RMC Research & Education Foundation

Because the best can become better!

The RMC Research & Education Foundation Presents:

Pervious Concrete Research Compilation:

Past, Present and Future

Updated June 2008

Compiled by:
Dr. Heather J. Brown
Concrete Industry Management Program
Middle Tennessee State University

CONCRETE INDUSTRY MANAGEMENT

This page intentionally left blank.

Pervious Concrete Research Compilation
Past, Present and Future
Revised June 2008

Investigator: Dr. Heather J. Brown
Concrete Industry Management Program
Middle Tennessee State University

PLEASE NOTE: TO ACCESS THE LINKS INCLUDED WITH THIS DOCUMENT, YOU MUST BE CONNECTED TO THE INTERNET.

Research Categories

Additional Information

APPLICATIONS AND CASE STUDIES

Porous Pavements: The Overview
Ferguson, B. K., University of Georgia
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. F. and Schindler, A. K., Auburn University
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.

Case Study of a 10 Year-Old Subdivision with 200 Pervious Pavement Driveways
Amekuedi, G., Ready Mixed Concrete Company
This presentation highlights the performance of 200 pervious pavement driveways placed in 1995 in a residential subdivision.

The Use of Pervious Concrete at Wal-Mart
Pool, A. V., National Ready Mixed Concrete Association
This presentation highlights the use of pervious concrete at a number of Wal-Mart stores, including two environmental "experimental" Wal-Mart stores.

Pumped-in-Place Permeable Grout Systems, Permeation Grouting Bechtel Corporation Technical Grant, pp. 1-44, 2002
Yen, P. T., Sundaram, P. N., and Godwin, W. A.,
The technology of grout injection to provide structural support beneath foundations has been practiced in construction since 1802. The materials have traditionally been a mixture of portland cement, water and often a filler, such as sand. This is mixed as a slurry and pumped into the desired area, usually the interface between constructed foundations and the in situ soil or rock, forming a structural bond that is rigid and not normally pervious.

ACPA, Cement-Treated Permeable Base for Heavy-Traffic Concrete Pavements, IS404, 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, 2004 Pages 13 to 14
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 (CCPC 2003). (See Figures 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 - Journal of Materials in Civil Engineering, Volume 7, Number 4, November 1995b, pages 286 to 289
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 - Concrete International, American Concrete Institute, August 1988, pages 20 to 27.
Meininger, R. C.
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 - Special Report 89-12, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N. H., 20 pp, 1989
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.

Laboratory Study of Porous Concrete for its Use as Top Layer of Concrete Pavements - Proceedings of the Fifth International Conference on Concrete Pavement and Rehabilitation, Purdue University, Indiana, USA, 1993, Vol.2, pp. 125-139
Onstenk, E., Aguado, A., Eickschen, E., and Josa, A.
A laboratory study of porous concrete for its use as top layer of concrete pavements.

An Overview of Porous Pavement Research - Water Resources Bulletin. Vol. 18 no. 2, pp. 265-270, (1982a)
Field, R., Masters, H. and Singer, M.
This paper discusses the economics, advantages, potential applications, and status 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.

Status of Porous Pavement Research - Water Research Vol. 16 no. 6 pp. 849-858 June 1982, (1982b)
Field, R., Masters, H. and Singer, M.
This paper discusses the U.S. Environmental Protection Agency's porous pavement research program along with the economics, advantages, potential applications, and status 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 to reduce both stormwater runoff volume and pollution. In addition, groundwater recharge is enhanced.

Heavy Metal Retention Within A Porous Pavement Structure - Department of Civil Engineering, Urban Water Management, University of Essen, Universitaetsstrassee15, 45141 Essen, Germany
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. Porous pavement structures with four different subbase materials were tested in rigs.

Performance Assessment of Portland Cement Pervious Pavement Used as a Shoulder for an Interstate Rest Area Parking Lot - Stormwater Management Academy - University of Central Florida
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 Allows Water to Pass Through - ©2008 Portland Cement Association
Pervious concrete is made from carefully controlled amounts of water and cementitious materials used to create a paste that forms a thick coating around aggregate particles. Unlike conventional concrete, the mixture contains little or no sand, creating a substantial void content – between 15% to 25%.

Development of No-fines Concrete Pavement Applications - Journal of Transportation Engineering, Vol. 121, No. 3, May/ June 1995, pp. 283- 288
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.

Bellingham, WA, Case Study
A residential homebuilder was interested in sustainable construction and 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
Essentially, 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 Assists City of Sultan and Developer, Craig Morrison of CMI INC. - Elements: Sustainable Snohomish County, June 2006 Vol. II, Issue 5
O'dahl, C. A.
City of Sultan has pioneered pervious pavement in Snohomish County, WA. This groundbreaking project paves the way for pervious pavement as a proven technology to provide an alternative to traditional stormwater management on public streets.

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 – Courier, October 15, 2007
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.

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 - San Francisco Chronicle, December 2007
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
PCA Funded
Luck, J. D. and Workman, S., University of Kentucky
This project will demonstrate that pervious concrete can be used for solid/liquid waste separation and remediation in agricultural applications.

Permeable Concrete for Drainable Pavement Bases
Rapp, C. A.
Permeable concrete is gaining acceptance for use as a pavement base course. As shown in Figure 1, this material produces a finished base course that is highly porous but stable. These properties produce three benefits: 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. In this usage it reduces runoff by allowing water percolation but still prevents soil erosion.

Field Performance Investigation on Parking Lots
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.

Permeable Pavement Use and Research at Hannibal Parking Lot in Kinston, NC – NWQEP Notes
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.

Pervious Concrete - What, Why, & Where
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. When properly placed, pervious slabs will contain voids that would be filled by sand. Like a honeycomb these voids are held together with cement.

Pervious Concrete Pavement Permitting - Land Development Today. Dubuque, IA., August 2005, Vol. 1, No. 8, 2005
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. If you've never seen it before, it looks like pavement made out of a big, gray Rice Krispies treat. In technical terms, it is a concrete manufactured without fine aggregate. This creates a void structure in the concrete that allows stormwater to pass through at incredibly high rates — on the order of 500 inches per hour. As a developer, you're probably thinking and wondering how many wonderful ways you can use this on your new site. 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.

Construction Techniques

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., Sparkman, A., Tennessee Technological University
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., Iowa State University
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., Iowa State University
This paper describes the current state of practice in pervious concrete placement methods and presents results from a laboratory-based study to compare various placement practices and develop QA/QC criteria.

Pervious Concrete—The California Experience
Youngs, A., California Nevada Cement Promotion Council
Over the last two years, pervious concrete usage in California has grown to over 500,000 square feet annually. Unique delivery and construction techniques have contributed to the rapid rise in pervious concrete usage in the state.

Portland Cement Pervious Pavement Construction - Concrete Construction, Vol. 37 no. 9, 4p, (1992)
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 - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
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 and Green Building LEED points will be earned.

Soil and Base Prep - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
Whether for a pervious driveway or parking lot take test borings to establish whether soil will drain enough to support the right sub base and the pervious pavement. 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 - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
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.

Construction Method For Putting Pervious Concrete in Place - 2008 National Ready Mixed Concrete Association
Subgrade and Subbase Prep, Batching and Mixing, Transportation, Placement and Consolidation, Joint Placement, Finishing, Curing and Protection, Opening to Traffic

Important Factors When Installing - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
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.

Performance - 2008 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 - Concrete International, Farmington Hills, MI, March 2005, Vol. 27, No. 3, 2005
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. But, primarily we will focus on the concrete contractor's role in the success of the pervious pavement.

Durability and Maintenance

Construction and Maintenance Assessment of Pervious Concrete Pavements - Stormwater Management Academy - University of Central Florida
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.

Influence of Moisture Conditions on Freeze and Thaw Durability of Portland Cement Pervious Concrete
Yang, Z., Brown, H., and Cheney, A., Middle Tennessee State University
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., Ohio Ready Mixed Concrete Association
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., Cemstone
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, Silver Spring, Maryland, May 2004, 17 pages
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.

Permeability Predictions for Sand Clogged Portland Cement Pervious Concrete Pavement Systems - Elsevier Journal of Environmental Management, 2006
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.

Fatigue Behavior of Polymer-Modified Porous Concretes - Cement and Concrete Research, V. 29, No. 7, pp. 1077-1083, 1999
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.

Prevention - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
Some critics claim that Pervious 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. But inspection and some attention will keep it working for many years.

Maintenance - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
Pervious concrete is the easiest pavement product to maintain! Pervious concrete is not a new product. It was originally used in Europe back in the late 1940's. Properly placed and maintained pervious concrete will last for decades, and it has.

Pervious Concrete Pavement Surface Durability in a Freeze-Thaw Environment Where Rain, Snow and Ice Storms are Common Occurrences - Ohio Ready Mixed Concrete Association
Baas, W. P.
Following is a summary of replies we received from various entities when we asked them "In your ongoing research/experience with pervious concrete, have you noted/recorded any observations of the material's freeze-thaw durability at your installation sites or in your laboratory?"

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. PCPC is most often used as a pavement for parking lots. Field performance depends on the quality of the mixture as well as proper control of construction and curing. In addition to field observations and nondestructive testing, laboratory testing was performed on cores removed from some of the test sites. Generally, the PCPC installations evaluated have performed well in freeze-thaw environments, with little maintenance required.

Investigation into the Effect of Aggregate on the Freeze-Thaw Durability of Pervious Concrete
Kevern, J., Wang, K. and Schaefer, V., Iowa State University
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.

Is Pervious Concrete Strong Enough - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
Thus far it has been difficult to quantify the strength of pervious concrete. We have installed thicknesses of 6" through 10", and have found that with the correct mix and placement it has lasted for many years. We offer a 10 year limited warranty. 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.

Permeability Prediction 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. A theoretical relation was developed between the effective permeability of a sand-clogged pervious concrete block, the permeability of sand, and the porosity of the unclogged block.

Hydrological and Environmental Design

Hydraulic Performance Assessment of Pervious Concrete Pavements for Stormwater Management Credit - Stormwater Management Academy - University of Central Florida
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 - Submitted to the Interlocking Concrete Pavements Institute (2004)
Bean, E. Z., Hunt, W. F., Bidelspach, D. A., and Smith, J. T.
Surface infiltration study funded by the Interlocking Concrete Pavements Institute with each site's information included in the appendix. The report was completed in June, 2004. (50 p)

Hydrologic Design of Pervious Concrete - PCA
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 - American Society of Civil Engineers (ASCE) Journal of Hydrologic Engineering, Vol. 11, Issue 3, 2006
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., North Carolina State University
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 - Stormwater Management Academy - University of Central Florida
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 – A Master's thesis under the direction of Dr. William F. Hunt III, published by the Graduate School at North Carolina State University (2005)
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., Iowa State University
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.
http://www.ctre.iastate.edu/reports/mix_design_pervious.pdf

- Smaller aggregate produces higher strength
- River gravel generally produces higher strength than limestone
- The use of sand increases strength while slightly decreasing void ratio and permeability
- The use of fibers increases tensile strength and permeability without affecting other PCPC properties
- Proper compaction is key to producing durable PCPC
- Sand is required to produce freeze-thaw durable PCPC using the ASTM C666A procedure
- Well designed pervious concrete can meet strength, permeability, and freeze thaw requirements for cold weather climates

Low Impact Parking Lot Design Reduces Runoff and Pollutant Loads - Southwest Florida Water Management District, Brooksville, Fla., 225 pp., 2000
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., University of Texas at Austin
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 - Urban Stormwater Quality Enhancement, pp. 113-155, 1988
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 - Developments in Storm Drainage - A Symposium on Infiltration and Storage of Stormwater in New Developments. pp. 136-151, 1990
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 - Aberdeen's Concrete Construction Vol. 37 no. 9 pp. 660-2 Sept. 1992
Kozeliski, F. A.
Within the last nine 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. But heavier paving equipment and increasing traffic loads led to the use of denser, stronger base materials that were thought to be erosion-proof.

Reducing the Noise Generated in Concrete Pavements Through Modification of the Surface Characteristics - PCA R&D Serial No. 2878, Portland Cement Association, Skokie, IL, 2005
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 – The Concrete Producer Magazine, Nov 2005 issue
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.

Tire-Pavement Interaction Noise: Recent Research on Concrete Pavement Surface Type and Texture - International Journal of Concrete Pavements, Vol.1, No.1, December 2005, pp. 88-105, 2005
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 - APA Journal 65, no. 3, 1999
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 - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
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 – National Ready Mixed Concrete Association
Pool, A. V.
You know concrete parking lots are more attractive. You know they provide lower life cycle costs than higher maintenance cost alternatives (which means more money in owners' pockets). You know they provide higher levels of curb appeal. But did you know concrete parking areas are a much greener alternative than the black stuff? This article is going to outline some of the many ways concrete parking areas are GREEN.

Benefits of Pervious Concrete - 2008 Pervious Concrete Inc.
Item includes information on the Environmental Benefits, Developmental Benefits, and Financial Benefits of pervious concrete.

Construction and Maintenance Assessment of Pervious Concrete Pavements - Stormwater Management Academy - University of Central Florida
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 - Center for Transportation Research and Education Iowa State University
Weigand, P., Schaefer, V., and Suleiman, M.
Iowa Department of Natural Resources Funded
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.

University of New Hampshire Stormwater Center 2007 Annual Report
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

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, 2008
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., Middle Tennessee State University
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 – Interlocking Concrete Pavement Institute
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.

MIX DESIGN

Development of Mix Proportion for Functional and Durable Pervious Concrete
Wang, K., Schaefer, V.R., Kevern, J.T., and Suleiman, M. T., Iowa State University
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., Axim Italcementi Group
This paper 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., Degussa Admixtures, Inc.
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., Cemex
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 - Indian Concrete Journal, May 1966, pages 183 to 189
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 – ASCE Journal of Materials in Civil Engineering, Vol. 19, Issue 7, pp. 561-568, July 2007
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 - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
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 - National Concrete Pavement Technology Center, Feb 2006
Schaefer, V. R., Wang, K., Suleiman, M. T., and Kevern, J. T.
Sponsored by Iowa DOT, NCPTC, Iowa Concrete Association
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

Characterizing Enhanced Porosity Concrete Using Electrical Impedance to Predict Acoustic and Hydraulic Performance – Science Direct: Cement and Concrete Research, 2006
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., Tennessee Technological University
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 - submitted to the Journal of ASTM International, December 2005
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. Therefore, it was selected for determining G_{mb} of the PCPP cores. G_{mm} of PCPP cores must be determined in a compacted condition. Therefore, three modified techniques for determining the “effective” G_{mm} of PCPP were used. Air voids calculated from the effective G_{mm} will be referred to as effective air voids. Specifically, effective air voids are air voids accessible from the surface, which effect PCPP permeability. Thirty-three field PCPP cores were used in the study. The “cut bag method” using the INSTROTEK CORELOK SYSTEM was found to be the most accurate in determining the effective air voids of the PCPP cores. Further, compressive strengths of all cores were also determined. As expected, compressive strength of PCPP cores was inversely related to effective air voids. Correlation coefficients ranged from 0.367–0.989.

Certification, What Does it Mean? - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
An article on the new training programs for becoming pervious certified.
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 - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
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.

StoneyCrete Specifications for a Pervious Pavement System - Stoney Creek Materials L.L.C., Austin, Texas
StoneyCrete specifications for a Pervious Pavement System.

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 - © 2008 Charger Enterprises Inc.
Wolfersberger, C., Member ICC and Certified Green Builder
This nine page document is dedicated to all specifications involved throughout the pervious concrete placement process.

City of Olympia Specifications for Pervious Concrete Sidewalks
Section 8-30 applies to the construction of pervious concrete sidewalks, made of Portland cement, aggregate, water, and other approved admixtures.

Pervious Concrete Certification Program - National Ready Mixed Concrete Association, 2008
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 Pervious Specification, 8/22/2006
The work of this section includes subgrade preparation and installation of portland cement pervious pavement structures (i.e. porous concrete sidewalks).

Recommended Specifications for Portland Cement Pervious Pavement - The Carolinas Ready Mixed Concrete Association Inc.
This abbreviated specification is presented as a recommended guide for light traffic paving loading.

STRUCTURAL DESIGN AND PROPERTIES

Developing a Structural Design Method for Pervious Concrete Pavement
Delatte, N., Cleveland State University
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., Tennessee Technological University
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., University of Tennessee
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., Cement and Concrete Technology Center, Cemex
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., Quality Concrete
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 - Stormwater Management Academy University of Central Florida
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., Resubmitted early 2006 with revisions to ACI Materials Journal.
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 – ScienceDirect: Cement and Concrete Research, Vol. 33, 2003, pp. 381-386
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 - Masters Thesis, University of Central Florida, 132 pp., 2005
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 compare 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 - Journal of Materials in Civil Engineering, Volume 7, Number 3, August 1995a, pages 183 to 191.
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
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

Pervious Concrete Pavement: A Solution for Sustainable Communities - The Journal for Surface Water Quality Professionals, (2006)
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 and Benefits
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.

Current Activity

Side-by-Side Comparison of Pervious Concrete and Porous Asphalt – Funded in part by the RMC Research & Education Foundation

Pervious Concrete Mix Design for Wearing Course Applications – Funded in part by the RMC Research & Education Foundation

http://www.concretenetwork.com/pervious/design-ideas/pervious-concrete-washington.html

Pervious Concrete Research Underway at the Minnesota Department of Transportation

2007 Best Pervious Concrete Project MTSU Pervious Bus Transit Station

Serviceability of Pervious Concrete Pavements – Link not available
Mata, L. and Leming, M., North Carolina State University

Increasing exfiltration from pervious concrete into an underlying clay soil - Journal of Environmental Management – Link not available
Tyner, J. S., W. C. Wright, and P. A. Dobbs., University of Tennessee, 2008

These papers and presentations were showcased at the 2008 NATIONAL READY MIXED CONCRETE ASSOCIATION Concrete Technology Forum (a CD of the Forum's proceedings are now available from the National Ready Mixed Concrete Association):

Best Strategic Advances In Pervious Concrete Technology, *D. Huffman*

Pervious Concrete Pavement Hydrological Design Considerations and Methods, *J. Buffenbarger*

Design of Pervious Portland Cement Concrete Pavement—How Important is Strength?, *A. Marks*

Development of a Test Method for Assessing the Surface Durability of Pervious Concrete, *M. Offenberg and M. Davy*

A Retrospective Look at the Field Performance of Iowa's First Pervious Concrete Sections as of Spring 2008, *V. Schaefer, J. Kevern and K. Wang*

A Synthesis of Pervious Concrete Freeze-Thaw Testing Results, *J. Kevern, K. Wang and V. Schaefer* Sedimentation Effects on Pervious Concrete, *L. Mata and M. Fleming*

Modeling the Retention of Oil in Enhanced Porosity Concretes, *B. Bhayani, O. Deo, T. Holsen and N. Neithalath*

ASTM C 09.49 Subcommittee Activity on Test Methods for Pervious Concrete, *K. Obla*

Statistical Characterization of the Pore Structure of Enhanced Porosity Concretes, *K. Low, D.Harz and N. Neithalath*

The Effect of Compaction and Aggregate Gradation on Pervious Concrete, *K. Mahboub, J. Canler, B. Davis and R. Rathbone*

Self Consolidating Pervious Concrete for Overlay Applications, *K. Wang, J. Kevern and V. Schaefer*

SUMMARY AND FUTURE RESEARCH NEEDS

Applications and Case Studies

- Applications have been focused on parking lots and pedestrian pavements. More field applications of pervious overlays, low volume streets, highway shoulders, medians and swales needs to be researched for additional concrete opportunities.

Construction Techniques

- With the wide variety of placement techniques (plate compactor, vibratory screed, roller, high density paver), an attempt to standardize the equipment used is important. Compactive effort affects many properties of pervious concrete that are used for Quality Assurance/Quality Control (QA/QC) purposes
- As pervious pavement applications widen, attention will eventually turn to quicker turnaround on opening pervious pavements. No research has been focused in that area.

Durability and Maintenance

- Clogging, whether surface or within, needs to be further researched in terms of being able to monitor volume loss over time and the maintenance techniques that can be used to recapture volume. Removing cores for clogging observation is not a perfect science since water is used to remove cores which could disturb some of the sediment loading.
- Additional design elements due to heavy sediment loading to prevent failure of pavement.

Hydrological and Environmental Design

- Adsorption of grease and oil into pervious concrete pores and its long term impact.
- Growth and decomposition of biomass and aerobic digestion in a pervious system.
- Leaching of concrete materials into the groundwater and soils.

Mix Designs

- Byproduct research – cement kiln dust, high carbon ash, etc.

Specifications and Test Methods

- Development of observation wells for water quality testing.

Structural Design and Properties

- Work has started on developing a structural design method for pervious pavements and should be further emphasized.

** This list is solely the opinion of the investigator and other research areas should be considered if a lack thereof exists.

State and Regional Association and Local University Resources

Alabama

Alabama Concrete Industries Association

Arkansas

Arkansas Ready Mixed Concrete Association

California

Concrete Promotion Council of Northern California

California Construction and Industrial Materials Association

California Nevada Cement Association

Pacific Southwest Concrete Alliance

Colorado
American Concrete Pavement Association (ACPA) – CO/WY

Rocky Mountain Cement Council

Connecticut
Connecticut Ready Mixed Concrete Association

Florida
Florida Concrete Products and Association

University of Central Florida

Georgia
Georgia Concrete & Products Association

University of Georgia

Cool Communities

Hawaii
Cement & Concrete Products Industry of Hawaii

Illinois
Illinois Ready Mix Concrete Association

Indiana
Indiana Ready Mixed Concrete Association

Iowa
Iowa Concrete Paving Association

Iowa Ready Mix Concrete Association

Kansas
Concrete Promotion Group, Inc. of Greater Kansas City

Kansas Aggregate Producers' Association/Kansas Ready Mixed Concrete Association

Kentucky
Kentucky Ready-Mixed Concrete Association

University of Kentucky

Louisiana
Concrete & Aggregate Association of Louisiana

Maine
Northern New England Concrete Promotion Association

Maryland
Maryland Ready Mix Concrete Association and Promotion Council

Michigan
Michigan Concrete Association

Minnesota
Aggregate & Ready Mix Association of Minnesota

Mississippi
Mississippi Concrete Industries Association

Missouri
Concrete Council of St. Louis

Concrete Promotion Council of the Ozarks

Montana
Montana Contractor's Association

Nebraska
Nebraska Concrete and Aggregates Association

Nevada
Sierra Nevada Concrete Association

Southern Nevada Concrete & Aggregates Association

California Nevada Cement Association

New Mexico
New Mexico Ready Mixed Concrete & Aggregates Association

New York
New York Concrete Promotion Council

Northeast Cement Shippers Association

Clarkson University

North Carolina
Carolinas Ready Mixed Concrete Association

NC State

North Dakota
North Dakota Ready Mix and Concrete Products Association

Ohio
Concrete Promotion Council of Southwest Ohio

Ohio Ready Mixed Concrete Association

Oklahoma
South Central Cement Promotion Association

Pennsylvania
Pennsylvania Aggregate and Concrete Association

Penn State

Villanova University

South Carolina
Carolinas Ready Mixed Concrete Association

Southeast Cement Association/University of South Carolina

Tennessee
Tennessee Concrete Association

Texas
Texas Aggregate and Concrete Association

Cement Council of Texas

Virginia
Virginia Ready-Mixed Concrete Association

Washington
Washington Aggregate & Concrete Association

West Virginia
Builder's Supply Association of West Virginia

Wisconsin
Wisconsin Ready Mixed Concrete Association

Wyoming
American Concrete Pavement Association (ACPA) – CO/WY

CANADA
Cement Association of Canada

British Columbia Ready-Mixed Concrete Association

Manitoba Ready Mix Concrete Association

Atlantic Concrete Association

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.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.