The RMC Research & Education Foundation Presents:

Pervious Concrete Research Compilation:
Past, Present and Future

Updated October 2011

Compiled by:
Dr. Heather J. Brown
Concrete Industry Management Program
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RMC RESEARCH & EDUCATION FOUNDATION

CONCRETE INDUSTRY MANAGEMENT

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Research Categories

Applications and Case Studies

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., PCA and NRMCA
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
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
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
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

Low-Impact Development: A Modular Approach to Urban Retrofit Projects
Seeres, D. J.
As a municipal engineer, I've learned that everything is not as clear-cut as I would like it to be. There are so many variables that must be considered when looking at the feasibility of a project. I have worked as a municipal engineer for approximately 10 years and have had the opportunity to work in a city that is changing on a daily basis. As I progressed in my career, I migrated toward what I view as the most challenging and dynamic area of concentration: urban stormwater management. As a result, I've decided to write this article to share ideas and concepts with other professionals who can feel the same excitement as I do.

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

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.

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.
RMC Research & Education Foundation Funding, in cooperation with Rinker Materials and the Florida Department of Transportation
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 MN/Road 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., Cleveland State University
RMC Research & Education Foundation Funding
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.

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 dependant 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

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.

Reducing Impact
Beecham, T.
It's impossible for contractors to build sound structures on solid ground without soil disturbance. The particulates that can cause erosion onsite and can threaten water quality travel by way of dry soil meeting the air, vehicle tires, foot traffic, and water. As the EPA prepares to reissue its effluent limitation guidelines for construction sites, it's a good time to consider the impact a project will create well before putting pen to paper during the planning stages which may include the use of pervious concrete.

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 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.

Funding Stormwater Projects

The American Recovery and Reinvestment Act (ARRA) of 2009, aka the Stimulus Act, has provided funds for infrastructure projects in major cities and small cities all across the country. Those infrastructure projects include stormwater projects, with money channeled through the states' Clean Water Act and Safe Drinking Water Act State Revolving Funds. Some of the funding is in the form of 20-year, low-interest loans and some is loan forgiven—in effect, outright grants.

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.

RMC Research & Education Foundation Funding, in cooperation with Rinker Materials and the Florida Department of Transportation

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.

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., North Carolina State University
8th Biennial Conference on Stormwater Research & Watershed Management (Submitted)
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.

Measuring Hydraulic Conductivity in Pervious Concrete - Environmental Engineering Science. Nov 2006, Vol. 23, No. 6: 960-969 – *Link not available*
Montes, F., and Haselbach, L.
This presentation focuses on the hydraulic operations of a pervious concrete system including infiltration rates, storage capacity and clogging potential. A method of testing for the in situ infiltration rate of a pervious concrete system–an embedded single ring infiltrometer–has been developed and will be presented. The study consists of detailed analyses of several pervious concrete parking lots that have been in operation for 5 or more years.

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, 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.
RMC Research & Education Foundation Funding, in cooperation with Rinker Materials and the Florida Department of Transportation
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.

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.

A Field Study to Evaluate Permeable Pavement Surface Infiltration Rates, Runoff Quantity, Runoff Quality, and Exfiltrate Quality
Bean, E. Z.
The surface infiltration rates of 48 permeable pavement sites were tested in North Carolina, Maryland, Virginia, and Delaware. Two surface infiltration tests (pre- and post-maintenance) were performed on 15 concrete grid paver (CGP) lots filled with sand. Maintenance consisted of removing the top layer of residual material (13 - 19 mm (0.5 – 0.75 in)). Maintenance significantly ($p = 0.007$) improved the surface infiltration rate. The median site surface infiltration rate increased from 4.9 cm/h (1.9 in/h) for existing conditions to 8.6 cm/h after simulated maintenance.

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

Mix Design Development for Pervious Concrete in Cold Weather Climates
Kevern, J., Wang, K. and Schaefer, V.
PCA Funding
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. The link is to the Executive Summary that includes a brief summary of notable results from each chapter based on the project tasks. The final report is expected fall 2011.

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 loads 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.

Mix Design Development for Pervious Concrete in Cold Weather Climates
Schaefer, V. R., Wang, K., Suleiman, M. T., and Kevern, J. T.
Portland cement pervious concrete (PCPC) is being used more frequently due to its benefits in reducing the quantity of runoff water, improving water quality, enhancing pavement skid resistance during storm events by rapid drainage of water, and reducing pavement noise. In the United States, PCPC typically has high porosity and low strength, which has resulted in the limited use of pervious concrete, especially in hard wet freeze environments (e.g., the Midwestern and Northeastern United States and other parts of the world). Improving the strength and freeze-thaw durability of pervious concrete will allow an increase in its use in these regions.

Specifications and Test Methods

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
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.

522.1-08: 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 Project Specifications. The Architect/Engineer supplements this reference specification as needed by designating or specifying individual project requirements

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.

Measuring the Effective Air Void Content of Portland Cement Pervious Pavements - ASTM Journal of Cement, Concrete, and Aggregates, CCA, Vol. 25, No. 1, June 2003 – *Link not available*
The current literature indicates that air voids of Portland Cement Pervious Pavements (PCPP) should be 15–25%, to achieve desired permeability. However, there is no current AASHTO or ASTM test method to determine PCPP air voids. This study is an attempt to modify currently available hot-mix asphalt (HMA) air determination techniques for PCPP. The equation used to determine air voids in HMA is Percent Air Voids = $100(1 - G_{mb}/G_{mm})$. Where G_{mb} is the bulk specific gravity of the specimen and G_{mm} is the theoretical maximum specific gravity of loose HMA. Previous research on HMA cores at Tennessee Technological University (TTU) has shown the INSTROTEK CORELOK SYSTEM to be a most effective means of determining G_{mb} of a material with surface accessible voids.

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.

Recommended Specifications for Portland Cement Pervious Pavement

Carolinas Ready Mixed Concrete Association Inc.

Portland Cement Pervious Concrete Pavements have become increasingly popular as a method to meet water quality water run off regulations throughout the Carolinas. The most predominate use is found in driveways and parking area paving applications. This abbreviated specification is presented as a recommended guide for light traffic paving loading.

STRUCTURAL DESIGN AND PROPERTIES

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.

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. and Chopra, 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.

Strength Measurements of Field-Placed Pervious Concrete

Haselbach, L., Pierce, C., Pulis, K., 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
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.

SPECIAL PUBLICATIONS

These papers will be an ACI Special Publication “The Leading Edge of Pervious Concrete to be published in 2012

Brown, H.J., Measurement of TSS and Other Pollutant Removal by Pervious Concrete and Incorporation of Results into a Site Development Tool
Delatte, N., Field Performance of Portland Cement Pervious Concrete Pavement in Cold Weather Climates
Erickson, S., Architectural Pervious Concrete
Haselbach, L., The Declining pH of Waters Exfiltrated through Pervious Concrete

Kevern, J., Durability And Performance Of The Pervious Concrete Overlay At MnROAD
Neithalath, N., Models For Property Prediction Of Pervious Concretes
Offenberg, M., Development of a Test Method for Assessing the Potential Raveling Resistance of Pervious Concrete Pavements
Yang, Z., Frost Damage Mechanism and Durable Pervious Concrete Design

These papers will be part of ASTM Symposium on Pervious Concrete in December 2011

Enhancing Structural Performance of Pervious Concrete Rabin Tuladhar, James Cook University, Townsville, Queensland, Australia and Simon Nash, Department of Transport and Main Roads, Queensland, Australia

Performance of Pervious PCC by Field and Laboratory Testing, Including Void Structure, Unit Weight, Compressive and Flexural Strength Testing, William Denison, Titan America, Norfolk, VA, USA

Pervious Concretes Pore Structure Characterisation by 3D image analysis - Impact on their Permeability Samuel Meulenyzer, Eric Stora, Fabien Perez, Lafarge Centre de Recherche, Saint-Quentin Fallavier, France

More Information on ASTM C 1688 Variability L. K. Crouch, Ph.D., P.E. Tennessee Technological University, Cookeville, Tennessee, USA; John Hendrix, P.E. Tennessee Technological University, Cookeville, Tennessee, USA; Alan Sparkman, CAE, CCPf, LEED AP Tennessee Concrete Association, Nashville, Tennessee, USA; Daniel Badoe, Ph.D. Tennessee Technological University, Cookeville, Tennessee, USA

The Development, Implementation and Use of ASTM C1701 Field Infiltration of In Place Pervious Concrete Heather J. Brown, MTSU, Murfreesboro, TN, USA; Alan Sparkman, Tennessee Concrete Association, Nashville, TN, USA

Pervious Concrete for Use within the Plaza System Kevin D. Copeland, P.E., LEED AP, Wiss, Janney, Elstner Associates, Inc., Austin, TX, USA Tommy L. Lee, Wiss, Janney, Elstner Associates, Inc., Austin, Texas, USA

Pervious Concrete with Low Compactibility, Bruno Thibaut and Fabien Perez, Lafarge Centre de Recherche, Saint-Quentin Fallavier, France

Development of a Test Method to Determine the Raveling Potential of Pervious Concrete Matthew Offenberg, W.R. Grace, Canton, GA, USA

Potential Application of ASTM C1701 for Evaluating Surface Infiltration of Permeable Interlocking Concrete Pavements David R. Smith, MURPI, Interlocking Concrete Pavement Institute, Herndon, VA, USA; Kevin Earley, Nicolock Paving Stones, Collegeville, PA, USA; and Justin M. Lia, P.E., 4 Site Engineering, Port Jefferson Station, NY, USA

Improving the Aggregate to Cement Paste Bond Relationship in Pervious Concrete A. Brent Rollins, University of Tennessee at Chattanooga, Chattanooga, Tennessee, USA; Ariel P. Soriano PE, City of Chattanooga Engineering Department, Chattanooga, Tennessee, USA; Steven J. Wantling, Momentive Specialty Chemicals Inc, Hoover, Alabama, USA

University of New Hampshire Stormwater Center

The University of New Hampshire (UNH) Stormwater Center is dedicated to the protection through effective stormwater management. It conducts research to evaluate and enhance the performance of stormwater management systems. The center's evolving outreach program supports a wide range of stormwater managers who seek to build programs that protect water quality, preserve environmental values, and reduce the impact of stormwater runoff.

Presentations and Posters
Publications and Resources

International Concrete Sustainability Conference principally sponsored by the National Ready Mixed Concrete Association
The International Concrete Sustainability Conference provides learning and networking opportunities on the latest advances, technical knowledge, continuing research, tools and solutions for sustainable concrete manufacturing and construction. This link will provide information about past and upcoming conferences including proceedings, sponsors and exhibitors.

ADDITIONAL RESOURCES

The following links are from a websites dedicated to educating and explaining the fundamentals of using 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

LEED Reference Guide

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.