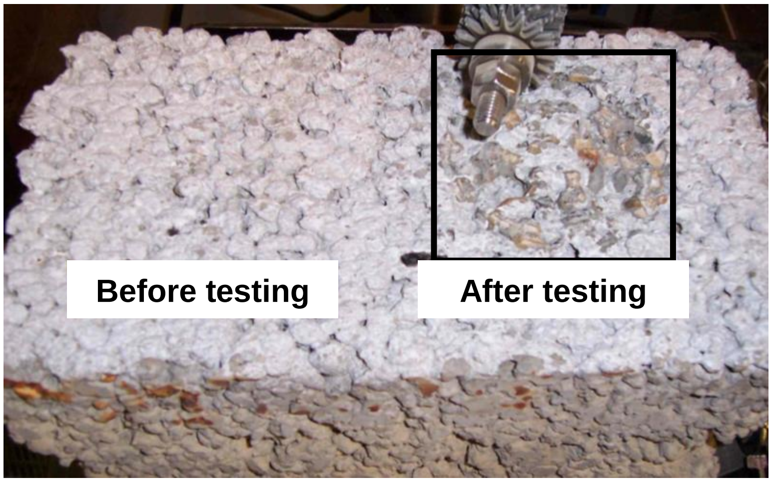

Figure 43. Surface before and after abrasion

After abrasion, three 75 mm (3 in.) core samples were extracted from each beam. The ends were then trimmed using a concrete slab saw to correct uneven surfaces and provide a uniform volume for porosity calculation. The porosity of the pervious concrete was determined by taking the difference in weight between a sample oven dry and submerged under water using Equation 1 (Park and Tia 2004) and the proposed procedure developed by Montes *et al.* (2005).

$$P = [1 - (\frac{W_2 - W_1}{\rho_w \mathrm{Vol}})]100(\%) \qquad \textbf{(1)}$$

Where:

P = sample porosity, %.
W_1 = weight under water, kg.
W_2 = oven dry weight, kg.
Vol = volume of sample, cm^3.
ρ_w = density of water @ 21ºC, kg/cm^3

After determining porosity, the concrete permeability was determined using a falling head permeability test apparatus (Kevern 2006). A flexible sealing gum was used around the top perimeter of a sample to prevent water leakage along the sides of a sample. The samples were then confined in a latex membrane and sealed in a rubber sleeve which was confined by adjustable hose clamps. The average coefficient of permeability (k) was determined following Darcy’s law and assuming laminar flow (Kevern 2006).

Calibration of Abrasion Apparatus

The strength and performance of pervious concrete is directly impacted by the *in-situ* density which is a factor of the mixture workability and compaction effort applied to the fresh concrete. It is well-understood that pervious concrete with high porosity and low unit weight has lower compressive strength and durability (surface particle raveling and freeze-thaw resistance) than denser concrete with the same mixture proportions. Some degree of compaction variability occurs during field placement and the American Concrete Institute (ACI) recommends the concrete placement be within ± 80 kg/m^3 (5 pcf) of the design unit weight (ACI 2006).

Before determining the effect of curing method on surface abrasion, samples with the same mixture proportions were placed at three different densities to determine variability of surface abrasion within the allowable density variation. Based on previous research (Kevern *et al.* 2005, Schaefer *et al.* 2006, Kevern 2006), a control mixture design was selected which contained river gravel aggregate, small portion of additional sand, and 15% fly ash replacement for cement. The freeze-thaw durability of the concrete has been previously investigated and similar mixtures were installed for the Iowa water quality study pervious parking lot (Jones 2006).

The mixture proportions for the initial study are shown in Table 22. The river (pea) gravel coarse aggregate had 97% passing the 9.5 mm (3/8 in.) sieve and 81% retained on the 12.7 mm (No. 4) sieve (#4PG). Additionally, 5% fine aggregate by weight of coarse aggregate (S5) was included. The fine aggregate was river sand with a fineness modulus of 2.9. The cement was Type II, marketed as a Type I-II, and the amount of cementitious material was fixed at 21% by the weight of aggregate (B21). Class C fly ash replaced 15% of the Type II cement by weight (FA15). Therefore the control mixture was designated as #4PG-B21-FA15-S5.

Table 22. Calibration mixture proportions

Design Unit Weight, kg/m^3 (pcf)	Design Void Content (DVC), %	CA kg/m^3 (pcf)	FA kg/m^3 (pcf)	PC kg/m^3 (pcf)	Fly Ash kg/m^3 (pcf)	w/c
1,940 (121)	22.5	1,340 (85)	70 (4)	270 (17)	40 (2)	0.27
1,870 (117)	25.0	1,400 (88)	70 (4)	280 (17)	40 (3)	0.27
1,810 (113)	27.5	1,450 (91)	70 (5)	280 (18)	40 (3)	0.27

The control mixture was placed at three density levels and cured under ideal laboratory conditions for 28-days (ASTM C192) and allowed to air dry 24 hours before abrasion testing. The results for the calibration specimens are shown in Figure 44 where the error bars represent the standard deviation for three replicate samples. While there was a slight decrease in average material abraded with increased density, 2.88g for the 1,810 kg/m^3 (113 pcf) sample to 2.58g for the 1,940 kg/m^3 (121 pcf) sample, comparing the standard deviation between samples, there was no significant difference in abrasion within the range of allowable density.

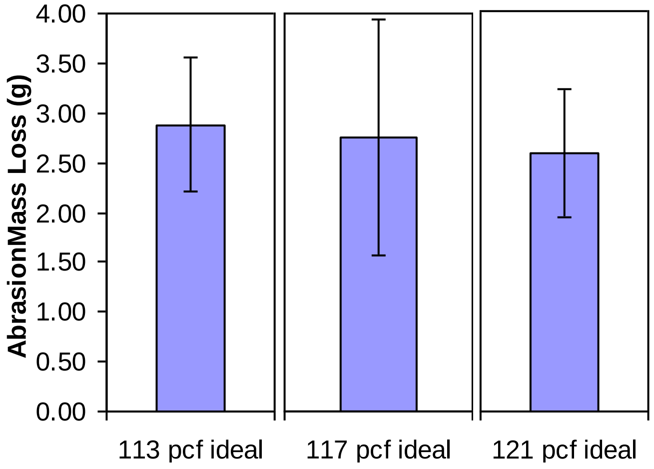

Figure 44. Abrasion results for calibration specimens

Field Trial Mixture Proportions

The mixture proportions for the field trials were based on the previously described control mixture and shown in Table 23. Additional modified concrete mixtures included an integral crystalline water proofing agent added per manufacturer's specification at 2% by weight of cementitious materials (X2) and the polypropylene fibers were added at 0.9 kg/m^3

(1.5 pcy) or 0.1% by volume (F1.5). One mixture also included 100% Portland cement as the binder.

Table 23. Mixture Proportions

Mixture #	Mixture ID	CA kg/m^3 (pcf)	FA kg/m^3 (pcf)	PC kg/m^3 (pcf)	Fly Ash kg/m^3 (pcf)	Xypex C-1000 kg/m^3 (pcf)	w/c
1	#4PG-B21-FA15-S5 (Control)	1,530 (91)	80 (5)	300 (19)	40 (3)	-	0.27
2	#4PG-B21-S5	1,530 (91)	80 (5)	340 (21)	-	-	0.27
3	#4PG-B21-FA15-X2-S5	1,530 (91)	80 (5)	300 (19)	40 (3)	190 (0.5)	0.27
4	#4PG-B21-FA15-S5-F1.5	1,530 (91)	80 (5)	300 (19)	40 (3)	-	0.27

Along with no curing method, five curing regimes were tested on the control mixture (Table 24). The external curing regimes included cured with plastic sheets for 7-days and 28-days. Curing compounds were sprayed on the concrete at the manufacture's recommended dosage rates and included, a standard white-pigment curing compound applied at 4.9 m^2/l (200 ft^2/gal), a soybean oil emulsion curing compound applied at 4.9 m^2/l (200 ft^2/gal), and a non-film forming evaporation retardant applied at 16.3 m^2/l (800 ft^2/gal).

In addition to the control mixture, one mixture containing 100% Portland cement was cured with plastic sheets for 7-days, one mixture containing fibrillated polypropylene fibers was cured with plastic sheets for 7-days, and one mixture containing the internal crystalline water proofing agent and surface cured with the non-film forming evaporation retardant. The internal crystalline water proofing agent is a dry powder integrally mixed with the cement to reduce the permeability of the cement paste (Xypex 2000). It was thought the mechanism in reduction of permeability would help seal in moisture and provide a more complete cure. The non-film forming evaporation retardant is designed to pair with the crystalline water proofing agent.

Table 24. Curing Regimes

Sample ID	Mixture #[1]	Curing Method
A	1	None
B	1	Plastic 7-days
C	2	
D	4	
E	1	Plastic 28-days
F	1	Soybean Oil
G	1	White Pigment
H	1	Non-film evap. retardant
I	3	

[1] **See Table 23**

Sample Preparation and Curing

The concrete was mixed according to ASTM C192 (2003) and the 150 mm x 150 mm x 525 mm (6 in. x 6 in. x 21 in.) beams were placed in order to simulate typical field placement and finishing operations. Two sample beam molds at a time were filled with fresh concrete using a shovel and rough finished to approximately 25 mm (1 in.) above the mold. An electrically-driven roller-screed was then used for final compaction and finishing as shown in Figure 45. The roller-screed rotates in opposite the direction to forward movement, which provides compaction and orients the coarse aggregate particles along the surface. Immediately after finishing, the samples were moved outside and the appropriate curing method applied. Figure 46 shows the samples before applying curing compound. Initially, the white-pigment and soybean oil emulsion look similar, but as the water evaporates from the soybean oil the oil penetrates into the concrete producing a slightly darker color than the control.

Figure 45. **Finishing using a roller screed**

Figure 46. **Fresh concrete with no curing compound**

The beams were demolded after 24 hours and transferred to a site designed to simulate field curing conditions. An area approximately 100 cm (42 in.) by 150 cm (60 in.) by 36 cm (14 in.) was excavated and filled with 20 cm (8 in.) of a drainable aggregate base (Figure 47). Beams were placed on the base and the edges filled with aggregate, as shown in Figure 48. After 28-days, the beams were removed and tested for tensile strength and abrasion.

Figure 47. **Aggregate base at test location**

Figure 48. **Initial beam curing**

All beams were cast and cured on July 12, 2006, when the high temperature was 26°C (79°F) and average wind speed was 7 kph (4.4 mph). The placing date was scheduled to represent extreme summer placing and curing conditions. During the first 7-days, which are critical to concrete curing, the average maximum air temperature was 32.3 °C (90.1 °F). The initial moisture deficit, potential evapotranspiration (ET) minus the actual precipitation, was 4.57 cm (1.80 in.) and increased to 11.2 cm (4.41 in.) over the entire 28-day curing period. Even though the relative humidity was high (~75%), drying conditions were caused by a substantial imbalance between evaporation and precipitation. Table 25 provides the average climatic data for both the first 7-days and the entire curing period.

Table 25. Climatic data for curing duration (ISU 2006)

	First 7-days	Entire 28-days
Avg. Max Air Temp, °C (°F)	32.3 (90.1)	30.2 (86.4)
Avg. Min. Air Temp, °C (°F)	18.8 (65.9)	19.1 (66.3)
Avg. 4" soil temp, °C (°F)	28.8 (83.9)	28.0 (82.4)
Avg. Max Wind speed, kph (mph)	24.6 (15.3)	23.7 (14.7)
Avg. Wind Speed, kph (mph)	9.0 (5.6)	8.7 (5.4)
Precipitation, cm (in.)	0.13 (0.05)	5.21 (2.05)
Potential ET, cm (in.)	4.70 (1.85)	16.41 (6.46)
Relative Humidity (%)	75.4	76.7

Results and Discussion

The soybean oil emulsion, when first applied, was milky white in color and as the water evaporated, the oil penetrated the concrete surface. After one day, the only indication of application was a slightly darker concrete color. The non-film forming evaporation retardant was diluted with water according to the manufacture’s specifications and surface applied. The consistency was similar to water and a majority of the curing compound permeated the sample whereas, the white pigment and soybean oil coated more of the surface particles.

The control mixture design (Mixture #1) was placed in 18 beams, finished two at a time, and then surface treatments were randomly applied, the modified mixture designs (Mixtures #2, #3, and #4) were also placed at that time. Results of the concrete flexural strength along with porosity and unit weight are shown in Table 26. The unit weight and porosity were determined from core samples extracted from the beams after MOR testing and represent an average of three test specimens per beam and the tensile strength from two beams. The core samples had a diameter of 75 mm (3 in.) and an approximate length of 150 mm (6 in.). The porosity values ranged from 17.5% to 23.1% for the control mixture (samples A, B, E, F, G, and H) and increased to 27.3% for the mixture containing fibers (D). Tensile strength followed a similar trend to the porosity, ranging from 1.10 MPa (162 psi) to

2.40 kPa (345 psi). The range of unit weight values for Mixture #1 were within the bounded variability evaluated during the calibration phase. Therefore, any differences in abrasion can be attributed to curing effects and not variability in unit weight.

Table 26. **Beam test results**

Sample ID	Mixture ID #[1]	Curing Method	Beam Porosity (%)	Beam Unit Weight kg/m^3 (pcf)	Flexural Strength MPa (psi)
A	1	None	23.1	1,820 (114)	1.80 (264)
B	1	Plastic 7-days	17.5	1,910 (120)	2.35 (344)
C	2		22.9	1,780 (111)	1.95 (286)
D	4		27.3	1,830 (114)	2.20 (319)
E	1	Plastic 28-days	17.8	1,930 (121)	2.40 (345)
F	1	Soybean Oil	21.3	1,865 (117)	1.95 (286)
G	1	White Pigment	16.7	1,890 (116)	1.70 (244)
H	1	Non-film evap. retardant	19.7	1,820 (113)	1.90 (273)
I	3		21.5	1,7501 (109)	1.10 (162)

[1] **See Table 23**

The flexural strength for the control mixture with no curing method was 1.80 MPa (264 psi). The mixtures covered in plastic had the highest strength, with the greatest increase over the control for the beams cured under plastic for 28 days. The maximum tensile strength was 2.40 MPa (345 psi) produced by the specimens cured under plastic for 28-days. However, there was only a slight increase in tensile strength between the samples cured under plastic for 7-days (2.35 kPa, 344 psi) and 28-days (2.40 kPa, 345 psi). Of the surface-applied curing methods, the soybean oil emulsion produced the greatest increase in strength over the control at 1.95 MPa (286 psi).

The concrete abrasion results for the control mixture cured under different conditions (samples A, B, E, F, G, and H) are shown in Figure 49, where an abrasion index of 100% represents the control mixture design allowed to cure in the field without any internal or surface-applied curing methods (sample A). A majority of mass loss was paste removed from the aggregate surface followed by abrasion of the aggregate with occasional removal of individual whole aggregate pieces. The average abrasion for the control mixture (A) was 7.37g (0.02 lb) per test. The mixtures cured under plastic had the best abrasion resistance between 55% (E) and 64% (B) of the control. Of the surface applied treatments, the soybean oil emulsion (F) had the best abrasion index at 82%, followed by the standard white pigment (G) at 86%, and non-film forming evaporation retardant (H) at 91%.

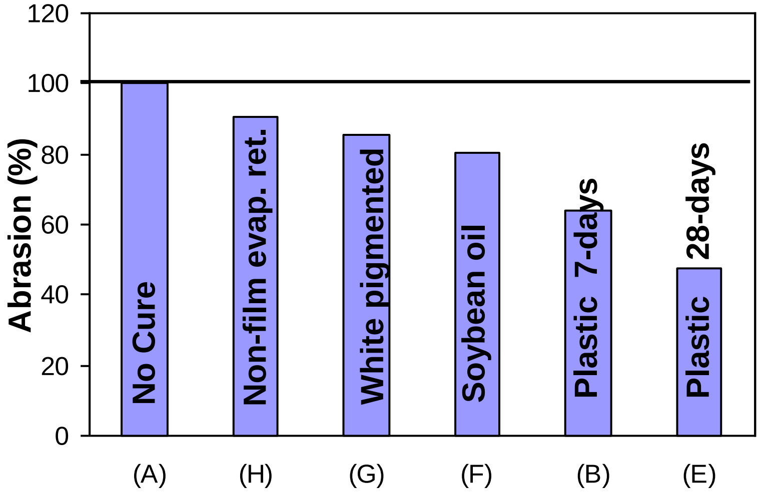

Figure 49. **Effect of curing regime on control concrete mixture properties**

Of the modified mixtures cured under plastic for 7-days, the only mixture that produced a significant decrease in strength was the internal crystalline water proofing agent with the non-film forming evaporation retardant (I), which reduced flexural strength by 40% from the control. The mixture containing fibers and cured under plastic for 7-days (D) produced an increase in flexural strength of 21% over the control, even though the unit weight was lower corresponding in a higher porosity.

The concrete abrasion testing results for the uncured control (A) along with the modified mixture designs (samples C, D, and I) are shown in Figure 50. When cured under plastic for 7-days, the mixture containing 100% Portland cement (C) had slightly better abrasion resistance than the mixture containing 15% fly ash (B) although, the durability increased for the fly ash mixture when cured under plastic for 28-days (E), as compared to samples (C) and (B). The mixture containing fibers (D) had similar abrasion to the control mixture (A), although the porosity was 7.9% higher than the average for the control mixtures. The lowest performing mixture contained the internal crystalline water proofing agent with the surface-applied non-film forming evaporation retardant (I) and had the highest AI at 219.

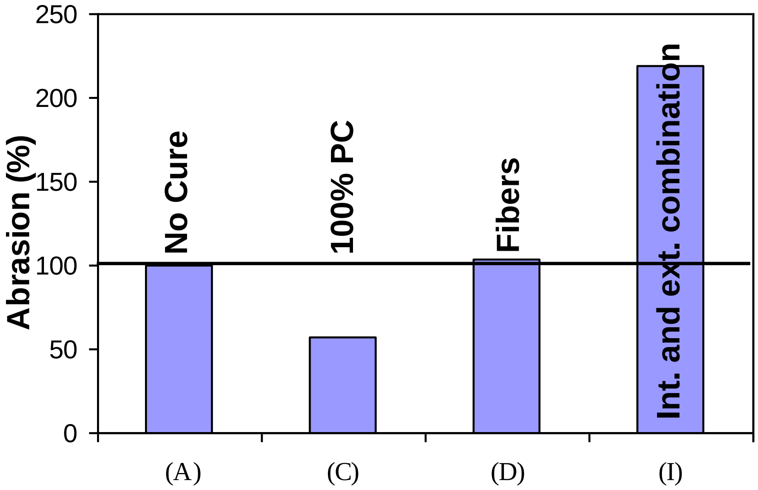

Figure 50. Modified mixture response to curing regime

Conclusions and Recommendations

From this study, the following conclusions and recommendations can be made.

- The samples cured under plastic had the best abrasion resistance and highest tensile strength. There was not a significant difference in tensile strength between samples cured under plastic for 7 or 28 days, although abrasion resistance did increase with covered curing time.
- Soybean oil has the potential to be used as an effective curing compound. In this study, the soybean oil emulsion produced the best surface durability and increase in tensile strength of the surface-applied curing agents.
- The addition of fibers has the potential to reduce surface abrasion and increase tensile strength while potentially increasing porosity and permeability. The “birds nest effect” caused by the fibers increased the porosity by 7.9% and yet produced a tensile increase of 21% over the control without significantly impacting surface abrasion.
- The rotary-cutter surface abrasion ASTM C944 method has the ability to differentiate between curing methods, allowing relative surface durability comparisons. Additional research is suggested to compare the abrasion of different aggregate types and to correlate with field conditions and behavior.

Future Research

Research on use of soybean oil as a curing compound for concrete is limited. The ability of the soybean oil to penetrate the concrete surface and reduce abrasion suggests that soybean oil may be an effective measure for protecting traditional concrete against deicers.

Since the fibers caused a substantial increase in porosity while increasing flexural strength and not impacting abrasion resistance, this suggests that mixtures containing fibers when compared to those without, at the same porosity, may have increased abrasion resistance. More research is required to more completely determine the effects of fibers on surface durability.

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CHAPTER 7. GENERAL CONCLUSIONS

Recent stormwater mandates implemented by the U.S. EPA have created interest for pervious concrete in freeze-thaw climates. While the material components are similar to conventional concrete, the idiosyncratic behavior required revaluating material effects and relationships. Many different factors influence the performance of conventional concrete and these factors also affect pervious concrete although limited data exists to support observed and expected responses.

The most crucial factors include the specific effect on freeze-thaw durability caused by the coarse aggregate type. Since the volume of paste in a pervious concrete system is much less than traditional concrete and exposure conditions much more severe, aggregate durability criteria must be determined for this specific application. The more extreme exposure conditions also require investigating the effect of air entrainment on the concrete mortar. Air entrainment improves freeze-thaw durability in conventional concrete but to date has yet to be evaluated in pervious concrete. In addition to mixture properties, construction practices must be modified to suit pervious concrete. While the workability of conventional concrete can be simply checked using a standard slump cone, no method currently exists to determine the workability of pervious concrete. However, workability of pervious concrete influences the ease of placement and density, which also controls the yield and ultimate durability. Determining pervious concrete workability will allow more consistency between placements and help quantify the effect various mixture components have on the fresh mixture behavior. Due to it’s very low water-to-cement ratio (~0.30) curing of pervious concrete is particularly important. Pervious concrete is currently cured under plastic instead of using a conventional curing compound. No research has previously been performed to evaluate the effect various common curing methods have on strength and durability. By studying the important issues, consistency and durability can be improved and baseline values established for future research.

This dissertation included a selection of papers encompassing a variety of important aspects in pervious concrete research, all to improve pervious concrete durability. The papers include 1) The effect of aggregate type on the freeze-thaw durability of pervious concrete, 2)

A novel approach to characterize entrained air content in pervious concrete, 3) Effect of curing regime on pervious concrete abrasion resistance, and 4) Evaluation of pervious concrete workability using gyratory compaction.

Summary of The Effect of Aggregate Type on the Freeze-Thaw Durability of Pervious Concrete

Preliminary results indicated that certain types of aggregate approved for use in traditional concrete experienced premature freeze-thaw deterioration when used in pervious concrete. Pervious concrete specimens were placed using coarse aggregate samples obtained from across the U.S. and Canada. A full complement of tests were performed on the aggregate and the concrete including freeze-thaw durability using the ASTM C666A, fully saturated procedure.

Results showed that generally a narrow range of gradations were used for pervious concrete aggregate in the U.S. Combination of the as-received gradations along with known beneficial amounts of additional fine aggregate allowed the creation of aggregate gradation criteria for pervious concrete. Of the aggregate specific properties, the natural aggregate density or Unrodded Unit Weight (URUW) controlled the resulting concrete density. Aggregate absorption was the most significant influence on concrete freeze-thaw durability. The average aggregate absorption for mixtures with acceptable durability was 0.82%. Concrete with acceptable freeze-thaw durability had durability factors greater than 37% using the 60% relative dynamic modulus, which had similar response to durability factors greater than 97% as determined using mass loss criteria. Now that general aggregate requirements have been established, a mixture proportioning criteria can be developed.

Summary of A Novel Approach to Characterize Entrained Air Content in Pervious Concrete

Entrained air content is a standard property tested on conventional concrete. The entrained air provides workability, cost savings, and most importantly improved freeze-thaw durability. Freeze-thaw durability of pervious concrete is a concern but the open structure of the cement paste-coated aggregate particles does not allow entrained air determination using the typical methods. Samples were placed using several dosage rates and types of air entraining admixtures on mixtures produced with two aggregate types. Characterization of the entrained air system was performed using a RapidAir 457 device which automates the ASTM C457 petrographic analysis. Freeze-thaw durability testing was performed on the samples using the ASTM C666A, fully saturated procedure.

Air entrainment increased the paste volume and improved workability, reducing the porosity and increasing density. The effect on workability of the air entrainment was more pronounced for a rounded river gravel aggregate than an angular limestone. Concrete with greater air entrainment and higher density had better freeze-thaw durability. A double dosage of the natural air entraining agent produced similar effects as the recommended dosage of the synthetic air entrainer. The RapidAir device was able to measure and quantify the amount of entrained air content in pervious concrete and distinguished between entrained air and larger water-permeable voids. The results suggest that air entraining agent be included in all pervious concrete mixtures for enhanced freeze-thaw durability and workability improvement.

Summary of Evaluation of Pervious Concrete Workability using Gyratory Compaction

The ultimate goal of a pervious concrete placement is a pavement with a smooth surface with enough porosity to infiltrate the required stormwater intensity, and enough strength for long-term durability. These requirements are all directly related to the concrete unit weight which is controlled by workability and compactive effort. Workability determination for conventional concrete is identified using a standard slump cone test, which does not yield useful data for the very stiff pervious concrete mixtures. Also, the design unit weight can be achieved either by a workable mixture or applying additional compaction energy to a very stiff mixture requiring two components to measure the fresh concrete workability behavior. Since pervious concrete is most often compacted using some type of roller and gyratory compaction simulates the kneading compaction from a roller, an asphalt gyratory compaction device was utilized for pervious concrete workability. However, typical asphalt compaction pressure does not represent the amount of energy applied by pervious concrete operations so the device was modified for a much lower pressure. Evaluation of the density output data produced the Workability Energy Index (WEI) which is the mixture consolidation behavior under it’s self-weight and the Compaction Densification Index (CDI) which represents the amount of additional energy required to achieve the Design Void Content (DVC). Samples were produced using the modified gyratory compactor and the effect on the workability parameters evaluated for binder content, water-to-cement ratio, and mixing time. Ranges of values were provided to define the mixture behavior.

The modified gyratory compactor produced specimens to the DVC for splitting cylinder tensile testing. Observation of the compaction output curve allowed defining both workability and compactibility criteria. Binder content had the greatest effect on the workability indices while water-to-cement ratio did not have as significant an effect in the range of commonly used water contents. Workability decreases with increased mixing time while the required compaction energy increases. Quantification of pervious concrete workability will allow determination of admixture effectiveness and allow tailoring mixture behavior for particular aggregate types and placement situations.

Summary of Evaluation of Curing Regime on Pervious Concrete Abrasion Resistance

Moisture loss in conventional concrete occurs at the surface and exposed edges, consequently chemical curing compounds applied to the surface prevent moisture loss and drying. Due to the nature of pervious concrete structure all portions of the slab are exposed to air, that coupled with the very low water-to-cement ratio means proper curing is even more crucial to long-term durability then typical concrete. Typically pervious concrete is cured under plastic for 7-days time, after which the site is opened to traffic. Until now, no study had been performed to evaluate which curing method was the most appropriate and provide test results. For this study, concrete beams were placed and randomly assigned a curing treatment. Flexural strengths and surface abrasion using the ASTM C944 rotary cutter method were used. Along with the control mixture, beams were also placed with other common mixture design components. The curing methods employed included no curing, cured under plastic for 7 and 28 days, white pigment, soybean oil, and a propriety compound. The specimens were then cured outside during July to represent the highest moisture loss possible.

Results showed that samples cured under plastic had the highest flexural strength and abrasion resistance. Of the surface-applied curing compounds, the soybean oil emulsion had the best performance. For the different mixtures cured under plastic for 7-days, the straight

Portland cement mixture had lower abrasion than samples containing 15% replacement of fly ash for cement. Although the mixture containing polypropylene fibers had higher porosity than the control, abrasion resistance was similar. Abrasion mass loss was not a function of concrete density when tested for mixtures placed within the allowed variability. The ASTM C944 surface abrasion method was able to distinguish differences between the various curing regimes.

Recommendations for Future Research

While the field of pervious concrete is expanding rapidly, there is not a consensus of properties or testing methods. The ASTM and ACI committees are just beginning to address the needs for laboratory and field placement, testing methods, and quality control procedures. The most important area for future research is the development and verification of methods; to place samples in the laboratory and the field, to determine fresh concrete workability, to verify consistency, and to verify in-place engineering properties. Once standard test methods are in place then comparisons can accurately be made between placement methods and mixture designs. The workability test presented in this dissertation now allows characterization of previously unknown properties. Mixtures can now be designed and tested to meet specific workability criteria using known material inputs. Now that workability can be measured other quality control test methods can be developed.

While there are standard methods to proportion conventional concrete, there are none for pervious concrete. To evolve the technology, a method of standard mixture proportioning must be determined that allows the common user to create successful mixture designs optimized for local materials and conditions. A greater number of producers with the ability to create site-specific mixture designs will improve competition and overall quality.

Mixture proportions designed in the laboratory may be strong and durable under ideal conditions. In the field rarely does the fresh behavior of a mixture resemble that from the laboratory. Consequently, the ultimate performance of a pavement is controlled by the placement techniques of the contractors and actions taken by the owner/agency and very little by the design engineer. Education of the contractors will lead to greater care taken during the crucial placement period and accurately describing expectations and required maintenance to owners will help prevent unnecessary failures. An operations and maintenance manual should be assembled for pervious concrete pavements to help determine required maintenance both for cleaning the surface and winter operations.

Construction of pervious concrete is currently very labor intensive with a small degree of mechanization. Creating mixtures that are placeable using current construction technology or developing construction equipment for pervious concrete will reduce construction costs and improve consistency. Once construction of pervious concrete becomes a standardized and more common process, quality and durability will increase. As pervious concrete becomes a common standardized material it will further become a staple of stormwater management techniques.

The failure of high strength pervious concrete occurs at the paste to aggregate bond interface. Increasing the bonding characteristics at the interfacial transition zone (ITZ) will improve strength and durability. Nanotechnology can modify very small-scale material properties to improve large-scale behavior. It has the potential to significantly increase the tensile strength of the cement paste which is the weakest fraction in all concrete, but especially in pervious concrete. Nano-modified cementitious materials show the greatest potential of improving ITZ characteristics in conventional concrete and may prove even more beneficial for use in pervious concrete. By controlling the nanoscale behavior, macrolevel properties can be improved.

While the focus of pervious concrete durability has primarily been freeze-thaw related and as pavements age, the potential for other durability related distresses must be investigated. A specific distress of concern is alkali-silica reaction (ASR), in which certain aggregate types react with excess calcium hydroxide in the pavement to form a gel that can imbibe moisture and swell. ASR can be minimized or prevented by eliminating moisture or reducing the paste permeability. Since pervious concrete is designed to infiltrate water and the thin paste layer becomes critically saturated quickly, ASR may occur more severely in pervious concrete than even in conventional pavement. Varying levels of ASR reactivity and mitigation techniques should be investigated to determine if reactivity criteria should be established for aggregate used in pervious concrete.

As infrastructure ages, maintenance must be performed to sustain serviceability. While a large number of pervious installations exist, no repair methods for restoring serviceability of these pavements exist. If a pervious pavement fails it is often completely removed and replaced, unfortunately the last resort for traditional pavements. Other methods of serviceability need to be explored including milling to remove poorly bonded particles, thin bonded overlays to stabilize raveling surfaces, combination of milling and resurfacing, and solutions to manage localized distresses. If repair methods are developed, then localized distresses can be remedied more cost effectively than full replacement.

Many preliminary questions have been answered. Only by continuing research and by identifying the most important areas for future research will the benefits be fully realized. Pervious concrete technology is becoming an essential tool for environmental sustainability and will be even more so in the future.

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