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Advancements in Thirsty Concrete

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Abstract- Pervious concrete has been used for many years in the southern United States but only recently have storm water 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.

Keywords- Infiltration, pervious beds, aquifers, coarse aggregate, workability.

I. 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.

1. 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:

1.1 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.

1.2 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.

3. 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.

II. 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 was 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 projects 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).

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 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.

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