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Virtual Pervious Concrete: Microstructure, Percolation, and Permeability

by Dale P. Bentz

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

Keywords: freezing-and-thawing; microstructure; percolation; permeability; pervious concrete; void.

INTRODUCTION

In the first years of the twenty-first century in the U.S., renewed interest has been expressed in pervious concrete pavements, mainly due to environmental issues.[1] According to Reference 1, these materials have actually been used for over 30 years in England and the U.S. and are also widely used in Europe and Japan as a roadway surface course to reduce traffic noise and improve skid resistance. Basically, a pervious concrete is simply produced by removing the fine aggregates from a concrete mixture and often using a much narrower distribution of coarse aggregates, leading to an increased voids content, typically on the order of 15 to 30%. These voids are at least partially connected (percolated) so that the pervious concrete not only has dramatically increased permeability to allow water penetration and filtration but also lower strength and potentially lower durability. As the volume of pervious concrete placed in service increases dramatically, research on this material and technology transfer activities are also increasing.[1-3] For example, ACI Committee 522, Pervious Concrete, was formed in 2001 to "develop and report information on pervious concrete," and ASTM International's Subcommittee C09.49, Pervious Concrete, was recently formed to deal exclusively with pervious concrete issues.

Some of the efforts within ASTM International will center on the development of standard test methods for unit weight and fluid permeability, as well as standard consolidation methods for preparing cylindrical specimens for further testing. Whereas previous studies have focused mainly on experimental measurements of the strength and flow properties of pervious concretes,[1-3] herein the focus will be on so-called virtual pervious concrete. The goal will be to develop a realistic three-dimensional (3D) computer microstructural model to represent pervious concrete and to compute its percolation and transport properties for comparison against available experimental data. A successful microstructural model should prove useful for assisting in the design of pervious concrete mixtures and also for examining durability aspects of pervious concretes, such as clogging and freezing-and-thawing durability. To aid in this objective, the computational programs used to create 3D microstructures and to compute percolation and transport properties have been documented[4,5] and are being made freely available to the public from the National Institute of Standards and Technology (NIST) anonymous ftp site: ftp://ftp.nist.gov/pub/bfrl/bentz/permsolver and ftp://ftp.nist.gov/pub/bfrl/garbocz/FDFEMANUAL.

RESEARCH SIGNIFICANCE

Pervious concrete is one of the fastest growing markets of concrete construction. As emphasis on environmental protection and building green is continuing to increase, the demand for pervious concrete will increase as well. A better understanding of the relationships between the microstructure and transport properties of pervious concretes will allow for better mixture proportioning and materials selection. The demonstration of a virtual pervious concrete that captures the percolation and transport properties of the real in-place material will also allow an extension to computational-based durability studies of pervious concrete, considering issues relevant to freezing-and-thawing resistance and clogging, for example.

COMPUTER MODELING

Microstructural models

Various microstructural models have been investigated to assess their suitability for creating virtual pervious concrete microstructures. First, the NIST hard core/soft shell (HCSS) model was examined.[6] It consists of a 3D continuum model for a three-phase material. Hard core spherical particles are surrounded by a soft shell and placed within a third bulk phase. Whereas the hard core particles cannot overlap, the soft shells can freely overlap with one another and even with the hard cores. Such a model seems a likely candidate to represent pervious concrete, if one considers the hard cores as the coarse aggregates, the soft shells as the (surrounding) cement paste, and the leftover bulk phase as the voids within the pervious concrete structure. Because this model is based on the random placement (parking and not packing) of the hard cores,[6] however, even when the particles were placed in order from largest to smallest, for realistic (for example,

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narrow) pervious concrete aggregate size distributions, the maximum achievable aggregate volume fraction remained below 40%, far below that of the 55 to 65% typical of real materials.

Next, a hybrid model was considered. First, a simple computational algorithm to drop (and roll) spherical particles of a specified size distribution into a 3D rectangular parallelepiped continuum volume was used.[7] This model employs periodic boundaries on the faces parallel to the direction in which the spheres are being packed. The central portion (in the direction of the dropping) of such a loosely packed particle system was then used as direct input to provide the particle center locations required by the HCSS computer program. The HCSS code was then used to surround each of these aggregates with a user-specified uniform thickness layer of cement paste varying between 0.1 and 1.0 mm (0.004 and 0.04 in.), each thickness corresponding to a separate 3D virtual pervious concrete. Once again, the remainder of the 3D volume was considered to be occupied by voids. With this hybrid model, it was easily possible to obtain realistic volume fractions of aggregate particles, and thus 3D virtual pervious concretes that matched their real counterparts in terms of volume fractions of aggregates, cement paste, and voids. For example, one model consisting of equal volume fractions of aggregates of diameters 4.75, 7.25, and 9.5 mm (0.187, 0.285, and 0.374 in.) was used with various thicknesses of paste shells to create virtual concretes with 62% by volume aggregates and voids contents ranging from 4 to 32% by volume. Each continuum microstructure, 100 mm (3.94 in.) on a side, was digitized into a 300 x 300 x 300 voxel cubic volume for subsequent computation of percolation and transport properties. Thus, each voxel was 1/3 or 0.333 mm (0.013 in.) in dimension. The ability of these models to capture the percolation and transport characteristics of real pervious concretes will be presented in the results that follow.

Finally, as the study progressed, it became clear (refer to the Results and Discussion section) that a microstructural model with a higher percolation threshold for the void phase was needed. Thus, a 3D reconstruction algorithm (computer program rand3d.c on the ftp site) based on filtering a 3D image of Gaussian noise with a measured correlation function[8] was employed to generate a set of 300 x 300 x 300 voxel digitized virtual pervious concretes, with void volume fractions ranging between 12 and 32%. In this case, the needed correlation functions were obtained from two-dimensional (2D) images from the hybrid HCSS virtual microstructures of similar porosity. These virtual digital image microstructures were also characterized with respect to their percolation and transport properties. It should be emphasized that the microstructural models presented herein do not specifically consider the gradients in vertical porosity distributions that may be produced during the compaction of pervious concrete specimens in the field.[9]

Percolation

The porous virtual pervious concrete microstructures were first evaluated with respect to their percolation characteristics, namely, the degree of connectivity of the voids in 3D space. A 3D burning algorithm developed previously for 3D digital images[10] was employed to determine the fraction of total void voxels that are part of a continuous pathway from one face of the microstructure to the opposite face, for each of the three principal directions (x, y, and z). One of the key microstructural parameters influencing transport (in addition to overall porosity and pore size) is the connectivity of the 3D void system. It is reported that for pervious concretes, based on permeability measurements for various void fractions, the percolation threshold for the voids is somewhere in the range of 10 to 15%.[1,2]

Conductivity

Next, the electrical conductivities of the virtual pervious concretes were computed using the C programming language version of a previously published finite difference computer program (dc3d.c).[5] Here, for comparison against experimental data,[3] the voids were considered to have a conductivity of one unit, with the remaining solids (paste and aggregates) considered to have a conductivity of 0. The program then returns the computed conductivity of the composite microstructure in each of the three principal directions. These values can be conveniently compared with the experimental data of Neithalath, Weiss, and Olek,[3] who recently measured the electrical impedance properties of a wide variety of pervious concretes.

Permeability

Finally, the permeabilities of the virtual pervious concretes were computed using a linear Stokes solver.[4,11,12] The permeability computer program applies a pressure gradient in one of the three principal directions and computes the resulting velocity vector field within the porosity. The Darcy equation[11] is then used to compute the equivalent permeability for the microstructure. A user's manual for this code is available[4] and the codes are also available for download at ftp://ftp.nist.gov/pub/bfrl/bentz/permsolver. The computed permeabilities can be compared with experimental measurements previously performed on a wide variety of pervious concretes.[1-3] The permeability codes have been validated previously by computing the permeabilities of both circular and square tubes;[4,13,14] for a square tube 25 voxels on a side, the error between computed and theoretical permeabilities was only approximately 0.01%, whereas for a circular tube with a diameter of 25 voxels, it was less than 2%.[4] In addition to being used for computing the permeabilities of virtual materials as demonstrated in the present study, these transport property computer codes are equally applicable to real 3D microstructures obtained from tomography data,[15] for instance.

RESULTS AND DISCUSSION

Microstructures

Representative 2D slices from the 3D microstructural models are provided in Fig. 1 and 2 for the hybrid HCSS and the filtered correlation reconstruction models, respectively. In the former case, all three phases (aggregates, cement paste, and voids) are identifiable, whereas in the latter case, only the solids (aggregates and paste) and voids are delineated. To the human eye, the void space in the hybrid HCSS model appears to consist of larger and somewhat more connected pores. Because the two microstructural models are clearly visually different, the next step was to undertake a quantitative analysis of their 3D percolation characteristics.

Percolation and transport properties

The 3D burning algorithm was applied to the various virtual pervious concretes and the results are presented in Fig. 3, which plots the fraction of the total porosity that is part of a percolated pathway versus the total porosity. Clearly, the two models exhibit vastly different percolation characteristics. Previously, the percolation threshold for the void space in the case of totally overlapping spheres has been determined to be 3.2 ± 0.4%,[16] and the hybrid HCSS model is observed to exhibit a similar value of approximately 4%. On the other hand, the correlation filter reconstruction algorithm yields a set of microstructures with a void percolation threshold near 10%, closer to the commonly quoted value for actual pervious concretes.[1,2] Thus, from a percolation standpoint, the reconstruction-based model appears to be more consistent with real pervious concretes than the hybrid HCSS model.

Next, the electrical conductivity and permeability of the virtual microstructures were considered. The computed relative electrical conductivities for the virtual pervious concretes as a function of void fraction are presented in Fig. 4. In Fig. 4, the experimental data from Neithalath et al.[3] are included; the actual values in Fig. 4 were obtained by multiplying the experimentally measured void fractions by their measured pore connectivity factors. According to the equations and definitions presented in Neithalath et al.,[3] this should be equivalent to the relative conductivity for the case where the pores are filled with a solution with a conductivity of one unit and the solids have a conductivity of 0 (in agreement

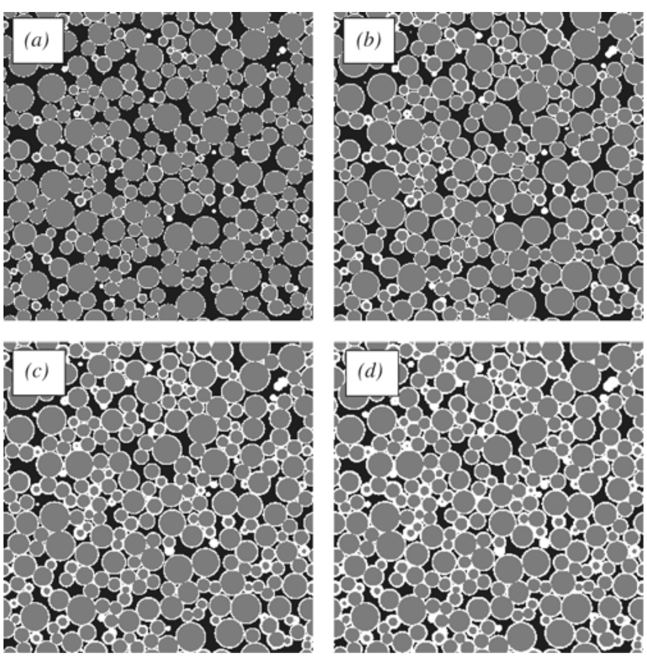

Fig. 1—Two-dimensional images from 3D virtual pervious concrete microstructures based on hybrid HCSS model. Aggregates are grey circles, surrounding cement paste is white, and voids are black. Porosities are: (a) 27.3%; (b) 22.4%; (c) 18.0%; and (d) 14.1%. Images are 100 x 100 mm (3.94 x 3.94 in.) in size.

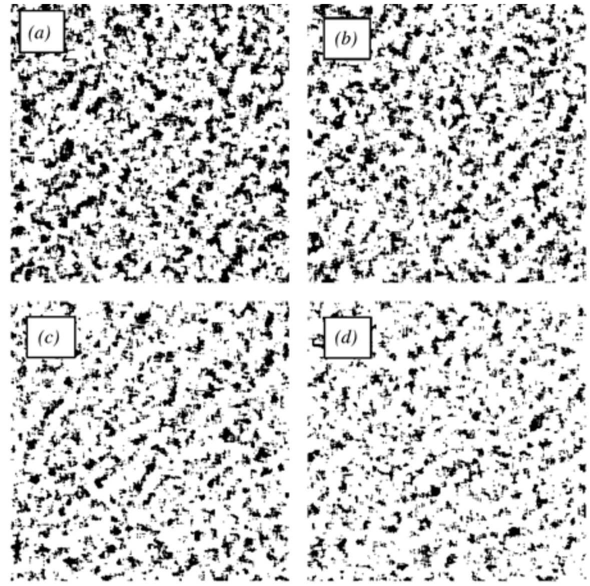

Fig. 2—Two-dimensional images from 3D virtual pervious concrete microstructures based on correlation filter reconstruction algorithm. Aggregates and cement paste are white and voids are black. Porosities are: (a) 27.4%; (b) 22.3%; (c) 17.9%; and (d) 14.1%. Images are 100 x 100 mm (3.94 x 3.94 in.) in size.

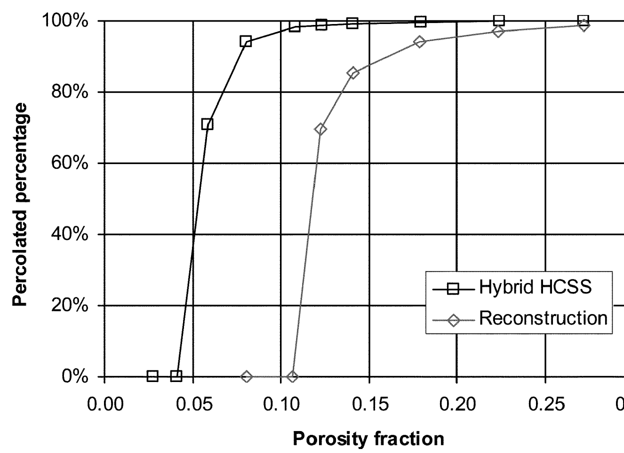

Fig. 3—Percolation plots for two virtual pervious concrete microstructural models.

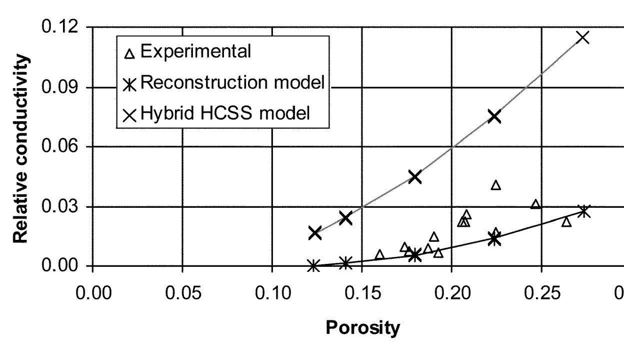

Fig. 4—Model and measured relative electrical conductivities for pervious concretes as function of porosity (void fraction). Experimental data are calculated from values provided by Neithalath et al.[3]

with the conditions used in the simulations). Once again, the agreement between experimental data and virtual data is clearly superior for the correlation filter reconstruction-based microstructures.

A similar comparison is observed for the permeability predictions, as shown in Fig. 5. Once again, clearly, the permeability values computed for the correlation filter reconstruction-based microstructures are in far better agreement with the experimental values taken from the literature[1-3] than are the ones computed for the microstructures based on the hybrid HCSS model. Not surprisingly, the microstructure model that better captures the percolation characteristics of real pervious concretes also provides estimates of conductivity and permeability that are in good agreement with those measured experimentally. Because permeability is also strongly dependent on (entryway) pore size,[7,8,11] the correlation filter reconstruction algorithm appears to be adequately capturing that aspect of the real pervious concrete microstructures. Whereas there is significant variability amongst the experimental values presented in Fig. 5, the reconstruction model produces permeability values that generally fall near the middle of the range of experimental data for any given porosity in the range of 12 to 32%.

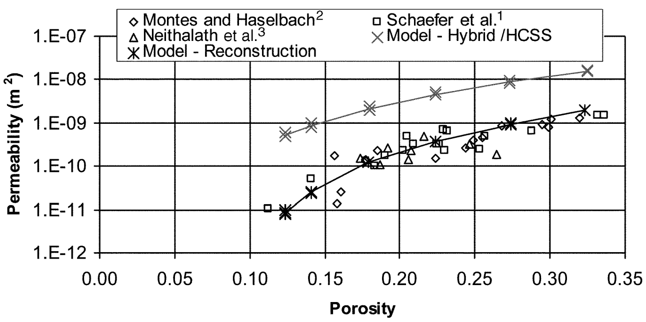

Fig. 5—Model and measured permeabilities for pervious concretes as function of porosity (void fraction). Experimental data are taken from indicated references.[1-3] Uncertainty estimates provided in references are as follows: for data of Montes and Haselbach,[2] repeatability in experimental values was within ±10% for a particular sample, whereas for data of Neithalath et al.,[3] coefficient of variation for three repeated measurements was on order of 20%. Permeability conversion: 1 m^2 = 1.01 × 10^{12} darcy.

The results in Fig. 3 to 5 have demonstrated that the virtual pervious concrete based on the correlation filter reconstruction algorithm produces a simulated void microstructure whose percolation characteristics and transport properties are quite close to those reported for various pervious concretes. Such a model could be used to predict the permeability, or conductivity, of a pervious concrete a priori. Another possibility would be to obtain a real 2D image of a pervious concrete, extract the voids, measure their correlation properties, and use this information to model a 3D pervious concrete whose transport properties could be computed, instead of making the corresponding physical measurements.

Additionally, the existence of a realistic 3D microstructure model should allow for the virtual examination of degradation potentials. For example, with regard to freezing-and-thawing durability, one can envision that in some pervious concretes, there exists a subset of the void space that fills with water, but does not drain. This accessible but not percolated porosity can be easily quantified by using the burning algorithm mentioned previously. Figure 6 provides a plot of both the accessible and the percolated void (porosity) fractions for virtual pervious concretes with various total porosities. The difference between these two would indicate porosity that is accessible, but perhaps not drainable. As the total porosity falls below approximately 20%, there exists a measurable (1% or more) fraction of such porosity that can easily fill with water but is not part of a connected pathway for drainage. This causes concerns with frost durability in this subset of pervious concretes.

Clogging potential is another possibility that can perhaps be examined using the virtual pervious concrete. Computationally, an algorithm similar to a mercury intrusion experiment can be used to examine the accessibility of the 3D porosity as a function of entryway pore size.[17] By equating this entryway pore size to the size of the particles causing the clogging, the clogging potential of various pervious concretes might be assessed. An example of this analysis is provided in Fig. 7 in which various diameter spherical particles (templates) have been intruded into the voids of two different virtual pervious concretes based on the correlation filter reconstruction algorithm and one based on the hybrid HCSS model. For

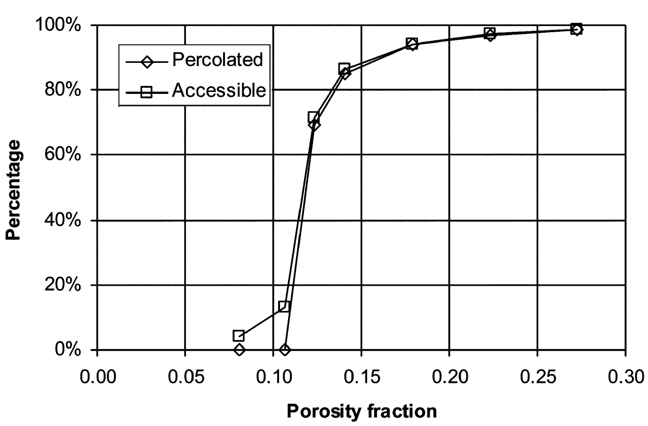

Fig. 6—Percolated and accessible percentages of total voids as function of porosity (void) fraction for virtual pervious concrete microstructures based on correlation filter reconstruction algorithm.

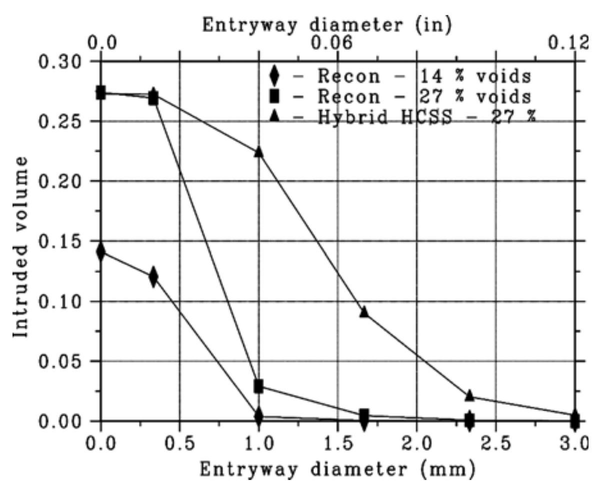

Fig. 7—Intruded volume fraction versus entryway pore diameter for virtual pervious concretes with different void fractions and based on two different microstructural models.

both of the correlation filter-based virtual pervious concretes, the infiltration of particles 1 mm (0.0394 in.) in diameter or greater could lead to considerable clogging, as indicated by the low intrusion volumes. For smaller particles (for example, 0.333 mm [0.013 in.] in diameter), the 14% porosity virtual pervious concrete should be more susceptible to clogging than the 27% one. The clogging results for the virtual pervious concrete based on the hybrid HCSS model indicates a much larger critical pore size, consistent with this model's higher permeability values in comparison with the reconstructed and real pervious concretes. With both a more percolated void network and a larger critical pore size, it would naturally be expected that the virtual pervious concretes based on the hybrid HCSS model would have a much higher permeability, as illustrated in Fig. 5.

CONCLUSIONS

The successful development of a virtual pervious concrete based on a correlation filter 3D reconstruction algorithm has been demonstrated. The virtual pervious concrete contains a 3D void structure that exhibits percolation characteristics and computed transport properties in good agreement with those of real world pervious concretes, based on available literature data. While in this study, the needed 2D correlation functions were obtained from the hybrid HCSS model, in the future, they may be obtained directly from 2D images of actual pervious concretes. When full 3D tomography data sets are available from actual pervious concretes,[1] the presented percolation and transport property computation codes may be conveniently used to compute percolation, conductivity, and permeability of the real materials. Finally, potential extensions of the virtual pervious concrete to exploring durability issues such as freezing-and-thawing resistance and clogging have been introduced.

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