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Characterization of pervious concrete through image based micromechanical modeling

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HIGHLIGHTS

- Microstructure of pervious concrete is analyzed through image analysis.
- Dependence and distribution of pore sizes, positions have been characterized.
- Existence of representative volumetric elements is discussed.
- Validation of the imaged based micromechanical analysis has been proved.

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ABSTRACT

Pervious concrete has been widely used in parking lots and airport fields. However, past experience has shown durability and strength of the pervious concrete remains a challenge for adopting them in wider applications, as the binding material proportion is low and the use of fine aggregates is nearly zero. When loading in compression, the failure appears first in the weak concrete zone induced by the random distribution of voids. The process continues until the failure of the whole specimen occurs. Thus, the position, size and shape distribution of voids in the pervious concrete microstructure control the overall behavior of the material. In this work, the influence of the distribution of voids on the strength, stiffness, and permeability of pervious concrete microstructure is studied by 2D image analysis and finite element modeling. The position and size distribution of the microstructure voids are first summarized through Fast Fourier Transformation (FFT) analysis. A finite element analysis is then conducted on the microstructure models regenerated through the derived microstructure characteristics using ANSYS Parametric Design Language (APDL). The effect of the sample size of 2D microstructures is studied by varying the section size and a possible representative volume element (RVE) is therefore found. Predicted stress-strain plots are generated for the 2D specimen under compressive load and the obtained results, including stiffness, strength and permeability are compared with the results from the experiments conducted following ASTM standards. The comparison between models and physical experiments showed around or above 90% accuracy, which validates the suggested micromechanical analysis method of the previous concrete composite.

1. Introduction

Due to a high percentage of porosity (10–25%), the 7-day compressive strength of typical pervious concrete is around 1500–2000 psi (10.3–13.8 MPa) [1], which limits its application and long term durability. Field investigations for pervious concrete pavements have shown excessive crack generation and spalling of the concrete surface, which eventually reduces the service life of the overall pavement system [2,3]. In cold weather regions, this issue is even more prominent due to the freeze-thaw cycles the pervious concrete experienced. Researchers around the world have implemented different mix designs and performed excessive experimental studies to find a sustainable pervious concrete mix [4–6]. Attempts have been taken to introduce fiber to the pervious concrete, but due to lack of effective fiber-concrete interface bonding, the strength improvement remained insignificant [7]. In order to understand the mechanical behavior and enhance the long term performance of pervious concrete, an image-based micromechanical model of the pervious concrete is suggested in this paper to

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enhance understanding of the relationship between microstructure and macro behavior of the material.

Jing Hu et al. discussed the nature of pore structure through backscattered electron (BSE) images of polished sections of cement paste material [8]. Pore size distribution was characterized and the critical pore size was determined for the cement paste at different hydration times. The influence of image resolution was also investigated in the study. Wong et al. presented a technique to distinguish pores from a normal backscattered electron image of cement-based material [9]. The study described a critical point where a small incremental gray value caused a sudden increase in porosity estimation, a condition termed as overflow. Lange et al. also explored the nature of pore structure through backscattered electron images of polished cement based material sections [10]. Image analysis techniques used in this study included sizing, two-point correlation, and fractal analyses. Pore size distribution from Mercury Intrusion Porosimetry (MIP) was compared to void size distribution derived from backscattered electron images. Igarashi et al. compared the microstructure of cement pastes revealed by SEM-BSE image analysis with a simulated structure generated by the CEMHYD3D hydration simulation model developed at University of Twente [11]. The spatial array of unhydrated cement particles was simulated by the model. However, spatial features in capillary pore structure obtained by the simulation were different from the microstructure derived on SEM-BSE images.

Pervious concrete collects pavement surface water and waste and filter them through its pore structures. Pervious concrete increases driver safety and enhance environment cleanness, which has been widely used in airport, parking lots, etc. However due to its weak weariness and strength, pervious concrete shows low durability and could not be applied to applications with high load demand. Enhancement of the strength and stiffness of the pervious concrete highly depends on the behavior of the microstructure. Based on this, the goal of this study is to propose a quick and convenient tool to characterize the porous microstructures of pervious concrete and predict its mechanical behavior through its microstructure. The whole paper is divided into five sections. In Section 1, position and size distribution of voids on the 2D electron microscopy image of the pervious concrete specimen are analyzed through SEM images. In Section 2, a micro-structure model regenerated with the derived distribution parameters in Section 1. In Section 3, a FEM model is created to model the progressive failure of the pervious concrete. In Section 4, the simulated results are then compared with the lab experiments. A summary is provided in Section 5 to conclude the study and opens the door for further application of the model to optimally design the pervious concrete.

2. Image analysis of pervious concrete specimen

2.1. Image analysis through ImageJ

The void distribution inside the pervious concrete is captured through electron microscope. The sample was attached to a 100 mm square plastic petri dish using hot glue and placed into a GE Phoenix X-ray computed tomography system (MicroCT) equipped with a 180 kV high power nanofocus X-ray tube. One thousand two hundred seventy-five projections of the sample were acquired for each scan at a voltage of 140 kV and a current of 250 mA. Detector timing was set to 1000 ms and the total acquisition time was 1 h and 6 min per scan. The sample magnification was 1.6× with a voxel size of 122.58 mm. For the larger sample size, 4″ diameter × 8″ height (φ 100 mm × 200 mm), the sample was divided into three separate scans. The acquired images from each scan were merged together and reconstructed into a volume data set using GE datos|x 3D computer tomography software version 2.2. The reconstructed volume was then viewed and manipulated using VGStudio Max 2.2 by Volume Graphics. 2D section was taken from two different specimens with a maximum size of 94.0 × 68.6 mm (3.7″ × 2.7″, batch 1) and 200 × 100 mm (8.0″ × 4.0″, batch 2) respectively. Several sections with a consistent increment ratio in sizes are taken from the full image (Fig. 1). These sections are then analyzed with the ''ImageJ'' software platform developed by National Institute of Health (NIH) [12].

The voids are first separated from the concrete matrix through a threshold gray value of the image (Fig. 2(b)). The voids are then outlined in the image showing their sizes and their positions in the matrix (Fig. 2(c)).

The position of each void has been located through the X and Y coordinate values of their centroid. The area of each void has been tabulated and the void percentage is then calculated from the area data. The pore size distribution is first analyzed through Fast Fourier Transformation (FFT) and the resultant distribution is then transferred to MATLAB to regenerate the pervious concrete microstructure. Different regeneration represents a virtual sampling of the pervious concrete matrix.

2.2. Fast Fourier Transformation (FFT) of the void distribution

From the image analysis data, the relative position (X and Y coordinates) of the voids for different section sizes was plotted as histograms to describe any possible pattern of the distribution. However, the plots showed that the distribution of voids through the entire section of specimen does not follow any apparent pattern with the increment of section size (Fig. 3). In this study, a Fast Fourier transformation (FFT) analysis is conducted on the void distribution obtained from the image analysis data and the dominant distribution frequencies are extracted.

The method of adopting FFT analysis for void characterization is not totally new. Moulinec and Suquet [13] adopted this method in characterizing the inhomogeneous distribution of porosity and studied its effect on the nonlinear behavior of a composite material. Nicolas Bilger et al. performed numerical simulations on different spatial distributions of voids [14] generated through the FFT derived distribution parameters. Three types of microstructures were investigated: random microstructures with no void clustering, microstructures with a connected cluster of voids, and microstructures with disconnected void clusters.

Using the derived statistical distribution parameter of voids, the porous microstructure is regenerated through a MATLAB code and fed to ANSYS for further analysis. The FFT distribution of voids on the actual image and the MATLAB generated microstructure is compared to confirm the accuracy of the distribution (Fig. 4). A close match of the void size distribution is clearly seen in Fig. 4. From Fig. 4, a major uniform distribution of void positions is observed, with a small clustering (around 5%) at locations of the 40% and 60% specimen dimension.

3. Micromechanical modeling of pervious concrete

An APDL code was written to cooperate the microstructure generation and load stress analysis in ANSYS.

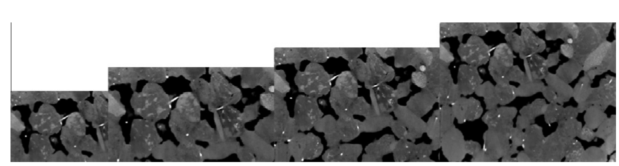

Fig. 1. Different section sizes from the same image.