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Computations of permeability tensor coefficients and anisotropy of asphalt concrete based on microstructure simulation of fluid flow

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Abstract

Asphalt concrete is the most widely used material for building the surface layer of pavements. It is a porous material that consists of a non-uniform arrangement of asphalt binder, aggregate particles and air voids. One of the primary factors controlling pavement performance is the fluid flow characteristics within the surface asphalt concrete layer.

This paper focuses on the numerical simulation of fluid flow in the three-dimensional (3-D) microstructure of asphalt concrete, and the calculation of permeability from the flow field. The asphalt concrete microstructure was captured using the non-destructive X-ray computed tomography (CT) technique. X-ray CT images were processed in order to identify and retain interconnected air voids and eliminate isolated voids. This image processing enhanced the efficiency of the model as it does not have to solve for flow in isolated voids that do not contribute to fluid flow. The X-ray CT images were analyzed and the results were used to determine the relationship between air void distribution and permeability directional distribution or anisotropy.

The computed permeability values were found to have good correlation with the experimental measurements. The major and minor principal directions of the permeability tensor were found to correspond to the horizontal and vertical directions, respectively. The results indicated that the non-uniform spatial distribution of air voids created more open flow paths in the horizontal directional than the vertical direction, and hence was the much higher permeability in the horizontal directions.

Keywords: Permeability; X-ray CT; Fluid flow; Microstructure; Anisotropy; Air void distribution

1. Introduction

Moisture damage in asphalt concrete can be caused by two primary mechanisms. The first mechanism is associated with the chemical interaction of water with asphalt and aggregates leading to the loss of cohesive bonding within the binder and loss of adhesive bonding between aggregates and binder [8,10]. The second damage mechanism is due to the build up of pore pressure in voids saturated with water under dynamic traffic loading. Moisture damage leads to excessive deflection, cracking, permanent deformation, and reduction in the load carrying capacity [9]. The first step towards controlling moisture damage is the development of experimental and analytical techniques to accurately assess asphalt concrete permeability and its relationship to the properties of the mix constituents.

Permeability of a material refers to its ability to transmit fluids through its voids when subjected to pressure or a difference in head. Three primary approaches have been typically followed for modeling and predicting permeability of porous media. The first approach aims at the development of a relationship between permeability and the probabilistic distribution of air voids similar to the one developed by Childs and Collis-George [5] and modified by Marshall [11]. Recently, Masad et al. [14] developed a relationship between asphalt concrete permeability and the probability

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density function of the distribution of air voids captured using X-ray CT. The second approach relies on analytically deriving equations that relate permeability to average parameters such as percent of air voids and tortuosity [4]. The third approach focuses on the development of numerical models that simulate fluid flow in reconstructed or captured microstructures of porous media [1,12,16,21,3].

Adler et al. [1] and Martys et al. [12] solved the Stokes equation for creeping or viscous flow in porous media. Masad et al. [16] used the staggered grid arrangement to solve the Navier–Stokes equations within the two-dimensional microstructure of porous media. Tashman et al. [21] modified the solution by Masad et al. [16] through employing a non-staggered grid arrangement instead of the staggered grid. Al-Omari and Masad [3] expanded the solution by Tashman et al. [21] to three-dimensional microstructures and presented results verifying the accuracy of the developed numerical model in describing the permeability of idealized microstructures such as packed spheres and parallel plates. They also simulated the permeability in three-dimensional microstructures of asphalt concrete specimens and compared the results to analytical solutions of lower and upper bounds of permeability.

2. Objectives

The primary objectives of this study are to:

1. Improve the numerical model developed by Al-Omari and Masad [3] in order to accommodate both creeping flow and inertial flow in the asphalt concrete microstructure. This is an important feature in order to analyze fluid flow in the different types of asphalt concrete mixes with a wide range of air void distributions in terms of size and connectivity.
2. Develop a method in order to process the microstructure images, used in the numerical simulations, in order to eliminate the isolated voids that do not contribute to fluid flow.
3. Use the numerical simulation results in order to calculate the permeability tensor coefficients and anisotropy for a wide range of asphalt concrete specimens. The computational results are supported with experimental measurements of permeability, and microstructure measurements of the directional and spatial distributions of air voids.

3. Fluid flow simulation model

The fluid flow model is formulated using the governing equations of the steady incompressible fluid flow. These governing equations are the continuity (Eq. (1)), and momentum equations (Navier–Stokes equations) in the x-, y-, and z-directions written in conservative forms in Eqs. (2)–(4), respectively. The only driving force for the velocity field is assumed to be the pressure difference between the inlet and outlet of the 3-D microstructure

$$\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=0 \tag{1}$$

$$\frac{\partial}{\partial x}\left(\rho uu-\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\rho uv-\mu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\rho uw-\mu\frac{\partial u}{\partial z}\right)=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial w}{\partial x}\right) \tag{2}$$

$$\frac{\partial}{\partial y}\left(\rho vv-\mu\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial x}\left(\rho vu-\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\left(\rho vw-\mu\frac{\partial v}{\partial z}\right)=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial w}{\partial y}\right) \tag{3}$$

$$\frac{\partial}{\partial z}\left(\rho ww-\mu\frac{\partial w}{\partial z}\right)+\frac{\partial}{\partial x}\left(\rho wu-\mu\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\rho wv-\mu\frac{\partial w}{\partial y}\right)=-\frac{\partial P}{\partial z}+\frac{\partial}{\partial z}\left(\mu\frac{\partial w}{\partial z}\right)+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial z}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial z}\right) \tag{4}$$

In Eqs. (1)–(4), velocity components in the x-, y-, and z-directions are u, v, and w, respectively. The applied pressure is represented by P, and fluid density and viscosity are represented by ρ and μ, respectively. The non-staggered scheme is used in developing the numerical model. Cell dimensions in the x-, y-, and z-directions are presented by Δx, Δy, and Δz, respectively. The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) was used to solve the momentum equations [19]. Following this method, the following expressions for the velocities in x-, y-, and z-directions can be obtained:

$$u_P=(1-\omega)u_P^0+\omega\frac{\sum_{\substack{i=n,s,e,w,lo,up\\ j=N,S,E,W,LO,UP}} a_iu_j+\left(\frac{P_W-P_E}{2}\right)\Delta y\Delta z+S_{\text{visc}}}{a_P} \tag{5}$$

$$v_P=(1-\omega)v_P^0+\omega\frac{\sum_{\substack{i=n,s,e,w,lo,up\\ j=N,S,E,W,LO,UP}} a_iv_j+\left(\frac{P_N-P_S}{2}\right)\Delta x\Delta z+S_{\text{visc}}}{a_P} \tag{6}$$

$$w_P=(1-\omega)w_P^0+\omega\frac{\sum_{\substack{i=n,s,e,w,lo,up\\ j=N,S,E,W,LO,UP}} a_iw_j+\left(\frac{P_{UP}-P_{LO}}{2}\right)\Delta x\Delta y+S_{\text{visc}}}{a_P} \tag{7}$$

In Eqs. (5)–(7), the capital letters (E, W, S, N, LO, and UP) represent the six nodal points of the cells adjacent to the current cell (P) (Fig. 1). The lower case letters represent the six edges of the current cell. Eqs. (5)–(7) calculate the velocity of the current iteration (u_P, v_P, or w_P) as the summation of two parts. The first part is carried from the previous iteration (u_P^0, v_P^0, or w_P^0); while the second part is calculated using the velocity coefficients (a_i) and velocity values at the different edges (u_j's, v_j's, and w_j's). The relaxation factor (ω) accounts for the share of each part and its value ranges from 0 to 1. The term S_{visc} accounts for the