Pervious Concrete Research Literature Review

August 2017

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Edited and Updated by the RMC Research & Education Foundation

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Research Categories

Note: The original document contained links to reports or abstracts. As links change frequently, we have converted this document to be a literature review and readers may do a search for the report or study of interest, some of which are only available through purchase. This document is intended to make the reader aware of resources available.

Applications and Case Studies

Pervious Concrete
Percoa, USA
Pervious concrete pavement is one of the leading materials used by the concrete industry in effecting significant "Green" industry practices and is recognized as a Best Management Practice by the U.S. Environmental Protection Agency (EPA) for providing pollution control, storm water management and sustainable development. The increased interest in pervious concrete is due to those benefits in storm water management and sustainable development. This paper will provide technical information on the application, mixture design and construction methods of pervious concrete. It will also discuss many of the environmental and economic benefits of using pervious concrete.

Application of recycled aggregate porous concrete pile (RAPP) to improve soft ground
Kim, S., Lee, D., Lee, J., You, S. K., and Choi, H.
In this study, a series of laboratory chamber tests was carried out to evaluate the applicability of a porous concrete pile fabricated with recycled aggregates for soft ground improvement. The recycled aggregate porous concrete pile (RAPP) has been developed to replace natural aggregates and to overcome technical problems associated with the conventional compaction piling systems. The laboratory chamber tests for evaluating the performance of RAPP were carried out with a cylindrical mold of 280 mm in internal diameter and 580 mm in height. A replacement area ratio of 5% and three different loading steps were applied in the chamber tests. The experimental results of the surface settlement, excess pore pressure and vertical

stress distribution versus time were compared with those of the sand compaction pile (SCP) reinforced composite ground under the same experimental condition. In addition, the experimental results were compared with the numerical simulation using ABAQUS. The current study shows that the settlement reduction in the RAPP-reinforced system is significantly enhanced due to load transfer from the soil formation to the RAPP. Furthermore, the comparison of consolidation rates shows that the RAPP can also accelerate the consolidation of soft clay formation because the RAPP behaves as a vertical drain.

Pervious Concrete
Federal Highway Administration
This TechBrief presents an overview of pervious concrete and its use in pavement applications. General information on the composition of pervious concrete is provided, along with a summary of its benefits, limitations, and typical properties and characteristics. Important considerations in mix proportioning, hydrological design, structural design, construction, and maintenance are also described.

MnROAD Cell 64 Pervious Concrete: First Year Performance Report
Eller, A. J. and Izevbekhai, B. I.
This report evaluates the first year performance of the Pervious Concrete test cell #64 located in the parking lot on the south side of the MnROAD pole barn. Performance measures utilized for this report include examination of stress-strain response through loading from the 80 kip MnROAD truck and Falling Weight Deflectometer (FWD). The FWD deflection basins were compared to those obtained for normal concrete of similar thickness design. The second performance measure was the vibrating wire strain gauge sensor response. Elastic modulus values were computed from the sensor data. In addition, petrographic analyses of cores taken from the test pad and pavements were performed to determine the macroscopic and microscopic characteristics of pervious concrete pavement after the first year. Furthermore, a surface rating of the pavement was performed to corroborate petrographic and freezethaw data in order to ascertain the cause of any structural anomalies within the pervious concrete structure. Overall, the pervious concrete cell #64 is performing well after its first year. Normal sanding and salting operations do not appear to have impacted the pore structure within the pervious concrete to date. However, a more quantitative method of measuring flow through the cell and base materials is needed before a final conclusion can be made about the enduring ability of pervious concrete to pass water. Such a quantitative flow measurement method is currently under development.

The structure of the pervious concrete cell #64 remains strong after a year of FWD/MnROAD truck loading and normal usage by vehicular movement over the driveway. Microcracking observed from petrographics does not appear to be worsening. Spalling and raveling conditions appear to have stabilized and are surficial in nature. This report concludes that pervious concrete is performing well in cell 64, and with continuous monitoring there will be greater confidence in more low volume applications.

MnROAD Cell 64 Pervious Concrete: Third Year Performance Report
Rohne, R. J. and Izevbekhai, B. I.
This report evaluates the third year performance of the pervious concrete test Cell 64 located in the parking lot/driveway on the south side of MnROAD's pole barn. In this report, a device and procedure to evaluate the drainability of pervious concrete and a threshold for clogging was developed. In addition, the condition of the test cell was determined by Schmidt hammer

measurements and distress mapping using the Mn/DOT Pavement Distress Identification Manual. Watermark/thermocouple data was also recorded to measure freeze-thaw cycles. The number of freeze-thaw cycles at discrete depths in the pavement was then compared to impervious concrete test cells at MnROAD. The Mn/DOT and Cemstone petrographic reports on cores that had been taken 4.5 months after construction are also included, although they were outlined in previous reports.

It was found that the pervious concrete of Cell 64 experienced less freeze-thaw cycles than impermeable concrete pavements of similar thickness. The main change in surface distress from the first year to the third year of service was the presence of a longitudinal crack that extended the entire cell length and raveling of the top layer of concrete. Initiating at the pole barn at a joint in the concrete curb, the crack could have propagated the length of Cell 64 due to Falling Weight Deflectometer (FWD), traffic, or thermal loading. Knowledge of pervious concrete will be greatly expanded with the study of newly constructed test cells. These cells are Cell 85, Portland Cement Concrete (PCC) pervious on sand and 89, PCC pervious on clay on the MnROAD Low Volume Road.

Use of Pervious Concrete in Construction of Pavement for Improving Their Performance
Patil, V. R., Gupta, A. K., and Desai, D. B.
Our cities are being covered with building and the air-proof concrete road more and more. In addition, the environment of city is far from natural. Because of the lack of water permeability and air permeability of the common concrete pavement, the rainwater is not filtered underground. Without constant supply of water to the soil, plants are difficult to grow normally. In addition, it is difficult for soil to exchange heat and moisture with air; therefore, the temperature and humidity of the Earth's surface in large cities cannot be adjusted. This brings the phenomenon of hot island in city. At the same time, the plash on the road during a rainy day reduces the safety of traffic of vehicle and foot passenger. The research on pervious pavement materials has begun in developed countries such as the US and Japan since 1980s. Pervious concrete pavement has been used for over 30 years in England and the United States.

Pervious concrete is also widely used in Europe and Japan for roadway applications as a surface course to improve skid resistance and reduce traffic noise. However, the strength of the material is relatively low because of its porosity. The compressive strength of the material can only reach about 20 - 30MPa. Such materials cannot be used as pavement due to low strength. The pervious concrete can only be applied to squares, footpaths, parking lots, and paths in parks. Using selected aggregates, fine mineral, admixtures, organic intensifiers and by adjusting the concrete mix proportion, strength and abrasion resistance can improve the pervious concrete greatly.

522R-10: Report on Pervious Concrete
ACI Committee 522
This report provides technical information on pervious concrete’s application, design methods, materials, properties, mixture proportioning, construction methods, testing, and inspection. Pervious concrete is widely recognized as a sustainable building material, as it reduces stormwater runoff, improves stormwater quality, may recharge groundwater supplies, and can reduce the impact of the urban heat island effect.

Green Alley Program

City of Chicago

Chicago's Green Alley program is one of many environmentally friendly initiatives put forth by CDOT. Green Alleys are part of CDOT's "green infrastructure" -- which includes recycled construction materials, permeable pavements and other efforts. The program began as a pilot in 2006, and through 2010, more than 100 Green Alleys have been installed. The link is to a handbook that provides an overview of CDOT's Green Alley program.

Designing Pervious

Nasvik, J.

In 2009, a pervious concrete residential street project for the city of Shoreview, MN, a suburban area north of St. Paul, received national attention because it was the largest public street project in the country. This project also deserves a closer look because of the thoughtful and innovative forensic research conducted by the parties involved before the job even began.

Restoring the Chesapeake Bay Watershed

Buranen, M.

Pervious concrete is used in conjunction with other BMP's to address the sections of the Chesapeake Bay full of silt and runoff appearing muddy even at ground level. Years of unregulated agricultural runoff, the growing amount of impervious surface from suburban sprawl, and the bureaucracy of several states intertwined have been the causes.

Seattle Takes Natural Drainage to a High Point

Buranen, M.

Seattle's Natural Drainage System (NDS) consists of stormwater management projects that use low-impact development (LID) strategies to meet multiple goals within street rights of way (ROWs), which account for 25% of Seattle's total land surface. The projects work by infiltrating stormwater runoff, slowing it temporarily or lessening its volume, filtering, or removing pollutants through the use of soils and native plants, replacing impervious surfaces with pervious, and adding native vegetation.

Shoring up Shoal Creek

Kessel, J. S.

Shoal Creek, in Austin, TX, runs through Pease Park, a popular recreational area near the campus of the University of Texas. Like many urban streams, Shoal Creek exhibits problems related to flooding, erosion, and degraded water quality. Seeking to address these ailments where they occur within the park, the city of Austin is pursuing a comprehensive set of integrated solutions including a pervious parking lot intended to stabilize the stream channel, better manage stormwater, and restore heavily degraded riparian zones.

Green Stormwater

Brzozowski, C.

In Charlotte, NC, the Sanctuary—a development built by Crescent Communities of Raleigh, NC—is racking up awards for its environmentally sensitive features. The community features 187 homes on 1,300 acres bordering Lake Wylie in Charlotte. The Sanctuary's lodge was the first recreational facility in Charlotte and Mecklenburg County, NC, to be LEED certified. It incorporates many green features including a pervious concrete driveway.

A Laboratory for LID
Landers, J.
When Wetland Studies and Solutions Inc. (WSSI) decided to construct its new headquarters in Gainesville, VA, there was no question that the building and site would be developed in a manner that sought to limit untoward environmental effects, especially on an adjoining wetland and stream system. After all, the company—a consulting firm that specializes in water, natural, and cultural resources—is dedicated to fashioning ecologically responsible development. Ultimately, WSSI opted to showcase an array of low-impact development (LID) techniques for managing stormwater and environmentally friendly design and construction practices. The parking lot includes several permeable options including pervious concrete and permeable pavers.

Porous Pavements: The Overview
Ferguson, B.
Eight years of research have recently concluded with the first comprehensive review of porous pavement technology and applications resulting in the book, *Porous Pavement*, authored by Bruce Ferguson. It defines nine families of porous paving material each of which has distinctive costs, maintenance requirements, advantages and disadvantages for different applications, installation methods, sources of standard specifications, and performance levels.

Learning Pervious: Concrete Collaboration on a University Campus
Hein, M. and Schindler, A.
On the campus of Auburn University, architecture and construction students are working side by side with university facilities personnel as they learn by building with pervious concrete. Since the fall of 2003, six pervious concrete slab projects have been successfully built including: a sidewalk, a parking lot, a paved picnic area, and colored pervious arboretum walking trails. Each new project has been filled with learning opportunities as students and workers have experimented with the materials and application techniques of pervious concrete.

Pervious Concrete Pavement Permitting
Offenberg, M.
Pervious concrete is one of the hottest topics in the world of land development today. It is not a new technology, but it’s a technology that is being embraced in a world of sustainable development and expensive land. In technical terms, it is a concrete manufactured without fine aggregate. The purpose of this article is to demonstrate some projects that have been permitted and built around the United States and to share some ideas on how you may utilize pervious concrete in your next project.

2006 MnROAD – Pervious Concrete Sidewalk Project
Worel, B., Frentress, D. P., and Clendenen, J.
In a partnership agreement with Minnesota Department of Transportation (Mn/DOT), the Aggregate Ready Mix Association of Minnesota (ARM) constructed a pervious concrete sidewalk at the MnROAD facility in 2006. This sidewalk was constructed with three different types of pervious concretes, a colored pervious concrete (gray) mix with 3/8” minus granite aggregate (mix #1), a pervious concrete mix with 3/8’ minus gravel aggregate and 5% sand (mix #2) and a pervious concrete mix with Kraemer limestone aggregate, polypropylene fibers and 5% sand (Mix #3).

Case Study of a 10 Year-Old Subdivision with 200 Pervious Pavement Driveways
Amekuedi, G.
This presentation highlights the performance of 200 pervious pavement driveways placed in 1995 in a residential subdivision. Photos and data surrounding specific gravity and voids in the mixtures are presented.

The Use of Pervious Concrete at Wal-Mart
Pool, A. V.
This presentation highlights the use of pervious concrete at a number of Wal-Mart stores, including two environmental "experimental" Wal-Mart stores. Data is presented on mix design, placement methods and hydrological design.

Cement-Treated Permeable Base for Heavy-Traffic Concrete Pavements
American Concrete Pavement
In recent years, several agencies have experimented with or specified drainable pavements on interstate and other major roadways where experience has indicated the potential for pavement faulting and pumping. These drainable systems consist of highly permeable base courses and edge drains that are designed to carry infiltrated surface water away very rapidly.

Pervious Concrete Pavements On Slope
Tennis, P. D., Leming, M. L., and Akers, D. J.
Pervious concrete pavements have been placed successfully on slopes up to 16%. In these cases, trenches have been dug across the slope, lined with 6-mil visqueen, and filled with rock (Pg. 8 and 9). Pipes extending from the trenches carry water traveling down the paved slope out to the adjacent hillside. The high flow rates that can result from water flowing downslope also may wash out subgrade materials, weakening the pavement. Use of soil filter fabric is recommended in these cases.

Building and Nonpavement Applications of No-Fines Concrete
Ghafoori, N. and Dutta, S.
No–fines concrete is defined as a type of concrete from which the fine aggregate component of the matrix is entirely omitted. The aggregate is of a single size and finished product is a cellular concrete of comparatively low strength and specific weight. The cellular nature eliminates capillary attraction and provides greater thermal insulation and water permeability than exists in conventional concrete. The advantages of no–fines concrete for different construction purposes have long been recognized.

No-Fines Pervious Concrete for Paving
Meininger, R.
Results of a laboratory study of no-fines pervious concrete for paving are presented. Conclusions are drawn regarding the percentage of air voids needed for adequate permeability, the optimum water-cement ratio range, and the amounts of compaction and curing required. Recommendations are made regarding appropriate uses for this type of concrete.

Porous Portland Cement Concrete as an Airport Runway Overlay
Korhonen, C. J. and Bayer, J. J.
A company recently introduced a special mixing method for producing stronger porous portland cement concrete than that made using standard mixing techniques. The process,

which includes no admixtures, relies on a patented high-speed mixer to achieve the claimed results.

An Overview of Porous Pavement Research
Field, R., Masters, H., and Singer, M.
This paper discusses the economics, advantages, potential applications and future research needs of porous pavements. Porous pavements are an available stormwater management technique which can be used on parking lots and low volume roadways in order to reduce both stormwater runoff volume and pollution. In addition, ground water recharge is enhanced.

Heavy Metal Retention Within A Porous Pavement Structure
Dierkes, C., Holte, A., and Geiger, W. F.
Porous pavements with reservoir structure for infiltration of runoff from parking spaces and residential streets offer the opportunity to dispose of water without using additional space in urban areas. However, pollutants in urban runoff endanger soils and groundwater when pollutant retention in the structure is not sufficient. This paper reviews porous pavement structures with four different subbase materials tested for urban runoff quality.

Performance Assessment of Portland Cement Pervious Pavement Used as a Shoulder for an Interstate Rest Area Parking Lot
Wanielista, M. and Chopra, M.
A pervious concrete shoulder was constructed along a rest stop on Interstate 4 in central Florida. The shoulder was 90 feet long and 10 feet wide. The depth of pervious concrete was 10 inches. A 12-inch deep reservoir consisting of select pollution control materials was used beneath the pervious concrete. The shoulder was monitored over a one year period for wear and stormwater management.

Cast-in-Place Pervious Concrete Allows Water to Pass Through
Portland Cement Association
Pervious concrete is made from carefully controlled amounts of water and cementitious materials used to create a paste that forms a thick coating around aggregate particles. Unlike conventional concrete, the mixture contains little or no sand, creating a substantial void content between 15% to 25%. PCA covers the basics of constructing pervious concrete.

Development of No-fines Concrete Pavement Applications
Ghafoori, N. and Dutta, S.
No-fines concrete is a type of concrete from which the fine aggregate is totally omitted and single-sized coarse aggregates are held together by a binder consisting of a paste of hydraulic cement and water. The earliest application of no-fines concrete dates back to 1852. This paper covers the historical development of no-fines pavements.

Bellingham, WA, Case Study
City of Bellingham
A residential homebuilder interested in sustainable construction decided to try pervious paving in an alley that provides access to homes. This was the first application of a pervious concrete roadway in a Whatcom County right-of-way.

How Pervious Concrete Works: Article and Diagram
Concrete Network
Pervious concrete is a structural concrete pavement with a large volume (15 to 35 percent) of interconnected voids. Like conventional concrete, it is made from a mixture of cement, coarse aggregates, and water. However, it contains little or no sand, which results in a porous open-cell structure that water passes through readily.

Pioneering Pervious Pavement at Stratford Place Task Force
O'dahl, C. A.
City of Sultan has pioneered pervious pavement in Snohomish County. This groundbreaking project paves the way for pervious pavement as a proven technology to provide an alternative to traditional stormwater management on public streets. Only one other public road in Washington has been paved with pervious pavement. The Stratford Place residential demonstration project included 32,000 sf of previous pavement laid in place of concrete for one road, connecting driveways, and associated sidewalks on the 700 block of Fir Street.

Pervious Concrete: The Smart Stormwater Solution
Morrison, C. L.
You know the stuff: impervious to water, channels runoff. But what happens when - without sacrificing strength or durability - water drains right through it? Consider if roads and driveways, sidewalks and parking lots could let rain wash directly into the ground, where it's naturally filtered on its way to our aquifers. No runoff, no drains, no catch basins, detention vaults or piping systems. No kidding.

UNI Project Uses New Pervious Concrete
Erickson, J.
Two years ago Scott Ernst, manager of Benton's Concrete, took a class that mentioned concrete that lets water flow through it into the ground. Both students and instructors alike shrugged it off, thinking the idea may be there, but they won't see it any time in the foreseeable future. This paper reviews Mr. Ernst's first pervious project.

When it Rains, It's Porous: Concrete-Slab Driveways May Soon Be A Thing of the Past as New Paving Products Address Water Runoff Problem
Richter, J.
When the salesman at a new residential development turned a garden hose on full force, the water disappeared into the driveway. Not one drop ran into the street, the gutter and eventually the ocean. Instead, the pervious concrete at Heritage Lane, 12 new single-family houses on sale in Capitola (Santa Cruz County) earlier this year, absorbed the water and allowed it to percolate into the ground below.

Pervious Concrete for Solid/Liquid Separation and Waste Remediation
Luck, J. D. and Workman, S.
This PCA Funded study showed that few tests have been conducted on pervious concrete to determine the hydrologic characteristics of different concrete mixtures and their capability to separate solids from liquids. Consequently, laboratory tests on the pervious concrete specimens were used to determine the effects of porosity and permeability on solids transport through the concrete matrix. Compost composed of beef cattle manure and bedding was placed on top of the pervious concrete specimens and one liter of water was filtered through the compost and pervious concrete for two separate daily leaching events. The effluent from

both filtration methods were collected and analyzed for BOD, EC, DOC, ammonium, nitrate, nitrite, total nitrogen, soluble phosphorus, and total phosphorus.

Permeable Concrete for Drainable Pavement Bases

Rapp, C. A.

Permeable concrete is gaining acceptance for use as a pavement base course. The material's drainable nature protects the primary pavement from harmful effects of surface and subsurface water. Strength and durability of permeable concrete provide a highly protective cover over the aggregate base and a strong working platform for placing concrete pavement. Ease of construction is a significant cost and scheduling factor. The material can also be used for erosion control on side slopes and in paving ditches.

Field Performance Investigation on Parking Lots

Tu, D.

The purpose of this report will be to provide basic recommendations for design, construction and maintenance of pervious pavement based on data and test results collected from projects located in various geographical areas, which represent different soils, environmental conditions, materials and design parameters. Acceptance test criteria, optimum effective air void content, frequency of maintenance and maintenance techniques, effects of freezing and thawing cycles, degree of improvement in water quality in comparison to impervious runoff and performance with respect to drainability over time (clogging potential) are all being reviewed.

Permeable Pavement Use and Research at Hannibal Parking Lot in Kinston, NC

Hunt, B. and Stevens, S.

Over the past several years, stormwater runoff has been diagnosed as a severe problem in the United States, beginning with the creation of the NPDES Phase I Program in the mid-1990s. However, efforts to address stormwater runoff have been researched and developed since the middle of the twentieth century. In North Carolina, stormwater runoff has been an issue since the 1940's, triggered by massive flooding along the Roanoke River. Review of the benefits of utilizing permeable pavements is presented.

Pervious Concrete - What, Why, & Where

Houck, H.

Pervious concrete is a porous concrete paving material which permits rain and stormwater runoff to percolate through it rather than flood surrounding areas or storm drains. It is usually a mixture of 3/8" to 1/2" average diameter aggregate, hydraulic cement, other cementitious materials, admixtures and water.

CONSTRUCTION TECHNIQUES

History and Evolution of Internal Curing-Case Studies

Roberts, J., Butcher, R., Jones, B., Kalafat, M., and Vaughn, R.

First noticed by T. C. Powers, et al in 1948, [22] as beneficial for hydration by supplying water internally, specifiers and contractors in 2012 have grasped how the process of internal curing is implemented, how hydration behaves, and how improvements in mechanical properties, durability, and cost may be beneficial. To meet the time-dependent hydration needs of the concrete, having sufficient water internally available, when, as, and where needed, is vital for achieving optimum characteristic qualities. There is lower life cycle cost with internal curing

(IC) and frequently lower first cost. In 2012, the number of projects using internal curing is increasing at an escalating rate, because the process is simple and economically implemented. Pavements, bridges, buildings, and pervious parking lots are being started now in this recession, because specifiers and contractors are saving dollars, as they build longer lasting structures while costs and interest rates are low. Developed initially to reduce autogenous shrinkage in low water-cement ratio and high performance concretes, internal curing has been found to reduce drying shrinkage. Other benefits found include reduced permeability, increased compressive and flexural strengths, less warping, stronger interfacial transition zones, greater durability, and lower carbonation.

Advances in Porous Pavement
Hun-Dorris, T.
Pavements are an intrinsic, seldom-thought-about part of life, particularly in urban areas. However, for developers, industrial facilities, and municipalities addressing stormwater and associated water-quality guidelines and regulations, pavement stays very much at the forefront of planning issues. “Pavements are the most ubiquitous structures built by man. They occupy twice the area of buildings. Two-thirds of all the rain that falls on potentially impervious surfaces in urban watersheds is falling on pavement,” says Bruce Ferguson, professor and director of the School of Environmental Design at the University of Georgia in Athens.

Pervious Concrete Pavement
Davy, M.
In recent years, the development community, permitting agencies, engineers, and owners have been seeking out new and innovative ways to reduce stormwater runoff and build low-impact, sustainable communities. One of the “new and innovative” ways that assist in these efforts just might be a product that has actually been around for some time—pervious concrete.

The Changing Tide
Beecham, T.
Controlling water quantity and maintaining water quality are the goals of any good stormwater management plan. Yet sorting through and implementing requirements can sometimes seem overwhelming for contractors. Years ago, construction sites didn’t have to meet nearly as many stormwater management criteria as they do today. Developers often find themselves outsourcing software, installation of stormwater best management practices (BMPs), and maintenance services in an effort to protect the surrounding environment from any pollutants the runoff may carry, as well as from flooding.

Pervious PCC Compressive Strength in the Laboratory and the Field: The Effects of Aggregate Properties and Compactive Effort
Crouch, L. K., Smith, N., Walker, A. C., Dunn, T. R., and Sparkman, A.
Laboratory samples using three different gradations of crushed limestone and two different gradations of gravel were compacted at six various compactive efforts using a consistent pervious concrete mixture design. Cores from four field demonstrations were also obtained. The effective air void content (voids accessible to water at the surface) and compressive strength of the pervious concrete samples were determined and compared.

Effect of Compaction Energy on Pervious Concrete Properties
Suleiman, M., Kevern, J., Schaefer, V. R., and Wang, K.
This paper summarizes a study performed to investigate the effects of compaction energy on pervious concrete void ratio, compressive strength, tensile strength, unit weight, and freeze-thaw durability. Laboratory results show that compaction energy affects pervious concrete compressive strength, split tensile strength, unit weight and freeze-thaw durability.

Pervious Concrete Construction: Methods and Quality Control
Kevern, J., Wang, K., Suleimen, M. T., and Schaefer, V. R.
This paper describes the current state of practice in Portland Cement Pervious Concrete (PCPC) placement and also presents results from a study performed at Iowa State University to determine a field level QC/QA check for fresh PCPC. Test slabs were placed using a variety of techniques currently employed for field placement of PCPC. Results show that PCPC samples with void ratios ranging from 15% to 20% have 7-day compressive strengths of about 3,000 psi and permeabilities of about 300 in./hr., both values have been shown suitable for pervious concrete applications. Results from this study expand on those findings.

Pervious Concrete—The California Experience
Youngs, A.
Pervious concrete has been around for a number of years in the U.S., but was commercially introduced into California in 2000. The acceptance of this material has grown steadily – in Northern California alone 360,000 square feet of pervious concrete was placed in 2005, with over 1.3 million square feet specified for placement in 2006. Much of the growth in pervious concrete in this region is due to improvements in mix design and placement techniques which have resulted in more durable and aesthetic installations.

Portland Cement Pervious Pavement Construction
Paine, J.
Unique mix design calls for special mixing and placing techniques. When properly proportioned and placed, pervious concrete pavements provide a smooth, durable riding surface while retaining an open surface texture that allows water to pass.

Proper Installation of Pervious Concrete
Wolfersberger, C.
Good pervious concrete installation is an investment with an excellent pay-off. It is a team effort. If the site engineer knows how to use it effectively it will be a tool that will help convert the site into a green zone. The aquifer will be refreshed, trees will be protected and flourish. Proper installation will ensure long term viability of this project and Green Building LEED will be earned.

Soil and Base Prep for Pervious Concrete
Wolfersberger, C.
Whether for a pervious driveway or parking lot, taking test borings to establish whether soil will drain enough to support the right sub base and the pervious pavement is essential. This boring machine will bring to the surface soils that contain significant levels of silt or clay that are either highly compressible, lack cohesion or will expand or contract with the absorption of moisture.

Placement, Curing, Contractors
Wolfersberger, C.
Compaction is done in two steps in quick succession. First, after the pervious concrete is poured from the ready mix chute and leveled with come-alongs and rakes the first compaction is done with a vibratory screed and then second, with a set of compaction rollers. This creates a slab where the top 1½" has smaller voids to trap pollutants which can be removed or which volatize in sunlight.

The Components Under the Pervious Slab
Wolfersberger, C.
While the engineered mixture is important there are other factors to consider such as: having a suitable base of soil, sand or crushed stone; having a drainable water table, sufficiently below the pavement is also important. Other factors are the proper preparation of an appropriate compacted, sub-base free of all organic matter, the correct concrete mixture, the designed mixing procedure, prompt placement, finishing and proper curing.

Pervious Concrete Performance
National Ready Mixed Concrete Association
The creation, placement, and curing of concrete are all done on-site, rather than in a factory under uniform conditions. Although pervious concrete can be mixed by the same suppliers and delivered by the same trucks as dense concrete, its unique physical characteristics require a contractor with specialized experience.

Producing Pervious Pavements
Offenberg, M.
Construction of pervious concrete is different from plain concrete pavements in that the contractor is responsible for an extra level of quality control. Acceptance of the material is not based on strength and smoothness, but porosity and thickness, so it takes a different mindset to build. The purpose of this article is to help identify each party's responsibility and identify the keys for their success. Primarily the focus is on the concrete contractor's role in the success of the pervious pavement.

DURABILITY AND MAINTENANCE

Evaluation of the Effects of Deicer Chemical Methodologies on Pervious Concrete & Development of a Deicer Chemical Testing Method for Pervious Concrete
Haselbach, L.
There is strong evidence and instances that suggest certain de-icing chemicals and salts can negatively affect pervious concrete and initiate a rapid degradation of the paste matrix, aggregate bonding, pavement durability and strength. A number of project locations have reported a failure of pervious concrete pavements within the last year as a result of their exposures to deicers and salts in the very severe winter of 2013-2014. These instances suggest there is a required necessity to better understand what is causing this disintegration of pervious concrete paste when exposed to deicer chemicals and evaluate mitigations to modify pervious concrete mix designs to enhance paste characteristics and quality, and to be more resistant to these widely-used chemicals. This research seeks to better understand what has contributed to these failures and evaluates pervious concrete paste characteristics that withstand harsh deicer and salt applications. *This report is available for download from*

www.rmc-foundation.org.

Pervious Concrete Pavement Maintenance and Operations Guide
National Ready Mixed Concrete Association
A pervious concrete maintenance and operations guide that details recommendations for scheduled maintenance, development of a maintenance plan and specific guidance for winter maintenance.

Durability and Performance of the Pervious Concrete Overlay at MnROAD
Kevern, J. T., Wang, K., and Schaefer, V. R.
This paper presents the results of studies conducted to develop a self-consolidating Portland Cement Pervious Concrete (PCPC) for overlay applications to reduce roadway noise, reduce splash and spray, and to improve friction as a surface wearing course. A variety of mixture variables were characterized for workability to develop a mixture for mechanized placement. During the fall of 2008, a 100 mm (4 in.) thick pervious concrete overlay on traditional concrete was constructed at a test facility. Construction is described as well as results of field tests to characterize the condition of the pavement seven months following construction. Performance testing of the overlay section included bond strength, permeability, skid resistance, and noise generation. The results of these studies show that effective PCPC overlays can be designed for wearing course applications.

Acoustic Properties of Clogged Pervious Concrete Pavements
Izevbekhai, B. I.
Minnesota Department of Transportation and many municipalities in Minnesota have built sidewalks, city streets, low volume roads, boat ramps and parking lots with pervious concrete. Since 2005 when the first pervious concrete initiative was constructed at the MnROAD facility, three test cells have been constructed, monitored and maintained. Paradoxically, non pervious pavements are similar to pervious pavements in their requirements for drainability for durability. However, pervious concrete requires that the voids should be connected and free of clogging agents for durability of conductive and acoustic properties. The effect of clogging and the characteristics of pervious concrete, clogged with various agents are examined. Desirable acoustic absorption and hydraulic conductivity are reduced when pervious concrete is clogged and may be restored with adequate maintenance practices.

Vertical Distribution of Sediments in Pervious Concrete Pavement Systems
Mata, L. A. and Leming, M. L.
Pervious concrete pavement systems (PCPSs) are a unique and effective means to address important environmental issues and support green, sustainable growth by capturing storm water and allowing it to infiltrate into the underlying soil. Sedimentation leading to clogging, however, is a potential problem in the serviceability of PCPS. The sedimentation rates of pervious concrete with 20% porosity were examined with three different soil types: sand, clayey silt, and clayey silty sand. Pervious concrete cylinder specimens were exposed to sediments mixed in water to simulate runoff with a typical load of soil sediments. Falling head permeability tests were performed on the specimens before and after exposure—that is, sedimentation. Results show that the exfiltration rate can be affected by sediment characteristics in some situations.

Evaluation of surface textures and skid resistance of pervious concrete pavement
Chen, Y., Wang, K., and Zhou, W.
Surface textures had long been recognized as primary factors to provide the skid resistance on pavements; however, no measurement of skid resistance on pervious concrete pavement with various surface texture parameters had been made. Fractal geometry was introduced in the present work to accurately simulate transect contour curves of pervious concrete specimens through fractal interpolation. It is proved that its fractal dimension (*D*) can be adopted to measure the skid resistance on pervious concrete pavement, overcoming the shortcomings of both macrotexture depth (D_T) and British portable pendulum number (N_{BP}). Combined with Fujikawa-Koike tire/road contact model, the optimization method of all surface textures was recommended for designing and constructing excellently skid-resistant and noise-absorptive pervious concrete pavement. In addition, evaluating of the abrasion process and attenuation of the surface textures on concrete pavement slabs was also the focus of this work based on accelerated abrasion test. Results show that the surface textures on pervious concrete pavement slabs is extremely durable, compared to those on conventional grooved or exposed aggregate concrete pavement slabs.

Cleaning Methods for Pervious Concrete Pavements
Hein, M., Dougherty, M., and Hobbs, T.
Pervious concrete paving systems increasingly are being applied as environmentally friendly alternatives to traditional impervious pavements. Pervious concrete (PC) systems have been shown to effectively reduce negative environmental impacts associated with impervious pavements, including stormwater pollution, noise, heat island effects, and soil erosion. Keeping PC pavements viable requires maintaining their ability to infiltrate water. The porous nature of PC invites solids such as soil particles and organic matter carried in storm runoff to become trapped in the surface over time, gradually decreasing infiltration rate (IR). The pavement, if left unmaintained, will become increasingly clogged. Since no standardized recommendation for cleaning PC currently exists, water management agencies in some states do not provide stormwater management credit for using PC systems. This research studied the effectiveness of power blowing, pressure washing, and vacuuming, as well as a combination of these methods for restoring IR on small area PC pavements. This study finds that pressure washing and vacuuming are equally effective as initial cleaning techniques, both increasing surface IR by over 90%. Combining vacuuming and pressure washing offers substantial gains over either method alone. These results are important for owners of small area PC pavements who have access to limited equipment.

Density is our Destiny
Montgomery, J. and Kevern, J.
Pervious concrete is a mix with 15% to 30% voids. The concrete industry has accepted that these values strike a balance between the hydrological and engineering properties of the concrete. When voids are less than 15%, the slab will not drain rapidly, but is durable; when greater than 25%, the slab will drain rapidly, but will lose some of the critical properties essential for long-term durability.

Exploring Porous Pavement Maintenance Strategies
MnROAD
Mn/DOT demonstrated a porous pavement vacuuming process using equipment owned and operated by Reliakor, a Minnesota based Company at MnROAD on November 4, 2009. Pervious concrete test cells and porous asphalt cells were vacuumed. Representatives

from Mn/DOT Metro District, Mn/DOT Research, Mn/DOT Tech Support, Mn/DOT Maintenance Research, the City of Minneapolis, DNR, and Reliakor Services Inc were in attendance.

Porous Overlay and Pervious Concrete Pavements at MnROAD: Two Year Performance
Akkari, A. and Izevbekhai, B.
This report discusses the two year performance of the three pervious concrete test cells at MnROAD for task 5 of LRRB Project 879: Pervious Concrete Pavement at MnROAD Low-Volume Road. Test cells 39, 85 and 89 were constructed to evaluate the possible benefits of pervious concrete in pavements, such as increased durability, sound absorption, and drainability. Continued monitoring of the test cells will develop an understanding of the long-term performance for more effective and efficient design of permeable pavements.

Laboratory Evaluation of Abrasion Resistance of Portland Cement Pervious Concrete
Wu, H., Huang, B., Shu, X., and Dong, Q.
High porosity with interconnected voids between aggregate particles is the primary characteristic of portland cement pervious concrete (PCPC), which, however, causes a significant decrease in its strength and abrasion resistance. In this study, latex and fiber were added to improve the abrasion resistance of PCPC mixtures. Laboratory tests were conducted to evaluate the performance of latex-modified pervious concrete with a particular focus on abrasion resistance. Test results show that adding latex desirably improved strength and abrasion resistance of PCPC, whereas fiber did not show a significant effect on the mechanical properties of PCPC. In addition, the asphalt pavement analyzer (APA) abrasion test was found to be feasible for evaluating the abrasion resistance of pervious concrete.

Performance Evaluation of In-Service Pervious Concrete Pavements in Cold Weather
Vancura, M., Khazanovich, L., and MacDonald, K.
Aside from clogging, structural failures, and dry concrete, there have been varying reports of pervious concrete material performance in regions that are classified as wet, freeze/thaw regions. While pervious concretes have been extensively evaluated in laboratory tests and their in-service performance evaluated in a few case studies, there does not exist a body of research that has evaluated the distresses that are specific to in-service pervious concretes in wet, freeze/thaw regions or that has investigated the causes of the distresses. This report is an extensive performance evaluation of twenty nine different projects. *This report is available for download from www.rmc-foundation.org.*

Freezing-and-Thawing Durability of Pervious Concrete under Simulated Field Conditions
Yang, Z.
This research investigates the durability of pervious concrete under simulated field conditions, including slow cyclic freezing and thawing, wet-dry environments, and salt applications. Specifically, this research examines the effects of materials and proportions and curing conditions on the freezing-and-thawing durability of pervious concrete. Generally, air curing causes a dramatic reduction in the freezing-and-thawing durability as compared with water curing. Silica fume additions are observed to improve the performance of water-cured pervious concrete during slow freezing and thawing while causing a significant drop in the performance of air-cured specimens. Polypropylene fibers are seen to enhance the resistance of pervious concrete to repeated freezing and thawing, whereas salt applications are noted to aggravate the deterioration.

Pervious Concrete in Severe Exposures
Kevern, J. T., Wang, K., and Schaefer, V. R.
Pervious concrete’s perceived lack of durability when subjected to cycles of freezing and thawing initiated several research projects at Iowa State University. Since late 2004, several aspects of pervious concrete have been investigated to determine mixture proportions for cold-weather regions of the U.S. The results of these studies are summarized in this article.

Your Own Pervious Installation
Ohio Ready Mixed Concrete Association
Deteriorated asphalt pavement around the drainage inlet in your parking lot may be an opportunity for pervious concrete. You could improve the drainage, repair the pavement and learn to use pervious concrete all in one project. Click on the drawing inside the document to download estimated quantities to construct your own miniature storm water detention system with a pervious concrete pavement cap.

Pervious Pavements
Gunderson, J.
Widespread misconception exists in the industry about pervious pavement systems, specifically about their functionality in cold-weather environments. The prevalent belief is that pervious pavements are not an effective stormwater management option for cold-weather climates because of concerns related to diminished permeability during freezing and that the material is not durable enough to withstand freeze-thaw conditions. Cold climates are typically very hard on constructed systems, and naturally, questions should arise about the effectiveness of pervious pavements in these environments—especially due to concerns about freezing of the filter media.

Construction and Maintenance Assessment of Pervious Concrete Pavements
Chopra, M., Wanielista, M., Ballock, C., and Spence, J.
The use of pervious concrete pavements continues to grow as builders and communities move toward sustainable development. Without proper maintenance, pervious pavement may become clogged and lose some of its permeability. This research addresses three main issues that are of interest to both the staff in water management districts and the concrete industry for widespread acceptance of pervious pavements: namely, 1. the design cross-section to ensure adequate infiltration, 2. credit for replacement of impervious areas, and 3. operational and maintenance issues.

Influence of Moisture Conditions on Freeze and Thaw Durability of Portland Cement Pervious Concrete
Yang, Z., Brown, H., and Cheney, A.
This study focuses on investigating the effects of moisture condition and freezing rate on the damage development in pervious concrete during cyclic freezing and thawing. A series of tests have been conducted in which pervious concrete specimens are preconditioned to different moisture contents and then exposed to slow or rapid freeze and thaw cycles. Resonant frequency is used to monitor the damage development in the specimens exposed to freezing and thawing. In addition, the mass change of each specimen is measured during the test.

Pervious Concrete Pavement Surface Durability in a Freeze-Thaw Environment Where Rain, Snow and Ice Storms are Common Occurrences
Baas, W.
This presentation will provide brief viewings from known on-going research on the freeze-thaw durability of pervious concrete, with a focus on observations of pervious concrete pavement installations in Ohio.

Freeze-Thaw Performance of Pervious Pavement in Minnesota
MacDonald, K.
A large scale set of test panels were constructed at the MnROAD facility in the fall of 2005. Three mixtures were utilized to evaluate the freeze-thaw performance of various mixtures, as well as to monitor the hydraulic performance of the system. The pavements were instrumented for temperature and frost penetration, as were the sub-grade materials. An update of performance after the first winter, in terms of freeze-thaw resistance will be presented. In addition, the relationship between laboratory testing and field performance will be discussed.

Freeze-Thaw Resistance of Pervious Concrete
National Ready Mixed Concrete Association
A considerably severe exposure condition on portland cement concrete elements is exposure to cycles of freezing and thawing. Since the 1930s, air entrainment has been used to enhance the freeze-thaw resistance of portland cement concrete exposed to an external environment. The typical deterioration of concrete exposed to freeze-thaw conditions is random cracking, surface scaling and joint deterioration due to D-cracking. An investigation into freeze thaw resistance for pervious concrete is examined.

Permeability Predictions for Sand Clogged Portland Cement Pervious Concrete Pavement Systems
Haselbach, L. M., Valavala, S., and Montes, F.
Pervious concrete is an alternative paving surface that can be used to reduce the nonpoint source pollution effects of stormwater runoff from paved surfaces such as roadways and parking lots by allowing some of the rainfall to permeate into the ground below. This infiltration rate may be adversely affected by clogging of the system, particularly clogging or covering by sand in coastal areas. Long term permeability predictions are investigated.

Fatigue Behavior of Polymer-Modified Porous Concretes
Pindado, M. A., Aguado, A., and Josa, A.
Highly permeable materials provide drainage and noise-absorption properties that are useful in pavement top layers. In such porous concretes, the voids reduce the mechanical integrity, which may have to be compensated for with the incorporation of non-conventional components, such as polymers. A basic property needed for the design of pavements is the fatigue behavior of the material, which has not been studied thoroughly for polymer-modified porous concretes.

Clogging Prevention
Wolfersberger, C.
Some critics claim that pervious concrete gets clogged with oil and debris. It can if not given minimum attention. Some common sense procedures will keep it performing indefinitely. All pavements require some maintenance depending on traffic and location. Pervious concrete usually requires much less. Inspection and some attention will keep it working for many years.

Maintenance of Pervious Concrete
Wolfersberger, C.
Pervious concrete is the easiest pavement product to maintain. Pervious concrete is not a new product as it was originally used in Europe back in the late 1940's. Properly placed and maintained pervious concrete will last for decades. This article covers some basic maintenance techniques.

Long-Term Field Performance of Pervious Concrete Pavements
Delatte, N. and Miller, D.
Portland cement pervious concrete (PCPC) has an excellent performance history in the Southeastern U.S., but until recently has seen little use in environments with significant freeze-thaw cycles. Therefore, assessment of actual field performance is important. This project documents field observations, and nondestructive testing results of PCPC sites located in the states of Ohio, Kentucky, Indiana, Colorado, and Pennsylvania. In addition to field observations and nondestructive testing, laboratory testing was performed on cores removed from some of the test sites. Generally, the PCPC installations evaluated have performed well in freeze-thaw environments, with little maintenance required. *This report is available for download from www.rmc-foundation.org.*

Is Pervious Concrete Strong Enough?
Wolfersberger, C.
It has been difficult to quantify the strength of pervious concrete. Installation thicknesses of 6" through 10" have found that with the correct mix and placement it has lasted for many years. Ultimate endurance of pervious concrete is dependent upon a well compacted porous base, fast, but controlled placement, uniform compaction and correct control joints. These factors control raveling and cracking.

HYDROLOGICAL AND ENVIRONMENTAL DESIGN

Effective Curve Number and Hydrologic Design of Pervious Concrete Storm-Water Systems
Schwartz, S. S.
The effective use of pervious concrete in environmental site design requires consistent design procedures integrating the structural and material properties of the pervious concrete pavement with hydrologic performance of the pervious concrete system. Design procedures to size pervious concrete storm-water systems are presented based on criteria for freeze-thaw protection and drawdown reliability. Hydrologic performance criteria are quantified by an effective curve number, estimated from simulated routing of design storm hydrographs using standard storm-water computations. Combining *operational* design criteria with the evaluation of hydrologic *performance* criteria, as an effective curve number, integrates pervious concrete systems with traditional storm-water management practice and emerging standards for environmental site design.

The Declining pH of Waters Exposed to Pervious Concrete
Thomle, J. N.
The focus of this study is on the pH changes over time in various stormwaters in contact with pervious concrete that has aged under varying ambient air restrictions. Elevated pH levels may

be a concern if exfiltrated directly to sensitive waters. This study was conducted to aid designers by determining the rate of pH decline under various conditions. For this study, laboratory prepared pervious concrete specimens exposed to three different levels of ambient air restriction, were periodically tested for pH using four different testing methods; infiltrating either deionized water or tap water through the specimens, or soaking the specimens in either deionized water or tap water. Obvious trends in pH decline were observed. Greater exposure to ambient air significantly increased the rate of pH decline. The tap water tests represented more typical stormwaters and had much lower pH readings than the deionized water tests. The pH of samples representative of typical, in-place conditions, declined sufficiently in well under a year for most typical field conditions. In addition, this study also includes the declining pH of water in contact with pervious concrete exposed to carbonate laden waters. The increased rate of carbonation is desired in many primary and secondary life applications of concrete in order to make the life cycle of concrete structures more carbon neutral. Most carbonation rate studies focus on concrete exposed to ambient air or air enhanced with increased levels of carbon dioxide under various conditions. A possible alternative mechanism for accelerated carbon sequestration in concrete was investigated in this research based on the pH change of waters in contact with pervious concrete. The results indicate that the pH of water in contact with pervious concrete exposed to carbonate species laden waters declined more quickly than when exposed to ambient air, which may indicate an increased rate of carbonation. It is theorized that the proposed alternative mechanism reduces the limiting rate effect of carbon dioxide dissolution in water and diffusion into the micro pores of the cement paste.

Water Quality Improvement Performance of Geotextiles Within Permeable Pavement Systems: A Critical Review

Scholz, M.

Sustainable drainage systems (SuDS; or best management practices) are increasingly being used as ecological engineering techniques to prevent the contamination of receiving water courses and groundwater. Permeable paving is a SuDS technique, which is commonplace in car parks, driveways and minor roads where one of their functions is to improve the quality of urban runoff. However, little is known about the water quality benefits of incorporating an upper geotextile within the paving structure. The review focuses on five different categories of pollutants: organic matter, nutrients, heavy metals, motor oils, suspended solids originating from street dust, and chloride. The paper critically assesses results from previous international tests and draws conclusions on the scientific rigor and significance of the data. Findings indicate that only very few studies have been undertaken to address the role of geotextiles directly. All indications are that the presence of a geotextile leads only to minor water quality improvements. For example, suspended solids are being held back by the geotextile and these solids sometimes contain organic matter, nutrients and heavy metals. However, most studies were inconclusive and data were often unsuitable for further statistical analysis. Further long-term research on industry-relevant and statistically and scientifically sound, experimental set-ups is recommended.

Surface and ambient air temperatures associated with different ground material: a case study at the University of California, Berkeley

Guan, K. K.

The urban heat island (UHI) phenomenon rises as urbanization increases. A key characteristic of urban areas is artificial surfaces, which can absorb and store great amounts of heat throughout the day. While standard pavements like asphalt and concrete have been extensively studied, newly introduced pervious pavements have not been intensively analyzed.

My study examined the surface temperatures of impervious, pervious, and natural ground materials and their association to ambient air temperatures in the urban microclimate. As a case study, I investigated an area on the University of California, Berkeley campus exhibiting open areas of asphalt, concrete, brick pavers, and grass lawns. I conducted field work mid- to late-winter and collected temperatures during the warmest time of day, between 2 p.m. to 4 p.m., using an infrared thermometer for surface temperatures and digital thermometer for air temperatures. Using ANOVA, I found differences in surface temperatures of each material, but air temperatures showed no significant difference. However, a correlation test showed strong and positive correlation between the surface temperature and air temperature of each material. An ANCOVA revealed that there was no significance between the rates of heating among materials. In conclusion, I determined that the UHI effect may be minimal during the winter in Berkeley.

An Investigation of Current Status of "Green" Concrete in the Construction Industry
Jin, R. and Chen, Q.
Concrete is the most largely consumed construction material worldwide. The production of raw materials used in concrete such as Portland cement requires a significant amount of energy input and causes various environmental problems (e.g., emission of greenhouse gases). The "green" concrete in this paper is defined as the concrete produced by utilizing alternative and/or recycled waste materials (such as fly ash and recycled concrete aggregates) to reduce energy consumption, environmental impact, and natural resource use. One of major issues associated with "green" concrete is how the alternative/waste cementitious and aggregate materials affect concrete properties compared with the conventional Portland cement concrete. Another important issue is whether all the benefits and barriers of producing "green" concrete have been adequately understood or addressed. In addition, it is unknown whether a consistent understanding of the current status of "green" concrete exists between academia and industry. This paper first discusses potential benefits of using alternative and/or waste materials in concrete production, followed by a review of previous studies on "green" concrete. The paper further investigates the current status of producing "green" concrete in the construction industry by surveying concrete suppliers/manufacturers in the U.S. The findings presented provide a deeper understanding on the production and implementation of "green" concrete.

Below ground effects of porous pavements—Soil moisture and chemical properties
Morgenroth, J., Buchanan, G., and Scharenbroch, B.
Impermeable pavements cover a considerable land area in cities. Their effect on the hydrological cycle is clear; as a barrier in the soil–atmosphere continuum they minimize rainfall infiltration and evaporation. Porous pavements are beginning to replace impermeable alternatives because of perceived hydrologic benefits. The impact of porous pavements on soil moisture and chemistry as they relate to urban vegetation was investigated in Christchurch, New Zealand. An experiment was established comprising 25 plots evenly distributed amongst controls (no pavement, exposed soil) and four different pavement treatments: a factorial combination of pavement type (porous, impervious) and pavement profile design (including or excluding a greywacke gravel base). Results indicate that pavements altered soil pH from moderately acidic (pH = 5.75) to more neutral levels (pH = 6.3). The effect on pH was greater beneath porous pavements, and also when a gravel base was included. Concentration of soil Al, Fe, and Mg decreased, while Na increased beneath pavements. Soil moisture was consistently higher beneath pavements than control plots, except following periods of heavy rainfall where high soil moisture muted all treatment effects. Throughout most of the study

period, soil moisture content was lower beneath pavement profiles designed with the gravel base, presumably due to the gravel acting as a capillary break to a distillation process, whereby soil moisture migrates upwards to the soil surface. In early autumn, when soil moisture content was lowest for all treatments, precipitation recharged soil moisture in control plots and beneath porous pavements. But impervious pavements prevented infiltration resulting in significantly lower soil moisture content beneath these pavements. Pavements can alter soil moisture and chemical characteristics, but the effects differ depending on pavement porosity and profile design. Implications of the results pertain to stress physiology of urban vegetation, in particular drought stress avoidance.

Temperature Behavior of Pervious Concrete

Kevern, J. T., Schaefer, V. R., and Wang, K.

To achieve the permitted stormwater effluent limits required by the Clean Water Act, many best management practices (BMPs) are being utilized to reduce the overall stormwater volume and provide initial pretreatment and pollutant removal. One such BMP is use of portland cement pervious concrete (PCPC), which allows stormwater to pass through the pavement into an aggregate base below to infiltrate. Until now, the temperature response of the entire system (concrete, aggregate base, and natural soil) was not known. Since PCPC is an infiltration-based BMP, once a frost line forms under the base the infiltrating capacity is reduced or eliminated. PCPC also is recommended for use in warmer climates as a cooler pavement alternative to conventional concrete or asphalt.

Stereology- and Morphology-Based Pore Structure Descriptors of Enhanced Porosity (Pervious) Concretes

Sumanasooriya, M. S. and Neithalath, N.

The pore structure features, such as the porosity, pore sizes and their distribution, connectivity, and specific surface area, play a dominant role in the structural and functional performance of macroporous materials like enhanced porosity concrete (EPC) (or pervious concrete). This paper deals with the analysis of such features for EPC using stereological techniques and mathematical morphology. Stereological methods based on area and line fractions and a morphological method based on two-point correlation provided similar porosity values for the mixtures studied. Stereology-based three-dimensional (3D) pore distribution density that indicates pore connectivity is compared to a hydraulic connectivity factor for permeability, and it is shown that the latter is a more sensitive parameter that can distinguish between EPC specimens made with aggregates of different sizes.

Calcium Hydroxide Formation in Thin Cement Paste Exposed to Air

Haselbach, L. M. and Liu, L.

In recent years, novel concrete mixtures have been adopted to address many environmental concerns. One of these is pervious concrete, which is being used to manage stormwater runoff. With large internal surface areas exposed to air, the reactions within pervious concrete may be different from those in traditional concretes. This paper focuses on how hydration in cement pastes varies for thin samples with increased exposure to air.

Preliminary Analysis of Summertime Heat Storage in Traditional vs. Pervious Concrete Systems

Boyer, M.

The urban heat island effect, where air temperatures are significantly higher in more developed areas than those of the surrounding countryside due to solar radiation retained in materials such as pavements, has increasingly become a concern during hot weather due to its negative impact on human health as well as human comfort and the natural environment. Currently one method of measuring how “cool” (helpful in mitigating urban heat island) a pavement may be is its solar reflectance index (SRI). LEED counts any pavement with an SRI greater than 29 as a “cool” surface. Many concrete pavements have an SRI greater than 29, but pervious concrete pavements typically do not because their rough surface does not reflect light as well. The hypothesis presented in this thesis is that pervious concrete has other beneficial properties, particularly its extensive void structure which may serve to insulate the ground from heat transfer thus also helping to mitigate the urban heat island effect.

Pollution Prevention and Good Housekeeping
Brzozowski, C.
Despite economic challenges, MS4 communities throughout the United States continue to put forth a significant effort in addressing one of the key elements of NPDES Phase II: pollution prevention and good housekeeping. As they tackle the NPDES Phase II measure of public education and outreach, stormwater managers are working against the backdrop of many larger social issues, from the problem of the homeless in urban areas to the economic situation and the resulting lack of funding.

Economical CSO Management
Gunderson, J., Roseen, R., Janeski, T., Houle, J., and Simpson, M.
Combined sewer overflows (CSOs) represent major water-quality threats to hundreds of cities and communities in the US that are served by combined sewer systems. CSO events cause the release of untreated stormwater and wastewater into receiving rivers, lakes, and estuaries, causing a host of environmental and economic problems. Costs associated with CSO management are expensive. The EPA estimates the costs of controlling CSOs throughout the country are approximately $56 billion (MacMullan 2007).

Exploring the Feasibility of Rainwater Harvesting in Southern California
Lucera, R.
Following the evolution of municipal separate storm sewer system (MS4) permitting in California reveals the growing number of regions within the state that are currently or are soon to face mandated “retain/reuse” requirements as part of any future development or redevelopment project. The retain/reuse aspect is interpreted in most instances to be satisfied by management approaches such as infiltration (groundwater recharge), evapotranspiration, and rainwater harvesting. However, southern California’s development future involves much more redevelopment and infill, as opposed to construction within greenfields. These infill areas are invariably in proximity to dense existing infrastructure and/or poorly draining soils. The risk of incorporating low-impact development (LID) measures such as bioretention and permeable pavement in these types of areas would typically be mitigated through the use of subdrain systems and other methods necessary to make the members of our geotechnical and legal communities sleep better at night.

Watersheds, Walkability, and Stormwater
Jacob, J. S.
Town centers, walkable urbanism, compact growth, new urbanism: these are all terms associated with a growing movement toward walkable urban development. Above all else, this increasingly popular pattern of development implies proximity of uses, and therefore much higher density. Higher density is a necessary antecedent to walkable and vibrant urban

neighborhoods. You can't have walkability without proximity. But higher density also means more impervious surface cover per acre, resulting in a higher pollutant load per acre. Recent research, however, shows that the kind of densities required for walkable urbanism may actually translate into less of a pollutant load, on a per capita basis, than that from an equivalent population at lower, suburban densities, and therefore less of a total pollutant load for a given population.

Reducing the Impacts of Stormwater Runoff at Portland's Powell Butte
Eder, A.
Powell Butte is a 578-acre nature park of vast meadowlands and forests, located in southeast Portland, OR, within easy reach of city dwellers. The park is bounded roughly by SE Powell Blvd. to the north, SE 141st Ave. on the west, SE 162nd Ave. on the east, and the Springwater Trail Corridor on the south (Figure 1). The butte, an extinct cinder cone volcano, rises near the headwaters of Johnson Creek—an urban creek with remnant populations of native salmon and steelhead. The park is Portland's second-largest park after Forest Park. Several BMPs were utilized including permeable pavement.

Green Infrastructure and Storm Depth Retention Criteria
Reese, A. J., Jawdy, C. M., and Parker, J. M.
This dawning awareness of a need for change is currently being expressed through changes in regulatory criteria throughout the country. These new criteria must boil the myriad of information and opinions into some sort of simplified abstraction of reality. The hope is that the newly developed criteria capture the basic physics with suitable accuracy to do what they are intended to do. In so doing, rule-of-thumb assumptions are proffered, then adopted, and by reason of use become the law and practice of the land.

Improving the Practice of Modeling Urban Hydrology
Peters, E. G.
As stormwater practitioners, if asked, we would all say that we are interested in protecting our water resources and preventing flooding or erosion of downstream properties. We may even be aware that very low levels of urban development (5% to 15% impervious surfaces) have been shown to result in degradation of streams (Booth and Jackson 1997, Wang et al. 1997, Short et al. 2005). Yet, the quality of our waters is still drifting downward.

Volume-Based Hydrology
Reese, A. J.
Every 20 years or so, urban stormwater practitioners seem to stop and take stock of how we are doing. Sixty years ago, we figured that efficient drainage was the way to do things, using separate stormwater systems of pipes. Twenty years ago, we found that detention ponds were failing for a number of reasons and switched to a more comprehensive master planning approach—that is, those who could afford all that modeling, understand its output, and had the wherewithal to actually construct regional systems for stormwater treatment. In the ensuing 20 years, we have seen the rapid diversification of stormwater design from a simple consideration of flooding and conveyance to channel erosion, stormwater pollution, groundwater recharge, and natural approaches to stormwater design including utilizing permeable surfaces.

Stormwater Infiltration in Clay Soils
Estes, C. J.
Stormwater runoff from impervious surfaces is causing devastating effects on the landscape of our developing watersheds. We are disrupting the natural hydrological cycle that supports our potable water supplies and natural fauna. Intentional stormwater infiltration can restore that cycle. However, the lack of awareness and the perceived lack of data are currently limiting its use. This article presents monitoring data for three sites in the North Carolina Piedmont that demonstrate the success of stormwater infiltration in clay soils.

Integrating Stormwater Into the Landscape
Baxter, R.
Rain falls on a rooftop, slides down a gutter, and flows out to a curbside. Following the slope of the street, the water joins rivulets from other roofs and gushes into a storm drain. As it journeys, it sweeps dirt, oil, and trash from the street, into the storm drain, and on through pipes until it is flushed out into a nearby creek or lake. Meanwhile, the business owner is paying his utility bill, including a hefty fee for irrigation water and air-conditioner electricity. During this brief rainstorm, this scenario is repeated on thousands of streets. What if we could change even a tiny portion—keep the stormwater on-site or give the business owner a break on his utility bills? What if we could extend this to each office building and home in the community?

Balancing Wetland and Stream Preservation With Stormwater Management Goals
Der, A. T.
In response to increasing regulatory authority over its water resources, the Maryland Department of the Environment (MDE) has combined various programs and processes into a "one-stop shop" where various issues can be addressed in a uniform and consistent manner. As part of this process, onsite conditions are assessed, potential primary and secondary impacts are identified, and mitigative practices are proposed sufficient to offset habitat loss and comply with water-quality standards. This is an effective approach when large-scale, complex projects are submitted for applicable wetland and waterway permits.

Maintenance Goes Underground
Brzozowski, C.
For capturing pollutants in stormwater runoff, many options are available, and a variety of underground separation and filtration systems on the market offer municipalities new options when it comes to retrofitting existing areas with stormwater treatment or building in small spaces. As with any BMP, regular maintenance is a key to optimal performance. As more cities opt for these manufactured stormwater systems, they're learning how to schedule and perform maintenance activities, and in some cases are basing their choices on the type of long-term maintenance that will be required.

Methods of Sizing Water Quality Facilities
Lenhart, J. H.
With the increasing number of agencies throughout the United States establishing regulations for the treatment of stormwater runoff, there is now an array of approaches to selecting and sizing BMPs to address different water quality parameters. Agencies are providing guidelines on how much water needs to be treated as well as on the extent of treatment, typically expressed in percent removal.

Developing Stormwater Treatment Systems to Remove Nitrogen
Herr, J.
As property is converted from natural to developed land use, impervious area is added and remaining pervious areas may be compacted by construction equipment traffic. These changes reduce the potential for rainfall to infiltrate into the ground and increase the post-development volume of stormwater runoff discharged from the site. In addition to an increase in runoff volume, human activities associated with development routinely increase the concentration of nutrients (nitrogen and phosphorus), suspended solids, heavy metals, and many other pollutants in stormwater runoff. The combination of increased runoff volume and pollutant concentrations results in significant increases in stormwater pollutant loads to receiving surface waters.

Increasing Exfiltration from Pervious Concrete and Temperature Monitoring
Tyner, J. S., Wright, W. C., and Dobbs, P. A.
Pervious concrete typically has an infiltration rate far exceeding any expectation of precipitation rate. The limiting factor of a retention based pervious concrete system is often defined by how quickly the underlying soil subgrade will infiltrate the water temporarily stored within the concrete and/or aggregate base. This issue is of particular importance when placing a pervious concrete system on compacted fine textured soils. This research describes the exfiltration from twelve pervious concrete plots constructed on a compacted clay soil in eastern Tennessee, USA. Several types of treatments were applied to the clay soil prior to placement of the stone aggregate base and pervious concrete in an attempt to increase the exfiltration rate, including: 1) control – no treatment; 2) trenched – soil trenched and backfilled with stone aggregate; 3) ripped – soil ripped with a subsoiler; and 4) boreholes – placement of shallow boreholes backfilled with sand.

Hydraulic Performance Assessment of Pervious Concrete Pavements for Stormwater Management Credit
Wanielista, M., Chopra, M., Spence, J., and Ballock, C.
Portland cement pervious concrete's ability to infiltrate water has encouraged its use for stormwater management. However, the material has suffered historically poor acceptance due to a lack of data related to long term infiltration rates and rainfall retention which leads to an undefined credit for stormwater management. *This report is available for download from www.rmc-foundation.org.*

Study on the Surface Infiltration Rate of Permeable Pavements
Bean, E. Z., Hunt, W. F., Bidelspach, D. A., and Smith, J. T.
Asphalt surfaces have greatly increased the amount of pollutant-carrying runoff entering surface waters. To counteract this, permeable pavement can be installed to allow water to infiltrate, thus reducing runoff and acting as a filter. This study tested the surface infiltration rate of 27 permeable pavement sites in North Carolina, Maryland and Delaware. One of these sites in North Carolina was monitored to compare pollutant loads of asphalt runoff to those in infiltrate. Concrete grid pavers (CGP) and permeable interlocking concrete pavers (PICP) were tested with pavement ages ranging from six months to 20 years. Two infiltration tests were run on 14 CGP lots filled with sand. The initial test was on the existing condition of the surface and second test was run after the removal of the top layer of residue (1.3 - 1.9 cm) to simulate maintenance. Maintenance improved the infiltration rate on 13 of 14 sites.

Hydrologic Design of Pervious Concrete
Leming, M. L., Malcom, H. R., and Tennis, P. D.
Pervious concrete can be an important part of context-sensitive construction and low-impact development (LID), used to improve water quality by capturing the “first flush” of surface runoff, reducing temperature rise in receiving waters, increasing base flow, and reducing flooding potential by creating short term storage detention of rainfall. In order to fully utilize these benefits, the hydrological behavior of the pervious concrete system must be assessed. The hydrological performance is usually a key parameter in decisions to use this material as a best management practice (BMP) for stormwater management. This publication provides an overview of design techniques for determining hydrological performance and provides an example spreadsheet for analysis.

Area Rated Rational Coefficient Values for Portland Cement Pervious Concrete Pavement
Valavala, S., Montes, F., and Haselbach, L.,
Surface area specific runoff coefficients were measured for non-clogged Portland cement pervious concrete systems according to the rational method. The systems were simulated with pervious concrete blocks with porosities ranging from 16 to 27% placed over sand sub-bases. Rainfall was simulated in a flume set up with surface slopes ranging from 2% to 10%. There was negligible runoff for typical rainfall events under 100 year’s frequency in South Carolina.

Principles and Techniques for Hydrologic Design of Pervious Concrete Systems
Leming, M. L., Malcom, R., Amekuedi, G., and Arent, W.
This paper describes the hydrologic design elements of a pervious concrete paving system using the "stage storage discharge" approach, including selection of an appropriate design rainfall event, integration of site characteristics and specified runoff limits, and the effects of various soil horizons. Emphasis is on "active" mitigation applications where the intent is to capture a significant portion of the runoff from an entire site, including permeable, impermeable, and vegetated areas. Results of an example feasibility study found that by using pervious concrete for a nine-acre parking lot would act hydrologically as if it were grass.

A Monitoring Field Study of Permeable Pavements in North Carolina
Bean, E. Z., Hunt, W. F., and Bidelspach, D. A.
8th Biennial Conference on Stormwater Research & Watershed Management Summary of water quality and quantity monitoring from three permeable pavement sites across North Carolina; one each in the Piedmont, Coastal Plain, and Coastal regions. Water quality data was collected from each site, while water quantity was only monitored from two sites.

Hydraulic Performance of Pervious Concrete Pavements
Chopra, M., Wanielista, M., Spence, J., Ballock, C., and Offenberg, M.
Pervious concrete is a mixture of coarse aggregate, portland cement, water, and admixtures. Lacking fines, this material has a void ratio that typically ranges from 15-20% allowing it to store and infiltrate stormwater. Pervious concrete has been used in lower traffic areas such as parking lots, shoulders, sidewalks, streets, and local roads. Though it has garnered significant interest in the past, there is still a great deal of concern about its durability, adequate infiltration capabilities, and clogging potential. This paper focuses on the hydraulic operations of a pervious concrete system including infiltration rates, storage capacity and clogging potential.

A Field Study to Evaluate Permeable Pavement Surface Infiltration Rates, Runoff Quantity, Runoff Quality, and Exfiltrate Quality
Bean, E. Z.
This document Includes detailed research backgrounds, methods, results, analysis, and conclusions dealing with surface infiltration rates, water quantity and quality performance of permeable pavements. It also includes the summary of a rainfall analysis for major municipalities across North Carolina and detention pond sizing study for different areas, land uses, and soil types in North Carolina.

An Overview of Pervious Concrete Applications in Stormwater Management and Pavement Systems
Schaefer, V. R., Suleiman, M. T., Wang, K., Kevern, J. T., and Weigand, P.
In this paper a summary of recent research efforts on pervious concrete mix designs for cold weather applications, reduction of road noise, stormwater management and constructability issues is discussed. In addition, the efforts to develop a comprehensive and integrated study for full depth and wearing course applications under the auspices of the National Concrete Paving Technology Center at Iowa State University are presented.

Low Impact Parking Lot Design Reduces Runoff and Pollutant Loads
Rushton, B. T.
An innovative parking lot at the Florida Aquarium in Tampa, Fla., is being used as a research site and demonstration project to show how small alterations to parking lot designs can dramatically decrease runoff and pollutant loads. Three paving surfaces are compared, as well as basins with and without swales, to measure pollutant concentrations and infiltration. Preliminary results from the first year of a 2-year study indicate that swales reduce average runoff amounts by 30% at this site and pervious paving reduces it by an additional 10-15%.

Stormwater Quality Benefits of a Permeable Friction Course
Barrett, M. E.
This project documents the impact of a permeable friction course overlay on the quality of highway stormwater runoff. A permeable friction course (PFC) is a layer of porous asphalt approximately 50 mm thick which is often applied on top of conventional asphalt highways to enhance safety. The quantity and quality of stormwater runoff from a four-lane divided highway in the Austin, Texas area was monitored before and after the installation of a PFC.

Permeable Pavement for Stormwater Quality Enhancement
Pratt, C. J.
Natural, permeable ground surfaces occur in various proportions within urban areas and are usually assumed to contribute little, if any, stormwater runoff to urban drainage systems. In some situations the natural ground surface is graded and shaped to convey stormwater from roof downpipes and paved surfaces to a drainage inlet, situated within the permeable, landscaped area of an urban development, but again little runoff is assumed to be derived from the natural surfaces, except in the case of snowmelt conditions.

Permeable Pavements: Design and Maintenance
Pratt, C. J. and Hogland, W.
Engineered, permeable pavements have been constructed in the United States, Sweden, and Japan and some other countries, to a lesser extent, over the last decade as a part of stormwater management strategies within urban areas. The surfacing of the constructions has

commonly been porous macadam, although latterly in Japan use has been made on footways of porous concrete paving blocks and slabs.

Permeable Bases Help Solve Pavement Drainage Problems
Kozeliski, F. A.
Within the last ten years, permeable bases under portland cement concrete pavements have become standard in some states. In the past, the chief function of a pavement sub-base was to provide uniform support. Heavier paving equipment and increasing traffic loads led to the use of denser, stronger base materials that were thought to be erosion-proof. After problems began to arise with standard sub-bases, the use of permeable bases started to take shape.

Reducing the Noise Generated in Concrete Pavements Through Modification of the Surface Characteristics
Neithalath, N., Weiss, W. J., and Olek, J.
Tire-pavement interaction noise is one of the significant environmental issues in highly populated urban areas situated near busy highways. Even though sound barriers and texturing methods have been adopted to minimize road noise, they have their own limitations. Because it is necessary to reduce the sound at the source has led to the development of porous paving materials. This report outlines the systematic research effort conducted in order to develop methods to reduce tire-pavement noise through surface modification of portland cement concretes. The basic tenet of this research is that carefully introduced porosity of about 15% - 25% in the material structure of concrete will allow sound waves to pass through and dissipate its energy.

Development of Quiet and Durable Portland Cement Concrete Paving Materials
Olek, J., Weiss, W. J., Neithalath, N., Marlof, A., Sell, E., and Thornton, W. D.
This report outlines the systematic research effort conducted in order to develop and characterize Enhanced Porosity Concrete (EPC) to mitigate the problem of tire-road interaction noise. The basic tenet of this research is that carefully introduced porosity of about 15% - 25% in the material structure of concrete will allow sound waves to pass through and dissipate its energy. EPC mixtures were proportioned with three different aggregate sizes, and the binary blends of these sizes. The physical and mechanical properties of these mixtures were studied in detail.

Silencing Concrete
Concrete Producer
In many areas of the country, one of the greatest complaints about new roads is traffic noise. Some believe asphalt should be specified because it flexes so much as tires pass over it, reducing the noise of the interaction. It’s no wonder engineers are recognizing that the noise caused by tires on pavement is increasingly a significant environmental issue. This article reviews ways to decrease the noise related to concrete pavements.

Tire-Pavement Interaction Noise: Recent Research on Concrete Pavement Surface Type and Texture
Neithalath, N., Garcia, R., Weiss, J., and Olek, J.
Several solutions have been proposed for quieter riding surfaces, including porous pavements, tining, and grinding. This paper deals with certain aspects of a recent large-scale research that has been carried out to examine the influence of cement concrete pavement surface type and

texture on noise generation. One pavement surface type (Enhanced Porosity Concrete – EPC), and one surface texturing method (transverse tining) is dealt with in detail in this paper.

Field Evaluation of Permeable Pavement Systems for Improved Stormwater Management

Booth, D. B. and Leavitt, J.

The contribution of impervious surfaces to the disrupted runoff process in an urban watershed is overwhelming. Nearly all the problems ultimately result from the loss of the water-retaining function of the soil in the urban landscape. Traditional solutions for stormwater management have not been widely successful; in contrast, permeable pavements can be one element of a more promising alternative approach to reduce the downstream consequences of urban development.

Environmental Benefits of Pervious Concrete

Wolfersberger, C.

When the time comes to demolish a concrete structure or pavement, the material need not be wasted. It can be crushed and used as aggregate, base material or as a paving material. Even rebar can be recycled. And while it is being crushed it is absorbing CO2. Concrete can be made porous. This is done by removing sand and fines from the mix, and adjusting the cement paste with admixtures for maximum strength. The base and the pervious concrete mix is made of sustainable materials.

Concrete Parking Areas Aren't White, They're Green

Pool, A. V.

You know concrete parking lots are more attractive. You know they provide lower life cycle costs than higher maintenance cost alternatives (which means more money in owners' pockets). You know they provide higher levels of curb appeal. But did you know concrete parking areas are a much greener alternative than the black stuff? This article is going to outline some of the many ways concrete parking areas are GREEN.

Construction and Maintenance Assessment of Pervious Concrete Pavements

Chopra, M., Wanielista, M., Ballock, C., and Spence, J.

The use of pervious concrete pavements continues to grow as builders and communities move toward sustainable development. One of the environmental benefits of pervious pavements is its stormwater management properties. However, without proper maintenance, pervious pavement may become clogged and lose some of its permeability. This research addresses three main issues that are of interest to both the staff in water management districts and the concrete industry for widespread acceptance of pervious pavements: namely, 1. the design cross-section to ensure adequate infiltration, 2. credit for replacement of impervious areas, and 3. operational and maintenance issues. *This report is available for download from www.rmc-foundation.org.*

Demonstration of Integrated Pervious Pavement System for Management of Stormwater Quality and Quantity

Weigand, P., Schaefer, V., and Suleiman, M.

The overall goal of integrated pervious pavement systems is two-fold: 1) to reduce volume of direct runoff from the pavement surface by direct infiltration of the water through the pavement surface and into the subbase/subgrade; and 2) to provide enhancement of stormwater quality by directing the sheet flow of water through the pervious concrete and underlying porous subbase structure. This project is focused on the design of PC pervious concrete for use in the cold wet-freeze environment found in Iowa and the Upper Midwest. It will evaluate the mix design for durability, porosity, and improved stormwater runoff management.

Environmental Benefits of Pervious Concrete

When the time comes to demolish a concrete structure or pavement, the material need not be wasted. It can be crushed and used as aggregate, base material or as a paving material. Even rebar can be recycled. And while it is being crushed it is absorbing CO2. Drive-thrus, gas stations, parking lots and driveways catch the most oil and grease. Roads are next. They also collect heavy metals from engines and catalytic converters, and harmful components from rubber tires. When it rains, they become large polluters.

Environmental Benefits

National Ready Mixed Concrete Association

Pervious concrete pavement systems provide a valuable stormwater management tool under the requirements of the EPA Stormwater Phase II Final Rule. Phase II regulations provide programs and practices to help control the amount of contaminants in our waterways. Impervious pavements-- particularly parking lots-- collect oil, anti-freeze, and other automobile fluids that can be washed into streams, lakes, and oceans when it rains.

Monitoring Pervious Concrete for Water Quality in a Laboratory and Field Environment

Brown, H. J.

This presentation presents an in-field and laboratory study that monitored hydrocarbons and heavy metals through the pervious concrete matrix over simulated rain events as well as normal weathering cycles. With the construction of a 300,000 square foot parking lot beginning in March 2006 on MTSU campus, a better understanding of how to install collection sites for water quality testing will also be presented. Porous pavement pollutant removal mechanisms include absorption, straining, and microbiological decomposition in the soil. Studies indicate removal efficiencies of between 82 and 95 percent for sediments, 65 percent for total phosphorus, and between 80 and 85 percent of total nitrogen. It also indicated high removal rates for zinc, lead, and chemical oxygen demand.

Study on the Surface Infiltration Rate of Permeable Pavements

Bean, E. Z. and Bidelspach, D. A.

Asphalt surfaces have greatly increased the amount of runoff going into surface waters. To counteract this, permeable pavement can be installed to allow water to infiltrate, thus reducing runoff. This study tested the surface infiltration rate of 25 permeable pavement sites in North Carolina, Maryland and Delaware using variations of the double ring infiltrometer test. Five different classifications of surfaces were tested with pavement ages ranging from six months to 21 years. Two sets of tests were run on 12 concrete grid pavers lots with sand. The initial test was on the existing condition of the surface and second test was run after the removal the top layer of residue (0.5 - 0.8 in. or 1.3 - 1.9 cm) to simulate maintenance. Maintenance improved the surface infiltration rate on 11 of 12 sites.

Vertical Porosity Distributions in Pervious Concrete Pavement

Haselbach, L. M. and Freeman, R. M.

Pervious concrete is an alternative paving material that may alleviate many of the environmental problems caused by urban runoff from developed areas. Additional research is important so that pervious concrete can be better specified and more effectively used. An important property of pervious concrete is porosity, which will affect the hydrological and strength properties of the material. This research shows that there is a vertical distribution of porosity in slabs placed with certain placement techniques.

Sedimentation of Pervious Concrete Pavement Systems
Mata, L. A.
Sedimentation leading to clogging is a potential problem in serviceability of pervious concrete pavement systems (PCPS). The sedimentation rates of pervious concrete with 20% porosity were examined with three different soil types: sand, clayey silt, and clayey silty sand. Pervious concrete beam and cylinder specimens were exposed to sediments mixed in water to simulate runoff with heavy and typical load of soil sediments. Falling head permeability tests were performed in the specimens before and after exposure. Results show that storage capacity will be minimally affected by sediment. Exfiltration rate, however, can be affected by sediment characteristics in some situations. A simple, economical test for estimating exfiltration rates of the system in these situations was also developed. The results of this study were used to develop design guidelines that complement the hydrological design of PCPS considering the effects of sedimentation of the system at end of service.

MIX DESIGN

Models for Property Prediction of Pervious Concretes
Deo, O., Sumanasooriya, M. S., and Neithalath, N.
Properties of a random porous material such as pervious concrete are strongly dependent on its pore structure features. This study describes the development of different models to understand the material structure – property relationships in pervious concretes. Several pervious concrete mixtures with different pore structure features are proportioned. The pore structure features such as pore area fractions, pore sizes, mean free spacing of the pores, specific surface area, and the three-dimensional pore distribution density are extracted using image analysis methods. The performance features modeled as a function of the pore structure features are: (1) the unconfined compressive strength, (2) permeability, and (3) permeability reduction due to particle trapping in the pores (clogging). A statistical model is used to relate the compressive strength to the relevant pore structure features, which is then used as a base model in a Monte-Carlo simulation for feature sensitivity evaluation. Permeability prediction is accomplished using the well-known Katz-Thompson equation that employs the pore structure features. An idealized 3-D geometry obtained from 2-D planar images of pervious concrete sections is used along with a probablistic particle capture model to predict the particle retention associated with clogging material addition and simulated runoff. These models are anticipated to be useful in designing pervious concrete systems of desired pore structure for requisite performance.

Particle Packing-Based Material Design Methodology for Pervious Concretes
Sumanasooriya, M. S., Deo, O., and Neithalath, N.
This paper presents a rational methodology based on particle packing concepts for the material design of pervious concretes. The virtual packing densities of the components of the mixture, the actual packing density of the mixture, and the corresponding volume fractions are used to determine a compaction index. To achieve the design porosity, adjustments to the material volume fractions and/or the compaction effort are required when only a hypothetical minimum paste volume fraction is used. These adjustments result in two distinct means of proportioning pervious concretes—one where extra paste volume is added and the other in

which a combination of a small increase in paste volume and additional compaction effort is used to achieve the design porosity. The compaction index is shown to be related to the porosity and the compaction energy. These relationships facilitate the development of iso-compaction energy curves. The compaction index-porosity relationship for a certain applied compaction energy is shown to be a powerful material design tool for pervious concretes. The designed and actual (fresh and hardened) porosities are found to be fairly close to each other. The influence of these proportioning methodologies on the hardened state properties (compressive strength and permeability) is also discussed.

The Use of Seashell By-Products in Pervious Concrete Pavers

Nguyen, D.H., Sebaibi, N., Boutouil, M., Leleyter, L., and Baraud, F.

Seashell By-Products (SBP) are produced in an important quantity in France and are considered as waste. This work investigated to use SBP in pervious concrete and produce an even more environmentally friendly product, Pervious Concrete Pavers. The research methodology involved substituting the coarse aggregate in the previous concrete mix design with 20%, 40% and 60% SBP. The testing showed that pervious concrete containing less than 40% SBP had strengths, permeability and void content which are comparable to the pervious concrete containing with only natural aggregate. The samples that contained 40% SBP or higher had a significant loss in strength and an increase in permeability and a void content from the control mix pervious concrete. On the basis of the results in this research, it was found that the natural aggregate can be substituted by SBP without affecting the delicate balance of a pervious concrete mix. Additional, it is recommended that the optimum replacement percentage for SBP in pervious concrete is 40 % direct replacement of natural coarse aggregate while maintaining the structural performance and drainage capabilities of the pervious concrete.

Utilization of recycled crumb rubber as fine aggregates in concrete mix design

Issa, C. and Salem, G.

There is no doubt that the increasing piles of used tires create environmental concerns. As waste continues to accumulate and availability and capacity of landfill spaces diminish, agencies are increasing application and use of recycled materials such as crumb rubber from tires in construction. The basic building materials in concrete construction are primarily aggregate and cement. The educated use of recycled materials can result in reduced cost potentials and may enhance performance; however, not all recycled materials are well suited for concrete construction applications. The two main reasons for not utilizing a reclaimed material are (1) addition of material is a detriment to performance, and (2) excessive cost. In this study, the performance of recycled materials crumb rubber as valuable substitute for fine aggregates ranging from 0% to 100% in replacement of crushed sand in concrete mixes is investigated. An acceptable compressive strength was obtained with up to 25% by volume replacement of fine aggregates with crumb rubber.

Investigating the effect of mixture design parameters on pervious concrete by statistical modeling

Sonebi, M. and Bassuoni, M. T.

In this study, the effects of water-to-cement ratio (W/C), cement content and coarse aggregate content on the density, void ratio, infiltration rate, and compressive strength of portland cement pervious concrete (PCPC) were investigated by statistical modeling. Two-level factorial design and response surface methodology (RSM) were used. The PCPC mixtures were made with W/C in the range of 0.28–0.40, cement content in the range of 350–415 $kg/m^3$and coarse aggregate content in the range of 1200–1400 kg/m^3. In addition, examples were given on using multi parametric optimization to produce isoresponses of a desirability function for PCPC satisfying specified criteria including cost. The results show that W/C, cement content, coarse aggregate content and their interactions are key parameters, which significantly affect the characteristic performance of PCPC. The statistical models developed in this study can facilitate optimizing the mixture proportions of PCPC for target performance by reducing the number of trial batches needed.

Properties of pervious geopolymer concrete using recycled aggregates
Vanchai, S., Wongsa, A., and Chindaprasirt, P.
In this paper, the use of recycled aggregates (RAs) for making pervious geopolymer concrete (PGC) was studied. PGCs were prepared from high-calcium fly ash (FA), sodium silicate (Na_2SiO_3) solution, sodium hydroxide (NaOH) solution, and two different types of RA viz., crushed structural concrete member (RC) and crushed clay brick (RB). The results were also compared with those of natural coarse aggregate (NA). Compressive strength, splitting tensile strength, total void ratio, and water permeability coefficient of the PGCs were determined. The results indicate that both RC and RB can be used as recycled coarse aggregates for making PGC with acceptable properties.

Mix Design Development for Pervious Concrete in Cold Weather Climates
Schaefer, V. R., Wang, K., Suleiman, M., and Kevern, J. T.
Recent stormwater management regulations from the Environmental Protection Agency (EPA) and greater emphasis on sustainable development has increased interest in pervious pavement as a method for reducing stormwater runoff and improving stormwater quality. Pervious concrete is one of several pervious pavement systems that can be used to reduce stormwater runoff and treat stormwater on site. Pervious concrete systems have been used and are being proposed for all parts of the United States, including northern climates where severe freezing and thawing can occur. The purpose of the research is to develop pervious concrete mixtures that have sufficient porosity for stormwater infiltration along with desirable porosity, strength, and freeze-thaw durability.

Performance Comparison of Laboratory and Field Produced Pervious Concrete Mixtures
Shu, X., Huang, B., Wu, H., Dong, Q., and Burdette, E. G.
Portland cement pervious concrete (PCPC) is an environmentally friendly paving material that has been increasingly used in parking lots as well as low volume and low speed pavements. Although specifications are available for the mix design and construction of pervious concrete, there still remains a need for laboratory tests to ensure the anticipated performance of laboratory designed pervious concrete. In this study, the performance of laboratory and field produced pervious concrete mixtures as well as field cores were evaluated and compared through laboratory performance tests, including air voids, permeability, compressive and split tensile strengths, as well as Cantabro and freeze–thaw durability tests.

An Integrated Study of Pervious Concrete Mixture Design for Wearing Course Applications
Schaefer, V. R., Kevern, J. T., and Wang, K.
This report presents the results of the largest and most comprehensive study to date on portland cement pervious concrete (PCPC). It is designed to be widely accessible and easily applied by designers, producers, contractors, and owners. Consequently, the chapters are all

written as standalone documents and may be read and understood individually. The project was designed to begin with pervious concrete best practices and then to address the unanswered questions in a systematic fashion to allow a successful overlay project. Consequently, the first portion of the integrated project involved a combination of fundamental material property investigations, test method development, and addressing constructability issues before actual construction could take place. The second portion of the project involved actual construction and long-term testing before reporting successes, failures, and lessons learned. *This report is available for download from www.rmc-foundation.org.*

Hitting the Mark

Kevern, J. T. and Montgomery, J.

Pervious concrete mixtures are generally proportioned to have 15 to 25% air void contents to ensure adequate infiltration rates and strength. New ASTM standards for determining density and void content as well as infiltration rate were recently used as part of the quality assurance program for the construction of a parking lot in Omaha, NE. Test placements were used to develop a compaction-density relationship for test samples, and this was correlated to the void contents of pavement samples. Workability tests and unit weight tests were used to screen 0loads to ensure that concrete was workable and could be consolidated to achieve a target air void content. Test cores taken after the pavement hardened showed that the quality assurance testing program was successful.

Mixture Proportion Development and Performance Evaluation of Pervious Concrete for Overlay Applications

Kevern, J. T., Schaefer, V. R., and Wang, K.

This paper describes the results of studies to develop pervious concrete for use as an overlay material over traditional concrete to reduce noise, minimize splash and spray, and improve friction as a surface wearing course. Workability and compaction density testing methods were developed to ensure constructability and placement consistency. The mixture testing matrix consisted of evaluating aggregate type and gradation, cementitious material amounts and composition, and various admixtures. Selected mixtures were tested for permeability, strength, workability, overlay bond strength, and freezing-and-thawing durability. The selected mixture was self-consolidating and slip-formable and was placed at the MnROAD testing facility during late October 2008. The test results indicate that pervious concrete mixtures can be designed to be highly workable, sufficiently strong, permeable, and have excellent freezing-and-thawing durability, thus being suitable for pavement overlays.

Laboratory Study of Porous Concrete for its Use as Top Layer of Concrete Pavements

Onstenk, E., Aguado, A., Eickschen, E., and Josa, A.

The main objective of this study is to optimize the composition of porous concrete with respect to strength, acoustic properties, drainage and durability and costs comparable to porous asphalt. The main parts of the work is summarized in optimization of mixtures and testing on those mixtures that showed advantages in several areas.

Effect of Aggregate Size and Gradation on Pervious Concrete Mixtures

Neptune, A. I. and Putman, B. J.

The purpose of this research was to determine the effects of aggregate size and gradation on the unit weight, strength, porosity, and permeability of pervious concrete mixtures. The water-cement ratio (w/c) and cement-aggregate ratio (c/a) were kept constant at 0.29 and 0.22, respectively, with a design unit weight of 2002 kg/m3 (125 lb/ft3). Fifteen different aggregate gradations were tested and categorized according to nominal maximum aggregate sizes (NMASs) of 9.5, 12.5, and 19.0 mm (0.38, 0.49, and 0.75 in.) and had a range of uniformity coefficients Cu. The results indicated that as the porosity increased, strength decreased and permeability increased.

Chemical Admixture System for Pervious Concrete
Koehler, E., Offenberg, M., Malone, J., and Jeknavorian, A. A.
Pervious concrete contains a high void content to allow the passage of water and is often used in pavements to reduce storm water runoff and ponding, improve water quality, and recharge groundwater. Successful pervious concrete for pavement applications must be quickly discharged from a ready mixed concrete truck, achieve consistent compaction without paste draining to the bottom of the pavement, allow sufficient time before the application of curing, and achieve adequate strength and durability. Obtaining these properties requires unique paste rheology and setting characteristics, which are enabled through the proper selection of chemical admixtures. In this paper, novel lab tests are used to quantify the effects of individual admixtures; namely a retarder, polycarboxylate-based high-range waterreducer, and bio-gum type viscosity modifying admixture. The benefits of using a combination of these three admixtures are demonstrated.

Development of Mix Proportion for Functional and Durable Pervious Concrete
Wang, K., Schaefer, V. R., Kevern, J. T., and Suleiman, M. T.
Pervious concrete mixes made with various types and amounts of aggregates, cementitious materials, and chemical admixtures were evaluated, and the effects of the mix proportions on the concrete porosity, water permeability, strength, and freezing-thawing durability were studied. Based on results, performance-based criteria are proposed for proportioning functional and durable pervious concrete mixes.

Practical Application of Pervious Concrete: Mix Designs That Are Workable
Blackburn, R.
This power point focuses on the development of a practical pervious concrete mix designs that are workable for placement by hand and machine with an emphasis on compaction. The effect of compaction on porosity and 28 day flexural strength are presented.

Making Pervious Concrete Placement Easy Using a Novel Admixture System
Bury, M., Mawby, C., and Fisher, D.
Through laboratory and field testing, an admixture system (consisting of a polycarboxylate-based water-reducer, cement hydration controlling admixture, and viscosity-modifying admixture) has been developed to improve workability. This paper will offer a description of the chemical admixtures used to improve the mixing, handling, and performance of pervious concrete. Test data will be presented, along with two test methods used to evaluate the performance of pervious concrete.

Fiber-Reinforced Pervious Pavement
Moody, G.
Polypropylene fibers are proposed as shrinkage and thermal reinforcement for pervious concrete in this presentation. Flexural testing of fiber reinforced pervious concrete in accordance with ASTM C 1399 showed that polypropylene fibers can attain residual flexural strength equal to temperature and shrinkage reinforcement. The addition of fibers was found to increase the spacing of the coarse aggregates, thus increasing the void content. The addition

of sand allowed for adjustment of the void content and to maintain the desired compressive strength.

Proportioning No-Fines Concrete
Jain, O. P.
No-fines concrete has great potentiality as a substitute for brick masonry in places where good brick is not available, especially if a large number of residential blocks of houses is to be constructed. The present investigation was undertaken in order to evolve a rational method of design of mixes for no-fines concrete for a required strength. The proposed method takes into account all the relevant properties of cement and aggregate. No-fines concrete can be produced with reasonable assurance about its strength and can be employed as a building material with confidence.

Aggregate Effects on Pervious Portland Cement Concrete Static Modulus of Elasticity
Crouch, L. K., Pitt, J., and Hewitt, R.
The effects of aggregate gradation, amount, and size on pervious portland cement concrete (PCC) static modulus of elasticity were compared using four different mixtures. A standard mix and three variable mixes using a uniform gradation, increased aggregate amount, and increased aggregate size were used. The effective air void content was determined for each mixture. The compressive strengths and static elastic moduli were determined and compared at equal void contents. For a uniform gradation, the compressive strengths and static elastic moduli appeared to be higher within an optimal range of voids; however, there was no statistically significant difference between the results from the different gradations. An increased aggregate amount resulted in a statistically significant decrease in both compressive strength and static elastic moduli due to the subsequent decrease in paste amount. While the compressive strengths were higher for mixtures containing smaller aggregate sizes, there was no significant difference between the static elastic moduli when different aggregate sizes were used. Further research is needed to understand the effects of aggregate size on the static modulus of elasticity of pervious PCC.

Mix, Forms, and Admixtures
Wolfersberger, C.
Pervious mixture suppliers must employ high quality control. Pervious mixes contain Portland cement, a nominal 3/8" or larger, Florida limerock aggregate, admixtures and minimum water as designed. In some locations, granite may be substituted. Almost all fine aggregate is eliminated from the mix to provide the necessary voids to allow the penetration of water. Typically pervious concrete has about 70% of the density of standard concrete paving mixtures.

SPECIFICATIONS AND TEST METHODS

522.1-13: Specification for Pervious Concrete Pavement
ACI Committee 522
This Specification covers materials, preparation, forming, placing, finishing, jointing, curing, and quality control of pervious concrete pavement. Provisions governing testing, evaluation, and acceptance of pervious concrete pavement are included.

This Reference Specification can be made applicable by citing it in the Project Specifications. The Architect/Engineer can supplement this reference specification, as needed, by specifying individual project requirements.

Development of a Test Method for Assessing the Potential Raveling Resistance of Pervious Concrete Pavements
Offenberg, M.
One of the key concerns with pervious concrete is the material's surface durability, specifically resistance to raveling. As the market for pervious concrete grew, this was one of the hurdles to broader adoption of the technology. This paper documents the process of developing a test method to determine the potential raveling resistance of a pervious concrete mixture. The process included a study with lab cast cylinders to compare the raveling resistance potential of pervious concrete mixtures using different aggregates, varying cement contents, and basic chemical admixtures. A refined procedure of the test method was developed after an unsuccessful ASTM round robin evaluation. The results from this new method will provide the industry with beginning correlations between basic mix ingredients and the surface durability of a finished pervious concrete pavement.

Development of High Quality Pervious Concrete Specifications for Maryland Conditions
Amde, A. M. and Rogge, S.
The study utilized aggregates that are used in SHA projects and the durability studies assumed Maryland weather conditions. Investigations were conducted to enhance the structural and durability characteristics of pervious concrete through the use of different admixtures. The admixtures included cellulose fibers, a delayed set modifier and a viscosity modifier. Pervious concrete specimens were tested for density, void content, compressive strength, split tensile strength, permeability, freeze- thaw durability, and abrasion resistance

Handbook for Pervious Concrete Certification in Greater Kansas City
Pervious Concrete Certification Program
Pervious Concrete is a specialty concrete used to allow water to intentionally pass through the surface of a pavement and allow stormwater to eventually absorb back into the surrounding soils or evaporate. This keeps runoff water from downstream urban flooding and erosion. It also breaks the cycle of water treatment plants needing to treat stormwater where municipalities have combined sewer and stormwater systems. Pervious concrete pavements are “best management practices” (BMP’s) to collect, clean and cool stormwater. This usually eliminates the need for detention/retention ponds, thus reducing construction expenses, safety issues, and maintenance costs.

Specifier’s Guide for Pervious Concrete Pavement Design Version 1.2
Colorado Ready Mixed Concrete Association
Pervious concrete pavement does not look or behave like conventional concrete pavement. The finished surface is not tight and uniform, but is open and varied, to admit large quantities of stormwater. Surface irregularities and minor amounts of surface raveling are normal. Traditional concrete testing procedures for slump are not applicable to this type of concrete. Instead, standard test methods identified in this guide are used to test for density (unit weight), void content, compressive strength, and thickness. This assures a durable, drainable pavement.

Predicting the Permeability of Pervious Concrete

Neithalath, N., Bentz, D. P., and Sumanasooriya, M. S.

The fundamental material characteristic that makes pervious concrete a sustainable material is its open pore structure. Characterization of the pore structure thus becomes important in the evaluation and prediction of pervious concrete performance. This article provides details on methods for characterizing pore structure features such as porosity, pore size, and pore connectivity and how to use these features to predict the performance of pervious concrete.

Pervious Concrete: Compaction and Aggregate Gradation

Mahboub, K. C., Canler, J., Rathbone, R., Robl, T., and Davis, B.

Pervious concrete is very different from traditional portland cement concrete (PCC). Therefore, there are open questions regarding the suitability of the current standard concrete testing protocols as they may be applied to pervious concrete. There are unique features associated with pervious concrete that may require special testing considerations. This paper examines the compaction and consolidation of pervious concrete. This study presents cylindrical specimen preparation techniques that will produce laboratory specimens that are similar to the field pervious concrete slab. Additionally, a simple correlation is provided that allows concrete designers to estimate the porosity of pervious concrete based on its aggregate bulk density when crushed limestone is used. This practical tool saves time when designing pervious concrete mixtures.

Virtual Pervious Concrete: Microstructure, Percolation, and Permeability

Bentz, D. P.

As the usage of pervious concrete continues to increase dramatically, a better understanding of the linkages between microstructure, transport properties, and durability will assist suppliers in mixture proportioning and design. This paper presents various virtual pervious concrete microstructural models and compares their percolation characteristics and computed transport properties to those of real world pervious concretes. Of the various virtual pervious concretes explored in this study, one based on a correlation filter three-dimensional reconstruction algorithm clearly provides a void structure closest to that achieved in real pervious concretes. Extensions to durability issues, such as freezing-and-thawing resistance and clogging, that use further analysis of the virtual pervious concrete's void structure are introduced.

Planar Image-Based Reconstruction of Pervious Concrete Pore Structure and Permeability Prediction

Sumanasooriya, M. S., Bentz, D. P., and Neithalath, N.

Transport properties of porous materials such as pervious concretes are inherently dependent on a variety of pore structure features. Empirical equations are typically used to relate the pore structure of a porous material to its permeability. In this study, a computational procedure is employed to predict the permeability of 12 different pervious concrete mixtures from three-dimensional (3D) material structures reconstructed from starting planar images of the original material. The 3D reconstruction process provides a relatively inexpensive method (instead of methods such as X-ray tomography) to explore the nature of the pore space in pervious concretes and predict permeability, thus facilitating its use in understanding the changes in pore structure as a result of changes in mixture proportions.

Comparison of test specimen preparation techniques for pervious concrete pavements
Putman, B. J. and Neptune, A. I.
The objective of this study was to evaluate different pervious concrete test specimen preparation techniques in an effort to produce specimens having properties similar to in-place pervious concrete pavement. Cylinders and slabs were cast using pervious concrete from three different paving projects using different procedures. The comparisons of cast specimens to pavement cores were based on infiltration rate, density, and porosity. Of the cylinder consolidation procedures tested, the standard Proctor hammer provided the least variability of results and yielded properties similar to the in-place pavement. However, 600 mm square slabs were even more consistent with the in-place pavement density and porosity.

Characterizing Enhanced Porosity Concrete Using Electrical Impedance to Predict Acoustic and Hydraulic Performance
Neithalath, N., Weiss, J., and Olek, J.
This paper presents a unique non-destructive method to determine the permeability of pervious concrete from electrical conductivity measurements. Combining the normalized electrical conductivity of pervious concrete determined using either alternating or direct currents with the porosity of the material, and applying it in a modified version of Kozeny-Carman equation, a new parameter called hydraulic connectivity factor is introduced. Using this factor, and the porosity, the hydraulic conductivity or permeability of pervious concrete is determined.

Determining Pervious PCC Permeability with a Simple Triaxial Flexible-Wall Constant Head Permeameter
Crouch, L. K., Smith, N., Walker, A. C., Dunn, T. R., and Sparkman, A.
A simple triaxial flexible-wall constant head permeameter was constructed for determining the permeability of pervious concrete in the range of 0.001 to 10 cm/sec (1 to 14,000 inches/hour). Laboratory samples using three different gradations of crushed limestone and two different gradations of creek gravel were compacted at six different compactive efforts using a consistent pervious concrete mixture design. The effective air void content and constant head permeability of both the field and laboratory pervious concrete mixtures was determined.

Effectively Estimating In-situ Porosity of Pervious Concrete from Cores
Haselbach, L. M., and Freeman, R. M.
Pervious concrete is an alternative pavement material which may help reduce nonpoint source pollution problems. The porosity of pervious concrete is an important parameter used for both pavement and environmental design and is dependent on field placement techniques. It is recommended that porosity be tested on field-placed specimens. It has been noted that some of the concrete is knocked out while coring from field-placed samples which may affect the porosity. This paper researches a methodology for estimating the in-situ porosity of pervious concrete from the porosities of cores taken from the field based on aggregate size, core size and porosity.

Certification, What Does it Mean?
Wolfersberger, C.
Due to the recent increase in interest in pervious concrete including EPA listing it as a BMP (Best Management Practice) for managing stormwater and recycling it into the aquifer, the shortage of qualified pervious installers has become obvious. Many industry associations, tool

and admixture providers are trying to remedy the problem by establishing training programs to teach concrete installers how to install pervious concrete.

Concrete Solutions for Sustainable Growth
Wolfersberger, C.
The world's population will continue to increase to about 6.9 billion by 2010! Developing countries will build more factories and homes. Their people will drive more vehicles and need more roads and parking lots. In the U.S. the number of vehicles registered increased to 226 million in 2006 (Source U.S. Census Bureau). More vehicles and roads mean more greenhouse gasses and atmospheric warming. Our planet, our country and our neighborhoods will feel the impact. The Census Bureau explains that for every 5 new cars registered, an area the size of a football field gets paved.

Predicting the Permeability of Pervious Concrete (Enhanced Porosity Concrete) from Non-Destructive Electrical Measurements
Neithalath, N., Weiss, J., and Olek, J.
The effectiveness of a pervious concrete pavement to transport water through it depends on the intrinsic permeability of the system. However, this characteristic is usually defined in terms of the porosity of the material. It has been observed that porosity alone is an inadequate indicator of the permeability of pervious concretes, since the permeability depends on pore sizes, geometry and connectivity also. This paper presents a unique non-destructive method to determine the permeability of pervious concrete from electrical conductivity measurements.

Pervious Concrete Specifications
Wolfersberger, C.
This specification is designed to become the central focus to define and regulate the Pervious Concrete work to be performed on a related job contract. It is designed as a description of work and the protocol to be observed by all involved in its installation. It is intended to be for the benefit of all involved, i.e., owners, architects, engineers, inspectors, suppliers, contractors and subcontractors. Since many ASTM, DOT and AASHTO standards often form a significant part of the contract documents and this specification, it is imperative that not only the Pervious Concrete Contractor, but the Ready-mix supplier, cement suppliers, aggregate suppliers, admixture suppliers and any other vendors or subcontractors, as well as any Architects, Engineers or Owner’s Agents be thoroughly familiar with this specification.

City of Olympia Specifications for Pervious Concrete Sidewalks
City of Olympia
This document gives a set of specifications applying to the construction of pervious concrete sidewalks, made of Portland cement, aggregate, water, and other approved admixtures. It gives other agencies and opportunity to specify sidewalks with a document for reference.

Pervious Concrete Certification Program
National Ready Mixed Concrete Association
The goal of this certification program, administered by the National Ready Mixed Concrete Association, is to ensure that knowledgeable contractors are selected to place the product and thereby minimize the chance for failure. Development of the Text Reference for the Pervious Concrete Certification program was funded by the RMC Research & Education Foundation.

K C Materials Lab Specifications on a Pervious Concrete Mix
Seattle Public Utilities
The work of this section includes subgrade preparation and installation of portland cement pervious pavement structures (i.e. porous concrete sidewalks). It conforms to applicable requirements the 2000 Seattle specifications as well as ASTM and AASHTO.

STRUCTURAL DESIGN AND PROPERTIES

Cellular concrete properties and the effect of synthetic and protein foaming agents
Panesar, D. K.
Cellular concrete consists of cement, water, aggregate and air voids. Cellular concrete can have between 10% and 70% air, which results in a material that is lightweight but may compromise the compressive strength and durability properties. Although it has been shown in the literature that less connected air voids yield a lower reduction in compressive strength, few studies have reported a detailed characterization of the microstructure of cellular concrete. It is critical to understand the impact of the microstructure and its implications on the development of strength, elastic modulus and transport properties in order to fully benefit from the lightweight properties, and this is the focus of this paper.

A mathematical model for complete stress-strain curve prediction of permeable concrete
Hussin, M. K., Zhuge, Y., Bullen F., and Lokuge, W. P.
An empirical equation to represent the complete stress-strain behaviour for unconfined permeable concrete with compressive strength ranging between 10-35MPa and porosity ranging between 25-15%, made with different combinations of aggregate size and sand ratios is proposed in this paper. A series of compression tests were conducted on 100 × 200 mm cylindrical samples using a modified testing method to determine the complete stress-strain behaviour of permeable concrete. Various existing models for low strength concrete and normal strength concrete were used and compared with the experimental data. Various parameters were studied and their relationships were experimentally determined. The only parameters need to run the model is the ultimate compressive strength and the density. The proposed empirical stress-strain equations were compared with actual cylinder tests results under axial compression, and demonstrated that the present model gives a good representation of the mean behavior of the actual stress-strain response.

Frost Damage Mechanism and Durable Pervious Concrete Design
Yang, Z.
One of the key concerns with pervious concrete is the material’s surface durability, specifically resistance to raveling. As the market for pervious concrete grew, this was one of the hurdles to broader adoption of the technology. This paper documents the process of developing a test method to determine the potential raveling resistance of a pervious concrete mixture. The process included a study with lab cast cylinders to compare the raveling resistance potential of pervious concrete mixtures using different aggregates, varying cement contents, and basic chemical admixtures. A refined procedure of the test method was developed after an unsuccessful ASTM round robin evaluation. The results from this new method will provide the industry with beginning correlations between basic mix ingredients and the surface durability of a finished pervious concrete pavement.

Strength, fracture and fatigue of pervious concrete

Chen, Y., Wang, K., Wang, X., and Zhou, W.

Pervious concrete is increasingly used in the pavements and overlays subjected to heavy traffic and in cold weather regions. In the present study, strength, fracture toughness and fatigue life of two types of pervious concrete, supplementary cementitious material (SCM)-modified pervious concrete (SPC) and polymer-modified pervious concrete (PPC), are investigated. The results indicate that high strength pervious concrete (32–46 MPa at 28 days depending upon the porosity) can be achieved through both SCM-modification, using silica fume (SF) and superplasticizer (SP), and polymer-modification, using polymer SJ-601. For both SPC and PPC, porosity significantly affects compressive strength, but it has little effect on the rate of strength development. Flexural strength of pervious concrete is more sensitive to porosity than compressive strength. Pervious concrete has more significant size effect than conventional concrete. PPC demonstrates much higher fracture toughness and far longer fatigue life than SPC at any stress level.

Structural Evaluation of Pervious Concrete in Pavement Test Sections

Armaghani, J.

An evaluation was made of the structural capacity of pervious concrete pavement on three base types including, virgin aggregate, recycled concrete aggregate, and Cellular Lightweight Permeable Concrete (CLPC). The objective was to determine the structural capability of pervious pavement to handle moderate truck traffic on city streets and low volume roads. Structural testing was performed using the Falling Weight Deflectometer (FWD). The FWD tests were performed on five pervious pavement test sections representing the three base types. Tests were also performed on a conventional concrete (PCC) pavement with stabilized base and results were used as a reference for structural capacity assessment of the pervious sections. The maximum FWD deflections and the deflection profiles of the different pavements sections were analyzed by comparing the deflection data among the various sections and the conventional concrete pavement. Results of the evaluation indicated that the pervious concrete pavement on CLPC has equal structural capacity to that of the previous concrete on aggregate base, and a higher structural capacity to that on recycled concrete base. The results also showed that the structural capacity of pervious concrete is adequate to handle moderate truck traffic on streets and low volume roads.

Porous Pavements Q&A

Ferguson, B.

As the use of porous pavements grows, designers and agencies all over North America are learning for the first time this new approach to stormwater management. People like me have been asked to speak to them hundreds of times in the last five years, in workshops, webinars, consulting sessions, and agency testimonies and reviews. The questions that are raised from all the diverse groups have a lot in common.

Developing a Structural Design Method for Pervious Concrete Pavement

Delatte, N.

This paper will review the current state of the practice on structural design of pervious concrete pavements, and outline a methodology for moving forward to develop a new, more appropriate structural design method. Design methods should identify the failure mechanisms for pervious concrete pavements, as well as the layer properties and thickness and joint detailing necessary to prevent failure.

Estimating Pervious PCC Pavement Design Inputs with Compressive Strength and Effective Void Content
Crouch, L. K., Sparkman, A., Dunn, T. R., Hewitt, R., Mittlesteadt, W., Byard, B., and Pitt, J.
This study uses a two-fold approach to obtain information on pervious concrete static modulus of elasticity (ASTM C 469), split tensile strength (ASTM C 496) and flexural strength (ASTM C 78). In the first approach existing correlations for normal concrete were applied to pervious concrete field and laboratory data. Secondly, the impact of effective void content on these properties was determined.

Pervious Concrete Pavement – How Important is Compressive Strength?
Marks, A.
As asphalt becomes more expensive and in short supply, and as the need to manage stormwater runoff increases, designers must revisit old assumptions and take a fresh look at how pavements need to work in a sustainable environment, and how to design and specify for them. Pervious pavements are a recent addition to the list of viable paving options, but as yet, there have been few ways to design them and to effectively predict their performance. This article offers some help to accomplish those tasks.

Laboratory and Analytical Study of Permeability and Strength Properties of Pervious Concrete
Huang, B., Cao, J., Chen, X., and Shu, X.
This paper presents a study in which the effects of aggregate gradations on the permeability and mechanical properties of pervious concrete were investigated. Pervious concrete with three aggregate gradations were characterized through laboratory tests. Air voids distributions were evaluated through image analysis. Theoretical and laboratory methods were employed to evaluate the permeability properties of the concrete mixtures. The mechanical properties of the concrete mixtures were characterized through the modulus of elasticity, compressive and split tensile strength tests.

Analysis of the Behavior of Filtration vs. Compressive Strength Ratio in Pervious Concrete
Flores, J. J., Martinez, B., and Uribe, R.
This paper characterizes different mixture designs using a proposed test that measures the filtering capabilities in relation to compressive and flexural strengths. The tests analyze the individual and accumulated influence of different factors that take part in the filterable concrete design, such as cement content, the addition of different percentages of sand, or the use of additives that modify the fresh-state properties.

Pervious Concrete Durability Testing
Erickson, S.
This paper presents results of a full-scale accelerated load test on a driveway into an aggregate and ready mix plant in Oregon. The trucks are 5-axle concrete mixers with a legal capacity of 70,500 pounds and 8 axle dump truck and trailer combinations with a legal capacity of 105,500 pounds. The pavement is divided in multiple test areas that range from four inch to ten-inch thick sections of pavement on an engineered base.

Compressive Strength of Pervious Concrete Pavements
Wanielista, M., Chopra, M., and Mulligan, A.M.
The pervious concrete system and its corresponding strength are as important as its permeability characteristics. The strength of the system not only relies on the compressive strength of the pervious concrete but also on the strength of the soil beneath it for support. Previous studies indicate that pervious concrete has lower compressive strength capabilities than conventional concrete and will only support light traffic loadings. This project conducted experimental studies on the compressive strength on pervious concrete as it related to water-cement ratio, aggregate-cement ratio, aggregate size, and compaction. *This report is available for download from www.rmc-foundation.org.*

Strength Measurements of Field-Placed Pervious Concrete
Haselbach, L. M., Pierce, C. E., Pulis, K. S., Montes, F., and Valavala, S.
Pervious concrete is an alternative paving surface with potential environmental benefits such as reduced stormwater runoff. There is a need for correlations between its environmental characteristics such as porosity and load-bearing properties such as strength so that designers can specify the product for multiple purposes. This paper evaluates several mechanical properties of two representative field-placed pervious concrete slabs, one produced with a low-porosity (P<20%) mixture and the other with a high-porosity (P>25%) mixture.

Experimental Study on Properties of Pervious Concrete Pavement Materials
Yang, J. and Jiang, G.
In this paper, a pervious concrete pavement material used for roadway is introduced. Using the common material and method, the strength of the pervious concrete is low. Using smaller sized aggregate, silica fume (SF), and superplasticizer (SP) in the pervious concrete can enhance the strength of pervious concrete greatly. The pervious pavement materials that composed of a surface layer and a base layer were made. The compressive strength of the composite can reach 50 MPa and the flexural strength 6 MPa. The water penetration, abrasion resistance, and freezing and thawing durability of the materials are also very good. It can be applied to both the footpath and the vehicle road. It is an environment-friendly pavement material.

Attainable Compressive Strength of Pervious Concrete Paving Systems
Mulligan, A. M.
The pervious concrete system and its corresponding strength are as important as its permeability characteristics. The strength of the system not only relies on the compressive strength of the pervious concrete but also on the strength of the soil beneath it for support. Previous studies indicate that pervious concrete has lower compressive strength capabilities than conventional concrete and will only support light traffic loadings. This thesis investigated prior studies on the compressive strength on pervious concrete as it relates to water-cement ratio, aggregate-cement ratio, aggregate size, and compaction and compares those results with results obtained in laboratory experiments conducted on samples of pervious concrete cylinders created for this purpose.

Laboratory Investigation of Compacted No-Fines Concrete for Paving Materials
Ghafoori, N. and Dutta, S.
In this study the physical and engineering characteristics of various no-fines concrete mixtures are investigated. No-fines concrete mixtures subjected to impact compaction are studied under unconfined compression, indirect tension, and static modulus of elasticity; and the

results are interpreted as functions of mix proportions. The effect of impact-compaction energies, consolidation techniques, mixture proportions, curing types, and testing conditions on physical and engineering properties are presented.

Structural Design of Permeable Pavements Worksheet
Craven County, NC
This 12 page document is dedicated to the four key elements to the structural design of permeable pavements: Total Traffic; In Situ Soil Strength: Environmental Elements; Actual Layer Design. A few examples from the eastern North Carolina market are used for structural examples.

Pervious Concrete Pavement: A Solution for Sustainable Communities
Davy, M.
In recent years, the development community, permitting agencies, engineers, and owners have been seeking out new and innovative ways to reduce stormwater runoff and build low-impact, sustainable communities. One of the “new and innovative” ways that assist in these efforts just might be a product that has actually been around for some time—pervious concrete.

Structural Design Considerations
National Ready Mixed Concrete Association
This section provides guidelines for the structural design of pervious concrete pavements. Procedures described provide a rational basis for analysis of known data and offer methods to determine the structural thickness of pervious concrete pavements. Pervious concrete is a unique material that has a matrix and behavior characteristics unlike conventional portland cement concrete or other pavement materials. Although these characteristics differ from conventional concretes, they are predictable and measurable. Projects with good to excellent performance over service lives of 20 to 30 years provide a great deal of empirical evidence related to material properties, acceptable subgrades, and construction procedures. Laboratory research in these areas has only recently begun.

Internal Curing Improves Flexural and Compressive Strength of Pervious Concrete
Roberts, J. and Vaughn, R.
The EPA’s successful installation at Edison, NJ of a pervious parking area triggered a test by Northeast Solite Corporation to ascertain the optimum amount of internal curing agents to use in order to materially improve the integrity of normal weight concrete pervious pavements. In order to reduce the raveling and increase the strength of the concrete, it was felt that internal curing of the concrete slab could add to the external curing with plastic that is the present standard curing method of certified pervious pavements. The amount of absorbent lightweight aggregate sand (LWAS) to replace some of the normal weight sand in the concrete mix has been known through research and constructed applications. Poured-in-place structural concrete, because of the need to address chemical and autogenous shrinkage and cracking, has relied on the Bentz et al formula (Concrete International, Feb 2005). This formula does not apply to pervious concrete. The internally cured sections did not receive poly protection or any special curing, other than internal. The 100 pound replacement of natural sand was found to be the optimum amount. The use of LWAS improved the flexural strength by 150% and the compressive strength by 200%. The LWAS used was preconditioned and meets ASTM C330 and C33 (except for gradation). Replacements were 50, 100, and 150 pounds of LWAS per

cubic yard, and only the control slab received standard curing with a 6 mil poly covering for 14 days [1]

Pervious Concrete Test Cells on MnROAD Low-Volume Road
Izevbekhai, B.
Local agencies are interested in pervious pavements ability to reduce storm water runoff by allowing direct infiltration through the pavement structure. However, concerns about the ability of pervious pavements to perform in Minnesota's extreme climate, maintenance needs, and effect on groundwater quality needed to be understood. This report includes the design, construction, and early performance of three pervious concrete test cells construction at MnROAD in 2008. These cells were constructed to evaluate the performance of pervious concrete pavements on a low-volume road in a cold weather climate. The three cells discussed in this report are as follows: porous concrete overlay, pervious concrete on granular subgrade, pervious concrete on cohesive subgrade. This report has the following chapters, which uniquely discuss each phase of this project: research synthesis; mix design, concept design, and geotechnical exploration; construction sequence; initial testing; hydrologic evaluation; early two year performance; implementation; effect of sound absorption on OBSI; and acoustic properties of clogged pavements.

Additional Resources

The following links provide additional information and resources related to pervious concrete:

http://www.perviouspavement.org/

http://www.concretethinker.com/applications/Pervious-Paving.aspx

http://www.pervious.info/

http://www.concretenetwork.com/pervious/

http://www.nrmca.org/aboutconcrete/cips/38p.pdf

http://www.astm.org/

Pervious Concrete Contractor Certification Information

Final Note: If you are aware of additional pervious concrete research or resources that were not included in this document, please e-mail the pertinent information or web link to Julie Garbini or Jennifer LeFevre at jgarbini@rmc-foundation.org or jlefevre@rmc-foundation.org, respectively. Special thanks to MTSU CIM intern, Shannon Allen, for her assistance in updating this document in 2012 and to Shaina Dunn and John Fultz (NSF REU students) for updating it in summer 2013.