Predicting the Permeability of Pervious Concretes from Planar Images

M.S. Sumanasooriya[1], D.P. Bentz[2], and N. Neithalath[3]

[1] Graduate Student, Department of Civil and Environmental Engineering, Clarkson University, Potsdam NY 13699 (sumanams@clarkson.edu)
[2] Chemical Engineer, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8615, Gaithersburg, MD 20899 (dale.bentz@nist.gov)
[3] Assistant Professor, Department of Civil and Environmental Engineering, Clarkson University, Potsdam NY 13699 (nneithal@clarkson.edu)

Abstract

This paper discusses the reconstruction of three-dimensional material structures of pervious concretes using two-dimensional digital images obtained from actual specimens, and computational permeability predictions using these reconstructed three-dimensional material structures. The computer programs developed at the National Institutes of Standards and Technology (NIST) are used to obtain three-dimensional structures based on two-point correlation functions of real two-dimensional images, and to evaluate the permeability of six different pervious concrete mixtures including three single sized aggregates mixtures and three blended aggregate mixtures. The reconstructed microstructures are found to have similar porosities as that of the actual specimens. Experimental permeability values are obtained using a falling head permeameter, and the predicted permeability values are compared with the experimental values. The predicted values of permeability are found to match the experimental values closely for specimens made with smaller sized aggregates, rather than those for specimens made with larger aggregates. This is because of the fact that the pores in specimens made with smaller sized aggregates are distributed more uniformly, thus satisfying the assumptions of homogeneity and isotropy in the two-dimensional and three-dimensional material structures.

Introduction

Pervious concrete (also called Enhanced Porosity Concrete, or porous concrete) is essentially a no-fines, gap-graded aggregate concrete that has an interconnected network of large pores, with volume fraction of large pores (pores in the millimeter size range) typically in the range of 15 % -30 % (ACI 522R-06, Tennis et al. 2004, Neithalath et al. 2005, 2006, Meininger 1988, Haselbach et al. 2006, Low et al. 2008). This material has been reported to be effective as a surface course of pavements to reduce the tire-pavement interaction noise and improve skid resistance (Brite/Euram report BE 3415 1994, Nelson and Philips 1994). The use of pervious concrete is on the rise in the United States during the last few years because of its ability to transport large amounts of water through its highly connected pore structure into the ground below, thus recharging groundwater and reducing stormwater runoff. The Environmental Protection Agency

(EPA) has designated the use of pervious concrete to be among the best management practices in reducing stormwater runoff.

Pervious concretes are primarily designed for water transport through its material structure while maintaining sufficient strength, durability, and abrasion resistance to serve as a pavement. Thus, porosity is considered to be its most important physical property. Several proportioning methods have been adopted to produce pervious concretes having porosities sufficient enough to transport water at desired rates (Meininger 1988, Wang et al. 2006, Marolf et al. 2004). A few laboratory test methods for permeability determination of pervious concretes are in practice (Neithalath et al. 2006, Montes and Haselbach 2006).

It is well known that permeability of porous materials also depend on other pore structure features such as the size and distribution of pores and pore connectivity. Previous studies have used electrical impedance-based methods to determine the pore structure features of pervious concretes that are significant in water transport (Neithalath et al. 2006) and acoustic absorption (Marolf et al. 2004). A better understanding of the influence of the pore structure on the performance of such macroporous materials is essential in order to develop materials science-based design procedures and better test methods for performance. Computational materials science has been applied in conventional concretes to study cement hydration and microstructure development (Bentz 2005), property development (Garboczi et al. http://concrete.nist.gov/monograph), and ionic diffusivity (Bentz et al. 1998). A recent study (Bentz 2008) has demonstrated the use of a virtual pervious concrete pore structure to relate the experimentally determined permeability values to the porosities of the virtual material structure. In this study, two-dimensional images from several real pervious concrete mixtures are subjected to a computational procedure that recreates a three-dimensional material structure to predict its permeability.

Experimental Program

The experimental program in this study consisted of six different pervious concrete mixtures made using three different aggregate sizes and their chosen combinations. Pea gravel was used as the aggregate. All the mixtures were made with a water-to-cement ratio by mass (*w/c*) of 0.33 and an aggregate-to-cement ratio by mass (a/c) of 5. The three different aggregate sizes used are denoted as #8 (100% passing #4 sieve or 4.75 mm and retained on #8 sieve or 2.36 mm), #4 (100% passing 3/8” sieve or 9.5 mm and retained on #4 sieve or 4.75 mm), and 3/8" (100% passing 1/2” sieve or 12.5 mm and retained on 3/8” sieve or 9.5 mm). Three pervious concrete mixtures were proportioned using each of these single sized aggregates, and three more mixtures were made using a combination of two of the three single sized aggregates. The blended aggregate mixtures that formed a part of this study were made using the following mass percentages: 50 % #8 and 50 % #4, 75 % #4 and 25 % 3/8", and 25 % #4 and 75 % 3/8" aggregates. The mixture proportions for all the six mixtures are shown in Table 1. The mixtures were mixed in a laboratory mixer, cast in 100 mm x 200 mm cylindrical molds, and consolidated using a combination of low amplitude vibration and tamping. For specimens to be used for permeability determination, a 95 mm diameter sleeve was placed inside the 100 mm diameter molds in order to accommodate the specimen in the permeability cell. The specimens were demolded after 24 h and stored in a moist environment for at least 7 d.

Table 1: Mixture proportions for the pervious concretes used in this study

Mix ID	Cement, kg/m^3	Water, kg/m^3	#8 aggregates, kg/m^3	#4 aggregates, kg/m^3	3/8" aggregates, kg/m^3
100-#8	309	102	1544	-	-
100 - #4	314	103	-	1568	-
100 - 3/8	312	103	-	-	1560
50 - #8 - 50 - #4	296	98	740	740	-
75 - #4 - 25 - 3/8"	301	99	-	1129	376
25 -#4 - 75-3/8"	319	105	-	398	1195

Porosity determination by volumetric method: The porosities of the pervious concrete mixtures were determined using a volumetric method described in (Neithalath et al. 2006). The 200 mm long cylindrical specimens were trimmed to 150 mm length by cutting 25 mm thick sections from the top and bottom. The specimens were immersed in water for 24 h to saturate the pores in the paste phase. The saturated specimens were removed from water, allowed to drain, and enclosed in a latex membrane. The bottom of the specimen was firmly sealed onto a stainless steel plate and the mass of the system was accurately measured. Water was then added to the top of the specimen until all the larger pores were filled with water, and the mass of the system was measured again. The mass of the added amount of water was converted into a volume, which when represented as a ratio to the specimen volume, provided the porosity (ϕ_v) of the specimens.

Preparation of planar images for feature extraction and use in the prediction model: The 200 mm long pervious concrete specimens were cut into 150 mm lengths as described earlier. These specimens were then further divided into three slices each of 50 mm thickness. The cut sections were ground to obtain a smooth surface for image acquisition. Considering both the faces of a single slice, a total of six images could be obtained from a single cylinder. Two such cylinders for each mixture were used in this study. Some of the faces of the cut sections could not be used because of irregularities and edge effects introduced while cutting. A total of four to six usable faces were used for each mixture for image acquisition.

The solid phases in the pervious concrete sections were painted white using a marker to enhance the contrast between the solid and pore phases. They were then scanned using a flatbed scanner over a clear plastic film and grayscale images were obtained. Image J ™ computer software (freely available from www.nih.gov) was used to perform the following image processing procedure. The acquired images were cropped into 590 pixel diameter circular images and converted into binary images by a thresholding operation based on an analysis of the greylevel histogram, to separate the pore and solid phases. The upper threshold of the greylevels for the features of interest (pores) was found to lie in between 120 and 130 for all the images that were examined. The noise in the thresholded images was then removed by despeckling and the use of filters. These images were used for analysis of the pore structure features such as the area fraction of pores, pore size distribution, and mean free spacing of the pores. To reconstruct the 3D microstructure in order to predict the material permeability, 400 pixel x 400 pixel square images were obtained from the circular images. Figure 1 shows the various steps adopted in image processing and analysis.

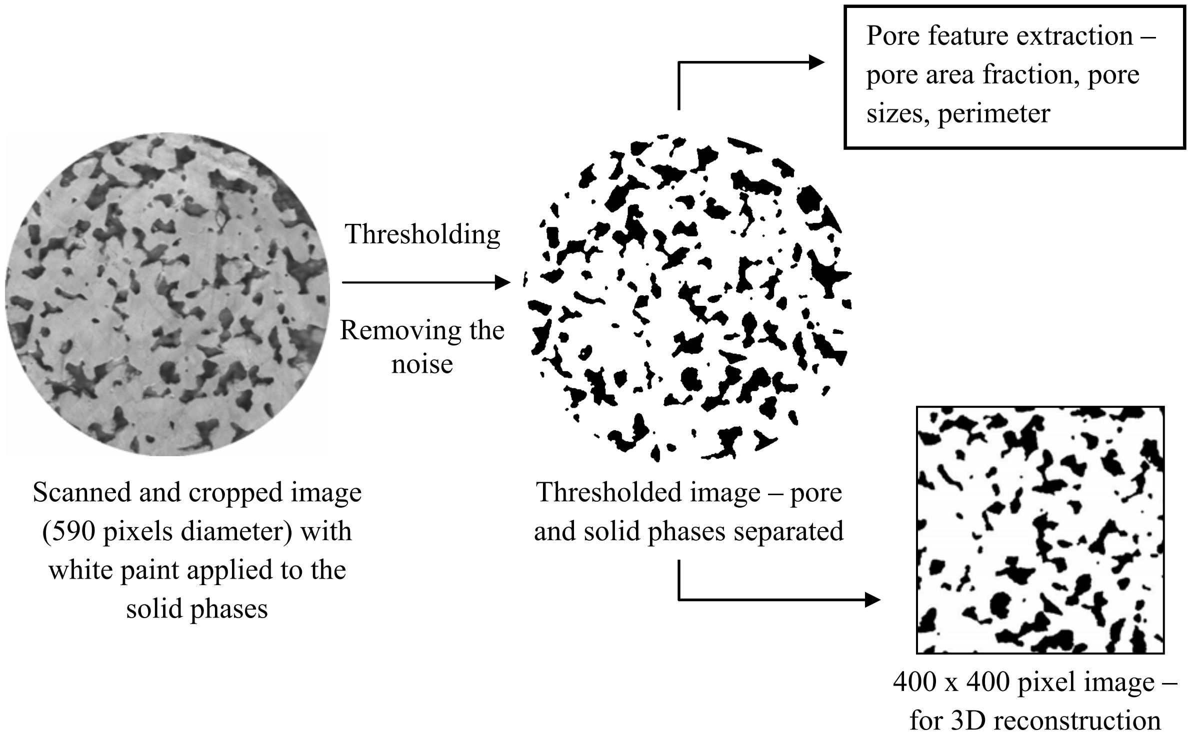

Figure 1: Image acquisition, processing, and analysis

Permeability determination: A falling head permeameter was used to experimentally determine the hydraulic conductivity of the pervious concrete mixtures. Details on the experimental set up can be found elsewhere (Neithalath 2004, Neithalath et al. 2006). 95 mm x 150 mm cylindrical specimens were used. Each specimen was enclosed in a latex membrane and placed in the permeability set up. Water was allowed to pass through the specimen and the time (t) required for water to fall from a head h_1 to h_2 was measured. The hydraulic conductivity (K in m/s) was calculated using Darcy's law shown in Equation 1.

$$K = \frac{A_1 L}{A_2 t} \ln\left(\frac{h_2}{h_1}\right) \quad (1)$$

A_1 and A_2 are the areas of the cross-section of the sample and the tube respectively and L is the length of the specimen. The hydraulic conductivity (in m/s) was converted into intrinsic permeability (m^2) using the density and viscosity of water, 1000 kg/m^3 and 10^{-3} Pa·s, respectively.

Experimentally measured porosities and permeabilities

The porosities of the pervious concrete specimens determined using the volumetric method and the image analysis procedure are shown in Table 2. The reported value of volumetric porosity (ϕ_v) for a mixture is the average for two or three different specimens. In the image analysis procedure, the areas of the individual pores as obtained from the thresholded images using the analysis features in Image J™ were summed up and divided by the total image area to provide the area fraction of pores. According to stereological theory, if random samples are used, then the porosity ϕ_v determined based on the specimen volume should be equal to the area fraction ϕ_A of the pores in a planar image. The average value of the area fraction of pores in all the images that were useful for further analysis (those without edge effects) is reported as ϕ_A in Table 2. It can be observed that the average ϕ_V and ϕ_A values are fairly close, with a maximum variation of less than 15 %. The number of slices used for imaging for each of the mixtures is also given in Table 2 along with the range of pore area fractions obtained using different images and the standard deviations in estimated pore area fractions. The pore size distributions, mean free spacing of the pores, and the nearest-neighbor distances were also extracted stereologically from these images, but they are not presented in this paper. These pore structure parameters are useful in characterizing pervious concrete mixtures made using different aggregate sizes and combinations, and are influential in dictating the material performance. The same images that were used for the determination of the area fraction of pores are used for 3D reconstruction, as will be detailed below.

Table 2: Porosities of pervious concrete specimens used in this study based on volumetric and image analysis determination procedures

Aggregate composition (% of each size fraction)	Volumetric porosity (ϕ_v), %		Area fraction of pores (ϕ_A), %			
	Average value	Standard Deviation	Average value	Range	Standard Deviation	No. of images
100 - #8	20.6	1.99	23.7	18.2 - 26.5	3.36	5
100 - #4	19.4	1.13	22.5	19.4 - 24.1	2.51	4
100 - 3/8	19.8	0.66	18.1	16.3 - 21.1	1.87	5
50 - #8 – 50 - #4	23.9	1.20	22.9	20.4 - 25.3	2.06	6
75 - #4 - 25 - 3/8"	22.6	2.11	20.5	18.6 - 24.1	2.10	5
25 - #4 – 75 - 3/8"	18.1	1.15	17.6	15.0 - 21. 9	3.05	4

The experimentally determined permeabilities are expressed as a function of the corresponding volumetric porosities in Figure 2. For a given pervious concrete mixture proportion, the porosities of all the replicate specimens are shown in this figure. The error bars correspond to the standard deviations of three separate permeability measurements on each specimen. The permeabilities are found to generally increase with porosity, as expected. However, it needs to be remembered that permeability is not just a function of the porosity alone; rather other pore structure features also exert a significant influence on permeability (Neithalath et al. 2006, Low et al. 2008).

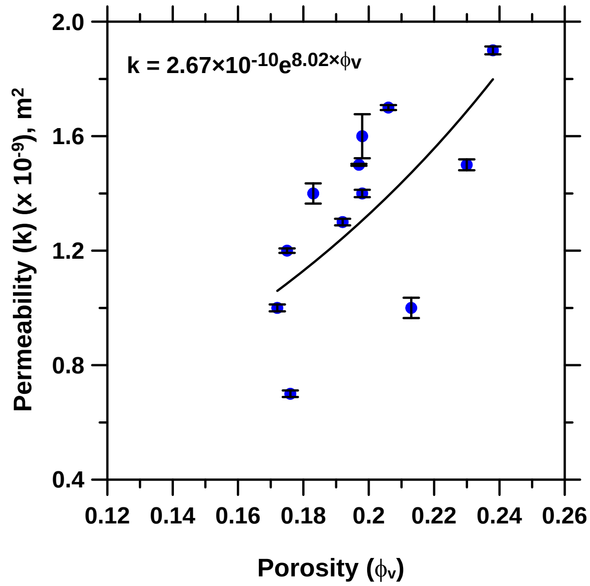

Figure 2: Porosity-permeability relationship for different pervious concretes

3D reconstruction from planar images and permeability prediction

The planar images obtained as described in an earlier section were used to generate three-dimensional reconstructed material structure of pervious concretes. The computer programs developed at the National Institutes of Standards and Technology (NIST) were used for this purpose. Autocorrelation (or two-point correlation) functions were determined for the pore phase of the 400 pixel x 400 pixel square images of pervious concretes. More details on the methodology of obtaining autocorrelation functions and their applications can be found in (Garboczi et al. 1999, Berryman and Blair 1986, Berryman 1985). A three-dimensional reconstruction algorithm along with the measured correlation function (Bentz 2008, Bentz et al. 2009, Bentz and Martys 1994) was then used to generate a 300 voxel x 300 voxel x 300 voxel digitized structure of a pervious concrete having the same volumetric porosity, pore surface area, and correlation as the original material. The reconstructed three-dimensional images were further modified by a sintering operation described in (Bentz and Martys 1994) to match the hydraulic radius of the two-dimensional parent image. All the computer programs required for these operations are downloadable from the NIST ftp site ftp://ftp.nist.gov/pub/bfrl/bentz/permsolver.

For each of the pervious concrete mixtures, the number of 400 pixel x 400 pixel square images used for analysis is shown in Table 2. Each two-dimensional image along with its autocorrelation function was used to generate separate three-dimensional structures of pervious concretes. A schematic of the methodology is shown in Figure 3.

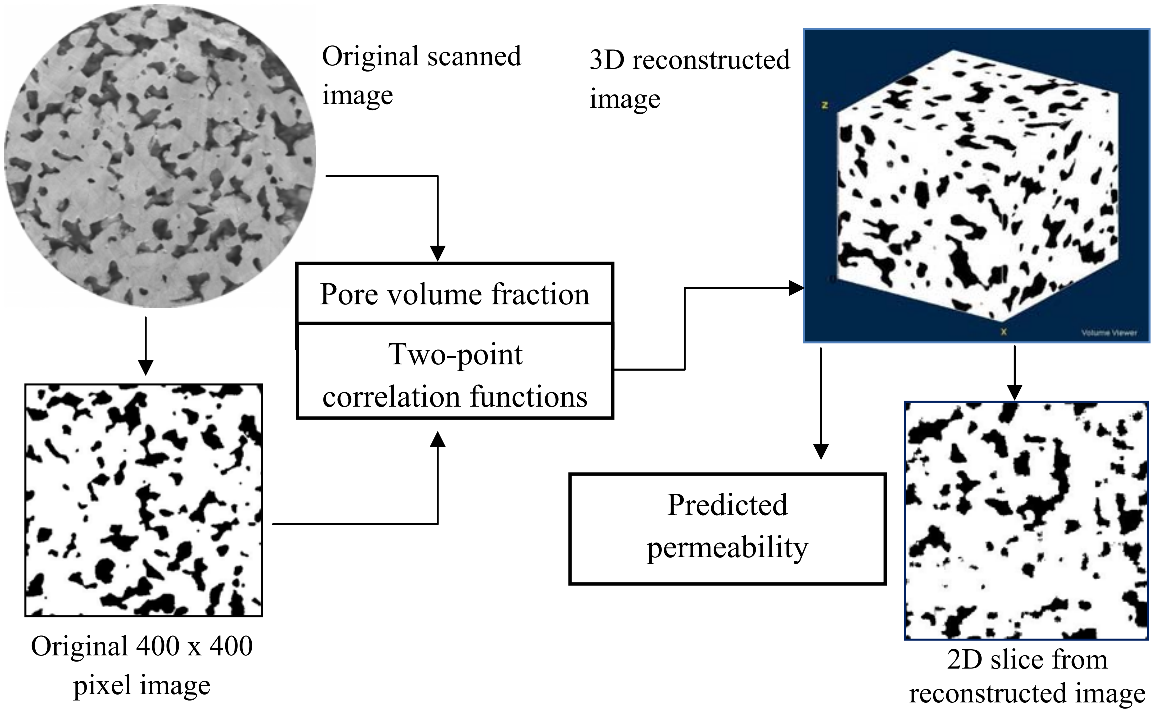

Figure 3: Steps involved in 3D reconstruction and permeability prediction

Figure 4 shows the typical pore structures of two of the original pervious concrete mixtures used in this study as well as random two-dimensional slices extracted from the respective reconstructed three-dimensional structures. A cursory observation shows that the original and the reconstructed material structures appear quite similar. Detailed analysis and comparison of the pore structure features of the original and reconstructed pore structures will be dealt with in a forthcoming publication.

The permeabilities of the reconstructed pervious concretes were computed using a Stokes permeability solver. NIST has developed a three-dimensional linear Stokes solver (Bentz and Martys 2007) to perform the calculations on three-dimensional microstructures consisting of pores and solids. Previous applications of this solver to porous materials can be found in (Bentz et al. 2009, Bentz 2008).

To compute the permeability of three-dimensional pervious concrete reconstructed structures, a pressure gradient (1 unit per voxel) is applied in one of three principal user-defined directions (X, Y, or Z). The program calculates the resultant fluid velocity vector field within each pore voxel for slow, incompressible steady-state fluid flow by using a finite difference solution for the linear Stokes equations. Once this finite difference solution converges sufficiently, the intrinsic permeability, *k*, of the three-dimensional structure is calculated by volume averaging the local fluid velocity (in the direction of the flow) and applying the Darcy equation:

$$u = -\frac{k}{\eta}\frac{\nabla P}{L} \qquad (2)$$

where u is the average fluid velocity in the direction of flow, ΔP is the pressure difference, L is the length of the porous structure where the pressure gradient was applied and η is the fluid viscosity.

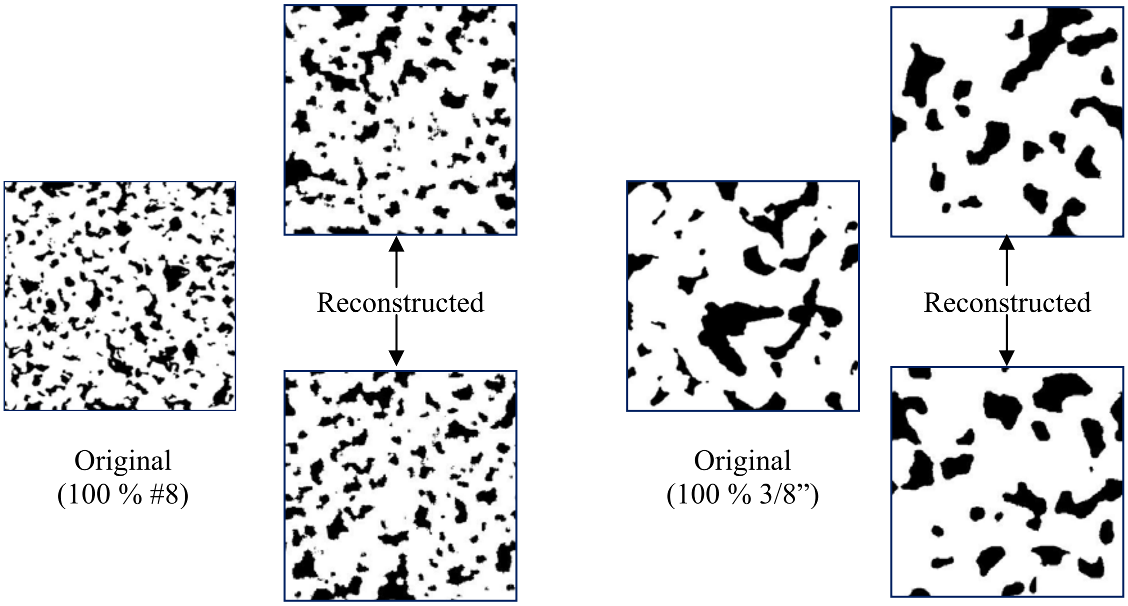

Figure 4: Two-dimensional images from the original pervious concrete specimens and the slices from reconstructed three-dimensional structures of two different pervious concrete mixtures

To obtain the permeabilities in all the three principal directions, three separate runs of the computer programs on the three-dimensional structure were executed by changing the direction of flow. The average of the values corresponding to three directions was taken as the predicted permeability for a particular three-dimensional pervious concrete structure. This procedure was repeated on three-dimensional structures generated using each of the two-dimensional images for a particular pervious concrete mixture, and the average value is reported as the predicted permeability for a particular mixture.

Figure 5 shows the experimentally measured permeabilities and the permeabilities predicted from the computational procedure applied on reconstructed three-dimensional structures of pervious concretes. It can be seen that the predictions match the experimental values fairly well for most of the pervious concrete mixtures evaluated in this study.

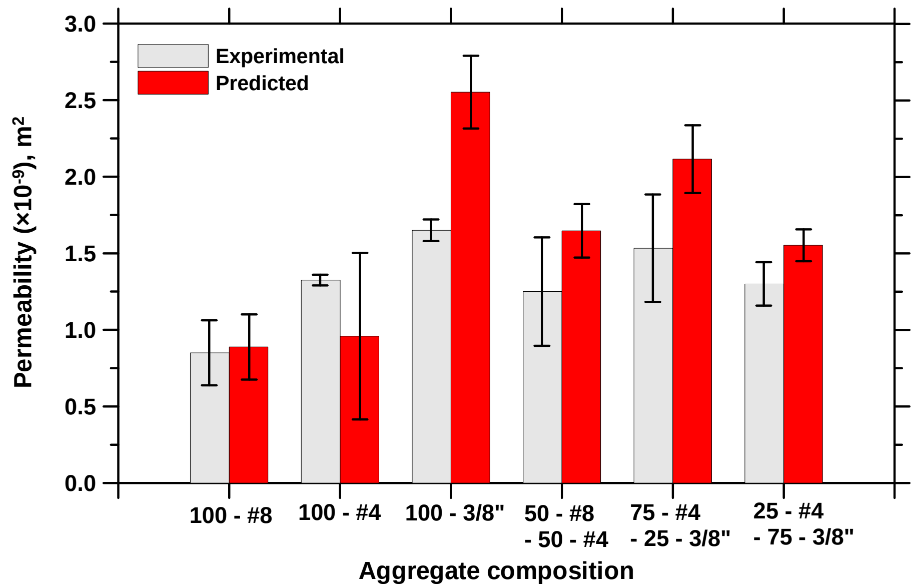

Figure 5: Comparison of the experimental and predicted permeabilities

The mixture that shows the least agreement between the experimental and the predicted values is the one made with 100 % 3/8” aggregates. This could be attributed to the assumption of isotropy made in the image-based three-dimensional reconstruction algorithm. As can be observed from Figure 4, the pores in the 100 % 3/8” specimen are larger and less uniformly distributed as compared to those in the 100 % #8 specimen. The specimens with smaller aggregate sizes (and thus smaller pore sizes) or a combination of larger and smaller aggregates have pores that are smaller and distributed more uniformly, thus satisfying the assumptions of homogeneity and isotropy in the 2D and 3D material structures, as well as providing a reasonable representative elementary volume. The error bars for the predicted permeability values represent the standard deviations of the predictions between different starting two-dimensional images, and those for the experimental permeability values represent the standard deviations for all specimens from a particular mixture proportion.

Conclusions

This paper has used a three-dimensional reconstruction algorithm that uses two-dimensional planar images of pervious concretes along with its volumetric porosity to predict its permeability. Three single-sized aggregate pervious concrete mixtures, and three mixtures with blended aggregates were evaluated as part of this study. The volumetric porosities as well as the pore area fractions from multiple planar images using image analysis procedures were determined for all the specimens. The planar slices extracted from the reconstructed 3D structures showed qualitative visual resemblance to their parent images. The predicted permeabilities were found to match the experimental values for most of the specimens used in the study. The predictions were less than satisfactory for specimens containing larger and less uniformly distributed pores, possibly because of the violation of the assumptions of a representative elementary volume and homogeneity and isotropy in the 2D and 3D material structures.

Acknowledgements

The third author gratefully acknowledges funding from a CAREER award (CMMI 0747897) from the National Science Foundation (NSF) towards the conduct of this work.

References

ACI 522R – 06, "Pervious concrete," American Concrete Institute Committee, 2006.

Bentz, D.P., "Virtual pervious concrete: Microstructure, percolation, and permeability," ACI Materials Journal **105**, 297-301 (2008).

Bentz, D.P., Garboczi, E.J., and Lagergren, E.S., "Multi-scale microstructural modeling of concrete diffusivity: Identification of significant variables," Cement, Concrete, and Aggregates **20**, 129-139 (1998).

Bentz, D.P., "CEMHYD3D: A Three-Dimensional Cement Hydration and Microstructure Development Modeling Package. Version 3.0," National Institute of Standards and Technology Interagency Report 7232, Technology Administration, U.S. Department of Commerce, June 2005.

Bentz, D.P., and Martys, N.S., "A stokes permeability solver for three dimensional porous media," National Institute of Standards and Technology Interagency Report 7416, Technology Administration, U.S. Department of Commerce, April 2007.

Bentz, D.P., and Martys, N.S., "Hydraulic radius and transport in reconstructed model porous media," Transport in Porous Media **17**, 221-238 (1994).

Bentz, D.P., Garboczi, E.J., Martys, N., Snyder, K.A., Guthrie, W.S., Kyritsis, K., and Neithalath, N., "Virtual testing of concrete transport properties," submitted to ACI Fall 2009 session on Material Science Modeling as a Solution to Concrete Problems, 2009.

Berryman, J.G., "Measurement of spatial correlation functions using image processing techniques," Journal of Applied Physics **57**, 2374-2384 (1985).

Berryman, J.G., and Blair, S.C., "Use of digital image analysis to estimate fluid permeability of porous materials: Application of two-point correlation functions," Journal of Applied Physics **60,** 1930-1938 (1986).

Brite/Euram Project BE 3415., "Surface properties of concrete roads in accordance with traffic safety and reduction of noise", Project BE 3415, November 1994.

Garboczi, E.J., Bentz, D.P., and Martys, N.S., "Digital images and computer modeling," Experimental Methods in the Physical Science, Methods in the Physics of Porous Media **35**, 1-41 (1999).

Garboczi, E.J., Bentz, D.P., Snyder, K.A., Martys, N.S., Stutzman, P.E., Ferraris, C.F., and Bullard, J.W., "An electronic monograph: Modeling and measuring the structure and properties of cement-based materials," http://concrete.nist.gov/monograph. (Accessed January 15, 2009).

Haselbach, L.M., Valavala, S., and Montes, F., "Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems," Journal of Environmental Management **81,** 42-49 (2006).

Low, K., Harz, D., and Neithalath, N., "Statistical characterization of the pore structure of enhanced porosity concrete," Proceedings in CD of the 2008 Concrete Technology Forum, National Ready Mix Concrete Association, Denver, 2008.

Marolf, A., Neithalath, N., Sell, E., Wegner, K., Weiss, J., and Olek, J., "Influence of aggregate size and gradation on acoustic absorption of enhanced porosity concrete," ACI Materials Journal **101**, 82-91 (2004).

Meininger, R.C., "No-fines pervious concrete for paving," Concrete International **10**, 20-27 (1988).

Montes, F., and Haselbach, L., "Measuring hydraulic conductivity in pervious concrete," Environmental Engineering Science **23**, 960-969 (2006).

Neithalath, N., "Development and characterization of acoustically efficient cementitious materials," PhD thesis, Purdue University, West Lafayette, Indiana, 2004, 269 pp.

Neithalath, N., Marolf, A., Weiss, J., and Olek, J., "Modeling the influence of pore structure on the acoustic absorption of enhanced porosity concrete," Advanced Concrete Technology **3**, 29-40 (2005).

Neithalath, N., Weiss, J., and Olek, J., "Characterizing enhanced porosity concrete using electrical impedance to predict acoustic and hydraulic performance," Cement and Concrete Research **36**, 2074-2085 (2006).

Nelson, P. M., and Phillips, S. M., "Quieter road surfaces", TRL Annual Review, Transportation Research Laboratories, UK, 1994.

Tennis, P,D., Leming, M.L., and Akers, D.J., "Pervious concrete pavements", Portland Cement Association, Skokie, IL, 28 pp, 2004.

Wang, K., Schaefer, V.R., Kevern, J.T., and Suleiman, M.T., "Development of mix proportion for functional and durable pervious concrete," Proceedings in CD of the 2006 Concrete Technology Forum, National Ready Mix Concrete Association, Nashville, 2006.