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Analysis of microstructure transport properties of pervious concrete using X-ray microtomography and Random Walk Simulation

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ABSTRACT

Pervious or porous concrete has been recently gaining attention as an eco-material toward a sustainable built environment for improved storm water management and flood control. Such material can be used as an alternative pavement surface that allows some of the rainfall to pass through the roadways and parking lots into the ground below, and thus reduces the nonpoint source pollution effects of storm water runoff. It is thus imperative to study its properties in order to evaluate and even predict its performance as a functional material. In this study, the microstructure and transport properties of pervious concrete were characterized using X-ray microtomography coupled with three-dimensional (3D) image analysis and computational simulation. Similar in principle to that of a medical computed tomography (CT) scanner, X-ray microtomography allows us to examine the virtual cross section of the pervious concrete at spatial resolution of few orders of micrometers without physically cutting the specimen. Using image segmentation and cluster labelling technique, the void structure can be extracted from the CT images of pervious concrete. Porosity, characteristic pore size and tortuosity were measured from the digitized 3D images of the connected void structure. The US NIST Permeability Stokes solver was also used to measure the permeability in the void spaces. Results of the computational simulation are discussed in this paper.

KEYWORDS: X-ray microtomography; image processing; porous media; tortuosity; permeability; Mathematica

1. INTRODUCTION

The use of pervious concrete as a road construction material has gained popular attention due to its capacity to prevent water flooding. The high porosity of this material enables water to pass through at a higher rate, consequently replenishing groundwater sources. Applications of pervious concrete vary from reduction of storm water volumetric flow rate and pollutant discharge (Ferguson2005, EPA 2000) which makes it a viable material for a variety of infrastructures. Other applications include slope stabilization, well linings, alleys (Tennis et al. 2004), and parking lots (Brown 2003;Tennis et al. 2004) which attests to the versatility of its use. Transport properties of pervious concrete are studied to assess the prospective applications and ensure compliance with engineering specifications (Tennis et al. 2004). Furthermore, other prospective use of fluid transport-property analysis is mix optimizations of different materials which can alternatively be used to make pervious concrete. Hence, it is important that different methodologies on characterization of pervious concrete are explored.

Several methods had been studied and used to evaluate the properties of pervious concrete. Specifically, x-ray computed tomography (CT) has been used for the diffusion measurements by quantitatively visualizing spatial distribution in the diffusive migration of elements. X-ray CT technique is preferred due to its non-destructive imaging at short-time periods (Nakashima, 2000). Utilizing 3d images also provides data in the evaluation of the durability characteristics of pervious concrete (Bentz, 2008) by means of creating a model through the use of various softwares such as National Institute of Standards and Technology (NIST) Permsolver.

In this study, properties of pervious concrete such as tortuosity, permeability and porosity are evaluated using available image processing programs (NIST Perm/Stokes Solver, ImageJ and Mathematika6.0) to assess their viability in non-destructive analysis of fluid diffusion characteristics.

2. METHODS

2.1. Image Processing

A three-dimensional object may be represented by an image sequence in image processing. Such image sequences or stacks may be obtained using techniques such as x-ray computed microtomography of materials. In a three-dimensional case, each value on the image grid is called a voxel – short for volume pixel. Each voxel contains information pertaining to its color or shade. Image processing software such as Image J may be used to derive information from these images or prepare them for further processing.

Stacked X-ray CT images are processed using ImageJ for thresholding, noise reduction and contrast enhancements. The images are scaled properly into cubic voxels (300x300x300). NIST Stokes/Permsolver requires scaling so as to avert recompiling existing program files for permeability calculations. After proper scaling of the images, the locations of the VOI's are defined and saved as new image sequences.

The stacked images allowing for 2D distribution observation of the connected porosity in a porous membrane are analyzed by designating a diffusion coefficient based on the value of gray scale level.

Samples used in this study were in the form of image stacks obtained from x-ray microtomography of pervious concrete. Two data sets were used in this study. From each data set, six volumes of interest (VOI's) were extracted. This is done using the Image J free software (Rasband, 1997).

2.2. Random Walk Simulation

Random walk simulation (RW) Method based on theoretical work started by Fokker and Planck on Markovian processes simulate advection-dispersion or Brownian motion as illustrated in some previous works (Ramarao and Tien(1992),Sardini, et al (2003)) is used in this study. Mathematika 6.0 is used in facilitating RW Simulation.

2.3. Porosity, Tortuosity and Permeability

Total porosity is defined as the ratio of the total pore volume and the volume of interest.

$$Total\ Porosity = \frac{Total\ Pore\ Volume}{Volume\ of\ Interest} \tag{4}$$

Effective porosity is defined as the ratio of the volume of the largest pore cluster and the volume of interest.

$$Effective\ Porosity = \frac{Volume\ of\ Largest\ Pore\ Cluster}{Volume\ of\ Interest} \tag{5}$$

Pore connectivity is defined as the ratio of the largest pore cluster and the total pore volume of the sample.

$$Pore\ Connectivity = \frac{Volume\ of\ Largest\ Pore\ Cluster}{Total\ Pore\ Volume} \tag{6}$$

2.4. Determination of Effective Porosity, Pore Connectivity and Tortuosity using Mathematica and ImageJ

Cluster labelling technique has been done to evaluate the connectivity of pores using the Wolfram Research Mathematica 6.0 program ClabelV3B.nb authored by Nakashima and Kamiya (2007), the connected pore voxels can be labelled and their corresponding volumes can be measured.

To determine the tortuosity of the sample, a separate Mathematica program, RWalkV3B.nb, is used to send *n* number of particles which start at random locations (voxels) in the pore space. At each time step, each particle will attempt to jump to a random adjacent voxel. If the adjacent voxel selected is a *solid voxel*, the particle will retain its position for that time step.

On the other hand, if the adjacent voxel selected is a *pore voxel*, it will become the new location of the particle. After a defined total time *t*, the random walks of all particles will cease and the mean square displacement (r^2) travelled by each particle will be calculated by the program. This information may be used to estimate the tortuosity of the sample.

The said programs are described in full in the paper by Nakashima and Kamiya (2007) and may be downloaded for free from (Web-1).

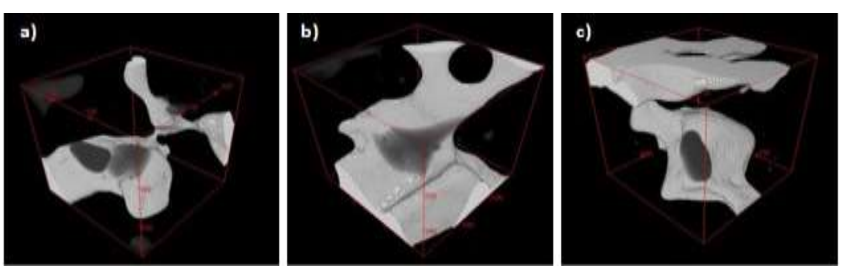
The effective porosity may be acquired after image processing for cluster labelling. To count the pore and solid voxels, the histogram function of ImageJ (with BoneJ plugin) by assigning 0 to the pore space accounts for the total porosity determination. Also, the void volume is determined by using the *isosurface* feature used to measure void volume. The void volume is then used to compute for the hydraulic diameter of the material.

2.5. Determination of Permeability using NIST Stokes Solver

NIST Stokes Permeability Solver was used to determine the permeability of pervious concrete along x, y and z directions. The software used is freely available at www.nih.gov.

3. DATA AND RESULTS

The pore spaces of the VOI's are shown in 3D using Image J software in Figure 1 below. The largest pore clusters were identified via cluster labelling using Mathematica software. The largest pore clusters were rendered using gray contrast. Effective porosity had also been determined using NIST Stokes Permeability Solver.



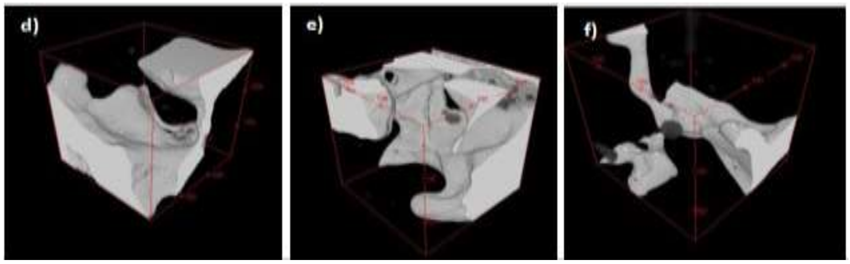


Figure 1: 3D Rendering of all VOI's: a) VOI 1; b) VOI 2; c) VOI 3; d) VOI 4; e) VOI 5; f) VOI 6.

The results of cluster labelling analysis are summarized in Table 1 below. The total count of solid and pore voxels may be used to calculate porosity and pore connectivity. Large pore clusters are characterized by low surface-to-volume (S/V) ratios, as seen evidently on the data. On the other hand, isolated pores have higher S/V ratios. As the number of isolated pores increases, the total S/V ratio of isolated pore space also increases.

Table 1. Summary of Cluster Labelling Results

Dataset #	VOI #	Total # of Solid Voxels	Total # of Pore Voxels	# of Voxels of Largest Pore Cluster	# of Isolated Pore Clusters	Surface-to-Volume Ratio (S/V) of Largest (Percolated) Pore Cluster	Total Surface-to-Volume Ratio (S/V) of Isolated Pores
1	1	22179327	4820673	4297203	133	0.058	0.164
	2	19933680	7066320	6887389	166	0.045	0.256
	3	19878504	7121496	6797125	58	0.051	0.184
2	4	18220472	8779528	8748711	334	0.043	1.248
	5	17901724	9098276	9078310	66	0.045	0.637
	6	23226566	3773434	3656408	178	0.072	0.346

Pore characteristics derived through image processing using Image J software and Mathematica version 6.0 are presented in the previous table are summarized in Table 2 below. Porosity values ranging from 18-34% having an average of 24.3% is within the range of 15-25%, a typical value for for pervious concrete (Montes, et al.(2006), Schaefer et. al.(2006)).

Table 2. Summary of Pore Characteristics

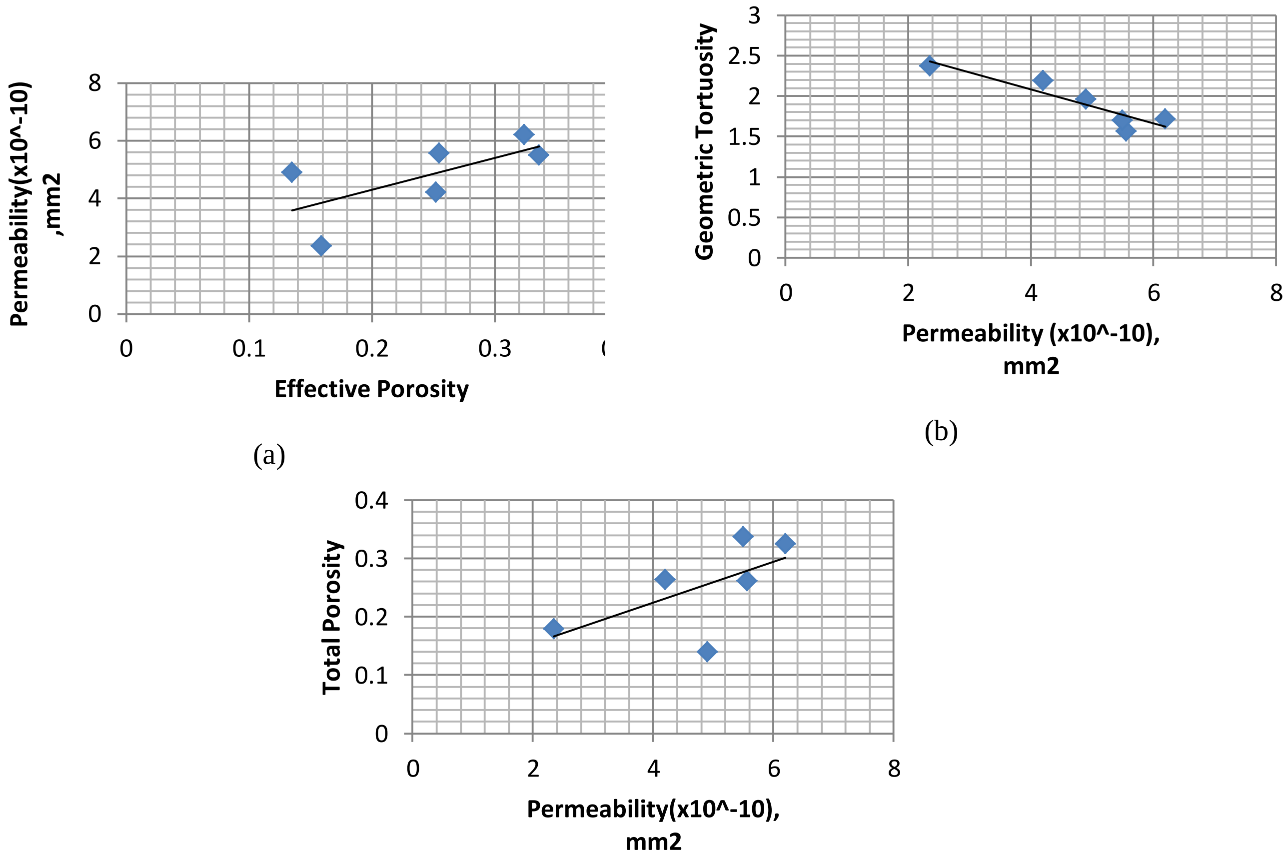
Dataset #	VOI #	Mean Pore Size,mm	Hydraulic Diameter,um	Total Porosity	Effective Porosity	Pore Connectivity
1	1	1.12	87.97	0.179	0.159	0.891
	2	1.06	89.71	0.262	0.255	0.975
	3	1.65	90.55	0.264	0.252	0.954
2	4	1.12	87.34	0.325	0.324	0.996
	5	1.52	77.54	0.337	0.336	0.998
	6	1.65	90.35	0.140	0.135	0.969

Diffusion properties of the porous media obtained using the random walk simulation for Mathematica program and the NIST Stokes Solver are summarized in Table 3.

Table 3. Summary of Diffusion Properties

Dataset #	VOI #	Slope of mean-square displacement	Geometric Tortuosity	Permeability X10^{-10}, mm^2
1	1	0.177	2.37	2.35
	2	0.403	1.57	5.56
	3	0.209	2.19	4.20
2	4	0.339	1.72	6.20
	5	0.347	1.70	5.50
	6	0.260	1.96	4.93

All fitted slopes on the mean-square displacement from the random walk Mathematica 6.0 program had a goodness of fit of 0.99, indicating that the particles have attained full diffusion.



(c)

Figure 2.0 Fluid flow characterization of microstructure of pervious concrete
(a) permeability vs. effective porosity, (b) geometric tortuosity vs. permeability, and (c) total porosity vs. permeability

4. CONCLUSION

This paper was able to demonstrate successful porous media characterization using non-destructive, computer-based techniques. This is useful in the evaluation of pervious concrete and other porous materials for a wide range of applications. Fluid transport properties have been determined including effective porosity, total porosity, geometric tortuosity, and permeability. Softwares used for analysis were Mathematica 6.0, ImageJ and NIST Stokes Permeability Solver. Resulting average effective porosity (24%) and permeability(4.78) is within range of existing values for modelled and actual pervious concrete.

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