Computational and experimental evaluation of hydraulic conductivity anisotropy in hot-mix asphalt

M. EMIN KUTAY†, AHMET H. AYDILEK‡*, EYAD MASAD¶# and THOMAS HARMAN§**

†Turner-Fairbank Highway Research Center-FHWA, 6300 Georgetown Pike Rm. F210, McLean, VA 22101, USA
‡Department of Civil and Environmental Engineering, University of Maryland, 1163 Glenn Martin Hall, College Park, MD 20742, USA
¶Zachry Department of Civil Engineering, Texas A&M University, 3135 TAMU, College Station, TX 77843, USA
§Turner-Fairbank Highway Research Center-FHWA, 6300 Georgetown Pike Rm. F210, McLean, VA 22101, USA

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Moisture damage in asphalt pavements is one of the primary distresses that is associated with the disintegration of the pavement surface, excessive cracking and permanent deformation. Moisture damage is a function of the chemical and physical properties of the mix constituents, and the distribution of the pore structure (microstructure), which affects fluid flow within the pavement. This paper deals with the relationship between the hot-mix asphalt (HMA) microstructure and hydraulic conductivity, which has traditionally been used to characterize the fluid flow in asphalt pavements.

Conventional laboratory or field measurements of hydraulic conductivity only provide information about the flow in one direction and do not consider flow in other directions. Numerical modeling of fluid flow within the pores of asphalt pavements is a viable method to characterize the directional distribution of hydraulic conductivity. A three-dimensional lattice Boltzmann (LB) fluid flow model was developed for the simulation of fluid flow in the HMA pore structure. Three-dimensional real pore structures of the specimens were generated using X-ray computed tomography (CT) technique and used as an input in the LB models. The model hydraulic conductivity predictions for different HMA mixtures were validated using laboratory measurements. Analysis of the hydraulic conductivity tensor showed that the HMA specimens exhibited transverse anisotropy in which the horizontal hydraulic conductivity was higher than the vertical hydraulic conductivity. Analysis of X-ray CT images was used to establish the link between fluid flow characteristics and the heterogeneous and anisotropic distributions within the pore structure.

Keywords: Hydraulic conductivity anisotropy; Asphalt concrete; Lattice Boltzmann; X-ray computer tomography; Image analysis

1. Introduction

Moisture damage is caused by destruction of the cohesive bond within the asphalt binder or the adhesive bond between the aggregate and asphalt binder. Adhesive debonding, which is manifested by stripping of the binder from the aggregates, is known to cause cracks, permanent deformation, and reduction in the load carrying capacity that might ultimately necessitate replacement of the entire pavement layer. A mix resistance to moisture damage is related to a number of factors that include asphalt film thickness, aggregate shape characteristics, surface energy of aggregates and binder, and pore structure distribution (McCann et al. 2005, Masad et al. 2006a,b). Kringos and Scarpas (2005) have recently introduced a numerical model to understand the physical and mechanical processes causing debonding of the binder from the aggregates due to moisture transport in asphalt pavements. The model idealized the aggregates as two-dimensional circular structures coated with a binder film, and analyzed the diffusion of water into the film and desorption of the binder film from the aggregate. The work by Kringos and Scarpas (2005) offered a numerical modeling framework to incorporate the different mechanisms associated with moisture damage.

A better understanding of the moisture damage phenomenon can be achieved through studying the relationship between the pore structure distribution and

*Corresponding author. Tel: +1-301-314-2692. Fax: +1-301-405-2585. Email: aydilek@eng.umd.edu
||Formerly Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Maryland, 1173 Glenn Martin Hall, College Park, MD 20742, USA. Email: mubammed.kutay@fhwa.dot.gov
¶Tel: +1-979-845-8308. Fax: +1-979-845-0278. Email: emasad@civil.tamu.edu
** Email: tom.harman@fhwa.dot.gov
fluid flow characteristics in hot-mix asphalt (HMA). Several analytical and empirical equations have been developed for the estimation of hydraulic conductivity, which is commonly used to describe fluid flow in porous media such as HMA (Kozeny 1927, Carman 1956, Walsh and Brace 1984, Al-Omari et al. 2002). Derivations of these equations are usually based on the approximation of pore structure with simple geometries, such as tubes and cones, and therefore the models may not be applicable to the complex pore structures of asphalt pavements.

Laboratory or field measured hydraulic conductivity of asphalt pavements is usually assumed to be the same in all directions. However, asphalt pavements have an anisotropic and heterogeneous internal pore structure, which has a direct influence on the spatial and directional distributions of hydraulic conductivities (Masad et al. 1999). For instance, recent macro-scale numerical studies concluded that most of the fluid flow in asphalt pavements occurs in the horizontal direction (Masad et al. 2003, Hunter and Airey 2005).

Numerical simulations at the micro-structural levels have been recently used to understand fluid flow characteristics in HMA. Al-Omari and Masad (2004) utilized a semi-implicit method for pressure-linked equations (SIMPLE) finite difference scheme to solve the Navier-Stokes equations for modeling of flow within the pore structure of asphalt specimens. They calculated the hydraulic conductivity tensor of eight different asphalt specimens, and concluded that longitudinal ($k_{xx}$) and transverse ($k_{yy}$) hydraulic conductivities are close to each other and are much higher than the vertical ones ($k_{zz}$).

In spite of the influence of the directional distribution of hydraulic conductivity on fluid flow in pavements, information is still lacking about this distribution. The components of the hydraulic conductivity tensor and their relation to the pore structure parameters, such as pore constriction areas in three different directions (i.e. $x$-, $y$- and $z$-directions), need to be explored to accurately estimate flow patterns in asphalt pavements. Such flow patterns can be used in the design of efficient pavement drainage systems that consider the directional distribution of hydraulic conductivity. They can also be used as part of numerical simulations of moisture damage at the microstructural level similar to the model developed by Kringos and Scarpas (2005).

In response to this need, a study was conducted to model fluid flow in asphalt pavements. X-ray CT was used to acquire real three-dimensional pore structures of asphalt specimens by eliminating the potential errors that might stem from idealized pore structure assumptions (Wang et al. 2003, Masad et al. 2006c). A three dimensional pore scale-based fluid flow model was developed by utilizing the lattice Boltzmann (LB) approach, one of the most reliable methods that is increasingly being used in various engineering applications in simulating single-phase, Newtonian and incompressible fluid flows (Chopard and Droz 1998, Rothman and Zaleski 1998, Kandhai et al. 1999, Chen and Doolen 2001, Succi 2001, Hazi 2003, Pilotti 2003). The hydraulic conductivities estimated by the model were compared with laboratory experimental measurements. The characteristics of the hydraulic conductivity of asphalt pavements in three different directions, longitudinal ($k_{xx}$), transverse ($k_{yy}$) and vertical ($k_{zz}$), and the effect of constrictions on these hydraulic conductivities were studied. The relationships between the normal and shear components of hydraulic conductivity were also investigated.

2. Modeling of fluid flow using lattice Boltzmann method

The LB method is a numerical technique for simulating viscous fluid flow (McNamara and Zanetti 1988). The method approximates the continuous Boltzmann equation...
by discretizing a physical space with lattice nodes and a velocity space by a set of microscopic velocity vectors (Maier et al. 1997). In the LB method, the physical space is discretized into a set of uniformly spaced nodes (lattice) that represent the voids and the solids (figure 1(a)), and a discrete set of microscopic velocities is defined for propagation of fluid molecules (figure 1(b)). The time- and space-averaged microscopic movements of particles are modeled using molecular populations called the distribution function, which defines the density and velocity at each lattice node. Specific particle interaction rules are set so that the Navier-Stokes equations are satisfied. The time dependent movement of fluid particles at each lattice node satisfies the following particle propagation equation:

\[ F_i(x + e_i, t + 1) = F_i(x, t) + \Omega_i - B_F \]  

where \( F_i \), \( e_i \) and \( \Omega_i \) are the particle distribution function, microscopic velocity and collision function at lattice node \( x \), at time \( t \), respectively. The subscript \( i \) represents the lattice directions around the node as shown in figure 1(b), and \( B_F \) is the body force and is given as \( B_F = -3w_i (e_i \cdot \nabla p) \) where \( \nabla p \) is the applied pressure gradient and \( w_i \) is the weight factor for the \( i \)th direction (Martys et al. 2001). The collision function \( \Omega_i \) represents the collision of fluid molecules at each node and has the following form (Bhatnagar et al. 1954):

\[ \Omega_i = -\frac{F_i - F_i^{eq}}{\tau} \]  

where \( F_i^{eq} \) is the equilibrium distribution function, and \( \tau \) is the relaxation time which is related to the kinematic viscosity of the fluid \( \nu \) through the relationship \( \nu = (2\tau - 1)/6 \). The pressure gradient that is set to trigger the flow is often termed as a density gradient in LB algorithms, since the following relationship (also called the equation of state) exists between density and pressure in the lattice space (Maier et al. 1997):

\[ P = \frac{c_s^2}{\gamma} \rho \]  

where \( P \) and \( \rho \) are pressure and density, respectively, and \( c_s \) is a constant termed the lattice speed of sound. Equilibrium distribution functions for different models were derived by He and Luo (1997). The function is given in the following form for the 3D 19-velocity lattice (D3Q19) model that was used in the current study:

\[ F_i^{eq} = w_i \rho \left[ 1 + \frac{e_i u}{c_s^2} + \frac{(e_i u)^2}{2c_s^4} - \frac{(u-u)^2}{2c_s^2} \right] \]  

where \( u \) is the macroscopic velocity of the node. The lattice speed of sound, \( c_s \), is equal to 1/3 for the D3Q19 lattice. The D3Q19 model has been commonly used by previous researchers and the weight factors for the model are \( w_0 = 1/3 \) for a rest particle, \( w_i = 1/18 \) for particles streaming to the face-connected neighbors and \( w_i = 1/36 \) for particles streaming to the edge-connected neighbors. The macroscopic properties, density (\( \rho \)) and velocity (\( u \)), of the nodes are defined by the following relations:

\[ \rho = \sum_{i=1}^{19} F_i \rho = \sum_{i=1}^{19} F_i e_i / \rho \]  

Kutay and Aydilek (2005) presented results verifying the accuracy of the D3Q19 LB model with well-known analytical and theoretical solutions of simple geometries. An excellent agreement was observed between these solutions and the LB simulations for Stokes flow around a cylinder and flow in circular tubes. The percent error ranged from 0.1 to 2%. It was also shown that the LB model was able to simulate fluid flow accurately, even at relatively low resolutions (low number of lattice sites). Kutay and Aydilek (2005) further evaluated the performance of the D3Q19 LB model through laboratory hydraulic conductivity tests conducted on unbound aggregate specimens. X-ray CT and mathematical morphology-based techniques were used to analyze the pore structure of the aggregates and these pore structures were input into the LB model. A relatively good agreement was observed between the model predictions and the laboratory data, and the difference in hydraulic conductivities was less than an order of magnitude.

3. Components of the hydraulic conductivity tensor

Darcy’s law for one dimensional flow is written in the following form:

\[ k_{zz} = \frac{(Q_z/A)}{i_z} \]  

where \( Q_z \) is the measured flow rate, \( i_z \) is the applied hydraulic gradient, and \( A \) is the specimen cross sectional area perpendicular to the direction of pressure gradient.
Equation (6) can also be written as:

\[ u_z = k_{zz} \nabla \frac{P_z}{\gamma} \]  

(7)

where \( \nabla P_z = (P_{z-in} - P_{z-out})/L \) is the pressure gradient in z-direction, \( L \) is the specimen length, and \( \gamma \) is the unit weight of the fluid (\( = 9.81 \text{ kN/m}^2 \) for water). The velocity vectors in each direction (figure 2) can be defined using the generalized Darcy’s formula, which is given in a tensor form as follows (Kutay 2005):

\[
\begin{bmatrix}
    u_x \\
    u_y \\
    u_z
\end{bmatrix} = -\frac{1}{\gamma_{\text{eff}}} \begin{bmatrix}
    k_{xx} & k_{xy} & k_{xz} \\
    k_{yx} & k_{yy} & k_{yz} \\
    k_{zx} & k_{zy} & k_{zz}
\end{bmatrix} \begin{bmatrix}
    \nabla P_x \\
    \nabla P_y \\
    \nabla P_z
\end{bmatrix}
\]  

(8)

where \( u_x, u_y \) and \( u_z \) are the average velocities in x-, y-, and z-directions, respectively. Solving equation (8) for the directional hydraulic conductivities was performed by applying a pressure gradient only in the z-direction to compute the three components of the hydraulic conductivity tensor (i.e. \( k_{xz}, k_{yz} \) and \( k_{zz} \)). Applying a pressure gradient in x-, y-, or z-direction and setting the pressure gradients in the other two remaining directions equal to zero in equation (8) (e.g. \( \nabla P_z \neq 0, \nabla P_x = 0 \) and \( \nabla P_y = 0 \) for flow in z-direction) reveals the following set of equations for directional hydraulic conductivities:

\[
k_{xz} = -\gamma_{\text{eff}}(u_x/\nabla P_z) \]

(9)

\[
k_{yz} = -\gamma_{\text{eff}}(u_y/\nabla P_z) \]

(10)

\[
k_{zz} = -\gamma_{\text{eff}}(u_z/\nabla P_z) \]

(11)

\[
k_{xx} = -\gamma_{\text{eff}}(u_x/\nabla P_x) \]

(12)

\[
k_{yx} = -\gamma_{\text{eff}}(u_y/\nabla P_x) \]

(13)

\[
k_{zx} = -\gamma_{\text{eff}}(u_z/\nabla P_x) \]

(14)
4. Materials and methodology

4.1 Material properties

The analysis of fluid flow in HMA included field cores and laboratory prepared specimens. The laboratory specimens were fabricated per AASHTO PP28 procedure in order to study a number of mixture variables that are likely to affect the pore structure distribution and hydraulic conductivity. The selected variables included the nominal maximum aggregate size (NMAS), compaction energy (number of gyrations in the gyratory compactor), and aggregate size distribution or gradation. Of the 36 laboratory specimens prepared for this study, 24 were Superpave dense graded mixtures and 12 were relatively permeable stone matrix asphalt (SMA) mixtures. For the Superpave mixtures, NMASs of 9.5, 12.5, 19 and 25 mm were selected. SMA gradations were selected from three different NMASs: 9.5, 12.5 and 19 mm. Number of gyrations was varied from 25 to 75 to cover a range of compaction energies. Seven 150-mm diameter field cores were obtained from the test sections of the accelerated loading facility (ALF) located at the Turner-Fairbank Highway Research Center (TFHRC) of the Federal Highway Administration (FHWA). Figures 3 and 4 provide the aggregate gradations of laboratory specimens and field cores, respectively. Table 1 presents the mix design properties of all the specimens used in this study.

4.2 Image acquisition and processing

The three-dimensional images of the specimens were generated using the X-ray CT technique. Two-dimensional image slices of the specimens were captured and the slices were stacked to reconstruct the 3D structure. An example of a reconstructed structure of an HMA specimen is shown in figure 5. The vertical resolution (Δz) of the two-dimensional grayscale images was registered by the aperture of the linear detector of the X-ray CT device, which was 0.8 mm. The horizontal resolutions, on the other hand, were directly related to the specimen diameter. A uniform resolution of 0.4–0.8 mm/pixel was achieved in all directions (x, y and z) by resizing the image slices using a bilinear interpolation. The captured grayscale images were converted into a binary form (black and white) using a morphological thresholding technique, where black areas (pixel values of 0) represent solid particles and white areas (pixel values of 1) represent air voids (Kutay 2005).

Following the generation of binary images, an additional task was performed to increase the speed of the simulations. An algorithm was developed to eliminate the isolated pores that had no connection to any of the outside boundaries (i.e. surface) of the specimen, and lattice nodes were generated only at the centers of each white voxel (three-dimensional pixel) that represented the interconnected pore spaces. It is important to mention that this step was not required for the LB simulations; however, the isolated pores were eliminated solely to speed up the simulation at each time step. Furthermore, decreasing the number of nodes reduced the total number of time steps to reach the steady state flow condition. More detailed discussion on X-ray CT technique, specifications of the device utilized in this study, and the methods followed for processing the captured images are provided by Kutay and Aydilek (2005).
4.3 Laboratory test methodology

The vertical hydraulic conductivities ($k_{zz}$) of the HMA specimens were determined using a flexible wall permeameter that was specifically developed for measuring hydraulic conductivity of 150-mm diameter and 70-mm long HMA specimens. Figure 6 shows the schematic drawing of the so-called “Bubble Tube Constant Head Permeameter”. The system allows the application of very low hydraulic gradients, accommodates high flow rates that are associated with testing of permeable asphalt specimens, and significantly minimizes sidewall leakage due to the existence of a membrane. The unique design also eliminates the use of valves, fittings and smaller diameter tubings, all which contribute to head losses that interfere with the test measurements.

The permeameter was placed in a bath to maintain constant tail water elevation (figure 6). The tub rim was located a few millimeters above the specimen top. As water flowed out of the reservoir tube through the specimen, air bubbles emerged from the bottom of the bubble tube. The total head difference through the specimen (H), which was constant during the test, was the height difference between the bottom of the bubble tube and the top of the tub. The total flow rate through the specimen (i.e. $Q_z$) was determined by noting the water elevation drop in the reservoir tube and multiplying it with the inner area of the reservoir tube minus the outer area of the bubble tube. Finally, the vertical hydraulic conductivities were calculated using Darcy’s law.

### 4.4 Modeling of fluid flow through the asphalt specimens using the D3Q19 LB model

The developed D3Q19 LB model was used to simulate fluid flow through reconstructed 3D images of HMA specimens.
specimens. Pressure gradients in the range of $9.97 \times 10^{-7} - 1 \times 10^{-3} \text{g/mm}^2 \text{s}^2$ were set between the inlet and outlet of each asphalt specimen during the LB simulations, in order to simulate the pressure boundary conditions occurring in the laboratory test permeameter. Although the gradients varied based on the resolutions of the captured images, they were all in the linear (laminar) region, where Darcy’s law is applicable. The curved faces of the cylindrical specimens were confined by solid nodes (i.e. black pixels) to simulate a typical membrane that confines the specimen in a laboratory test. The components of the velocity vector perpendicular to the density gradient at the inlet and outlet nodes were initially set to zero (i.e. no slip boundary condition).

The LB fluid flow simulations were run until a steady-state flow condition was achieved. The steady-state flow criterion was set such that the difference in the overall mean velocity in $z$-direction ($u_z$) between two consecutive steps was less than a threshold value. This threshold was selected to be 0.001% of the mean velocity of the current time step. It was also observed that the number of time steps required for flow stabilization varied from 1200 to 164,000, depending on the irregularity of the internal pore structure. In general, less number of time steps was required for specimens with less irregular pore-solid interfaces. Similar observations were also made by Duarte et al. (1992) in their 2D cellular automata-based model of flow through cylindrical obstacles placed between parallel plates.

5. Results and discussion

5.1 Simulated hydraulic conductivities and comparisons with the laboratory measurements

The total and effective porosities of the 43 specimens employed in the testing program are summarized in table 2. The effective porosity refers to the percentage of pores that are connected in the direction of the fluid flow simulation. The effective porosities were calculated using an image analysis algorithm that was developed as part of this study. The algorithm first labeled the interconnected white pixels by using a build-in-connected-component function that grouped the connected pixels based on a neighborhood criterion. The neighborhood criteria can be 6, 18 or 26 in a 3D model, and the 18-connected neighborhood criterion was selected for labeling in the current study. After the labeling was complete, the labeled groups that were not connected to both ends of specimen (top and bottom) were eliminated. This produced a pore channel that was connected to both ends of the specimen. A more detailed explanation of the image algorithm is provided by Kutay and Aydilek (2005).

The analyses revealed that 18 specimens had no interconnected pores between two opposite faces of a specimen. Some of these specimens could actually have some interconnectivity, but at a resolution smaller than that of the X-ray CT images (0.4 mm/voxel dimension). Of course, even if such interconnectivity existed, the hydraulic conductivity would be very small due to the
small sizes of the connected pores. This was evident in the laboratory measurements as the laboratory-based hydraulic conductivities of these eighteen specimens were 1–3 orders of magnitude lower than the hydraulic conductivities of those with effective porosities.

A summary of the vertical hydraulic conductivities ($k_{zz}$) based on LB simulations and laboratory measurements is given in table 2. Computed hydraulic conductivities based on equation (7) plotted against the laboratory measured hydraulic conductivities in figure 7 indicate that the two sets of hydraulic conductivities are in a very good agreement. It is interesting to note that specimens with comparable total porosities exhibited different hydraulic conductivities. For example, specimens 8 and 9 as well as specimens 4 and 5 had approximately the same porosities, but their hydraulic conductivities were different by more than an order of magnitude. An attempt was made to relate the total porosities to measured hydraulic conductivities, but the correlation was poor (Kutay 2005). Higher values of coefficients of determination ($R^2$) were found when the laboratory measured and LB-based hydraulic conductivities were plotted against the effective porosity in figure 8. However, the $R^2$ values are still low with 0.4 and 0.51 for laboratory measured and LB-based hydraulic conductivities, respectively. This finding suggests that the constrictions of flow channels (the location of minimum effective porosities) influence the values of hydraulic conductivities more than the average effective porosity of the entire channel. These constrictions caused a variation in flow throughout the depth of the specimens. Figure 9 is
given as an example to present the streamlines computed at the end of LB simulation for specimen 25C75. Herein, a streamline is defined as a line that is tangent to the velocity vectors everywhere in space. Flow streamlines in figure 9 clearly indicate that only a portion of the pores were utilized in the flow beyond a certain depth, i.e. existence of preferential flow pathways.

In order to study the influence of constrictions on fluid flow, the change of velocity and pore water pressure along the depth was investigated. Analysis of X-ray CT images indicated that the pore pressures and velocities did not vary linearly along the depth due to heterogeneous nature of the asphalt specimens. Figure 10 presents an example set of results for specimen 25C75. The pressure-depth relationship deviates from the linear behavior (i.e. nonuniform pressure gradient exists along the depth of the specimen) due to nonuniform distribution of pores in the specimens. Such behavior was also observed by Masad et al. (2006c) in modeling of fluid flow through asphalt specimens. Figure 10 also indicates that the maximum velocity and pressure gradient occurred at a depth of 58 mm, which was the depth where the pore cross sectional area had its lowest value (i.e. the constriction). The pressure gradient (the slope of the curve in figure 10(b)) at the constriction zone was significantly higher than the average pressure gradient possibly due to inertial flow occurring at this zone. Such high pressure gradients can lead to high shear stresses at the constriction zone, which in turn can contribute to the stripping of the binder from the aggregate and induce damage in the asphalt matrix.

### Table 2. Hydraulic conductivities based on laboratory measurements and LB simulations.

<table>
<thead>
<tr>
<th>Sample No</th>
<th>ID</th>
<th>Specimen ID</th>
<th>n (%)</th>
<th>n&lt;sub&gt;eff&lt;/sub&gt; (%)</th>
<th>k&lt;sub&gt;zz&lt;/sub&gt; (mm/s)</th>
<th>Lab. test</th>
<th>LB model</th>
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<td>12.3</td>
<td>8.18</td>
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<td>0.3560</td>
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<tr>
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<td>0.0200</td>
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<tr>
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<tr>
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<td></td>
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<td>0.0195</td>
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<tr>
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<td></td>
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Note: NC refers to the specimens with no interconnected macro pores (i.e. minimum size greater than 0.3 mm) between two opposite faces of a specimen; n, porosity; n<sub>eff</sub>, effective porosity; NA, effective porosity was not available due to lack of interconnected pore structure. The hydraulic conductivities observed in these specimens are possibly due to the flow in micro pores whose size is less than 0.3 mm, and this size could not be determined by the X-ray CT technique.
5.2 Evaluation of hydraulic conductivity anisotropy

The developed LB model simulates the flow in 3D pore structures of HMA. In order to investigate the components of the hydraulic conductivity tensor, a cubical sample was extracted from the X-ray CT images of the cylindrical specimens (figure 2). It can clearly be seen in table 3 and figure 11(a) that the horizontal hydraulic conductivities (i.e. \(k_{xx}\) and \(k_{yy}\)) were consistently higher than the vertical hydraulic conductivity (i.e. \(k_{zz}\)), and in some cases the difference was close to two orders of magnitude (e.g. 19C50 and 19SMA-A2). The \(k_{xx}/k_{zz}\) ratio ranged from 1.38 to 58.3 and from 1.53 to 52.7 for coarse-graded gyratory and SMA specimens, respectively. For the same specimens, the \(k_{yy}/k_{zz}\) ratio ranged from 1.78 to 76.1 and from 1.47 to 54.9, respectively.

On the other hand, the hydraulic conductivities in the two horizontal directions (i.e. \(k_{xx}\) and \(k_{yy}\)) were close to each other in magnitude. The \(k_{yy}/k_{xx}\) ratio ranged from 0.52 to 2.42 for all specimens, a relatively narrower range as compared to the ranges of the \(k_{xx}/k_{zz}\) and \(k_{yy}/k_{zz}\) ratios.

A plot of \(k_{xx}\) vs. \(k_{yy}\) in figure 11(b) confirms that the hydraulic conductivities in two horizontal directions were comparable within a 50% confidence interval. These results indicate that the asphalt specimens exhibited transverse anisotropy in which there was no anisotropy within the horizontal plane, while there were significant differences between the horizontal and vertical directions.

It should be noted that the Superpave mixtures were prepared under axisymmetric compaction forces that are not expected to induce directional differences in the pore structure or hydraulic conductivity within the horizontal direction. However, it is still possible that specimen segregation during mix preparation could cause relatively small differences between the \(k_{yy}\) and \(k_{xx}\) as obtained in this study. In general, these findings are in agreement with the results of another study conducted by Masad et al. (2006a,b,c).

5.3 Effect of directional distribution of effective porosity on anisotropy of hydraulic conductivity

In order to further investigate the cause of the relatively lower hydraulic conductivity values in \(z\)-direction, the variation of effective porosity in three different directions was plotted for all specimens. Example plots for specimen 25C75 in the \(x\), \(y\)- and \(z\)- directions are given in figure 12(a)–(c), respectively. The effective porosity at each distance along a given direction was determined by first computing the pore area on a plane perpendicular to the direction of interest. For example, the pore area is computed in the \(xy\)-plane when the effective porosity in the \(z\)-direction is considered. Then, the projected pore area was divided by the total area of the specimen on the \(xy\)-plane. As seen in figure 12, the minimum porosity in the \(z\)-direction is about an order of magnitude lower than that of the other two directions, which leads to a lower hydraulic conductivity in the \(z\)-direction.

It is well known that the constriction of the flow channels control the flow rate and hydraulic conductivity in porous media (Kenney et al. 1985, Fischer et al. 1996, Aydilek et al. 2005). These constriction zones are
typically associated with the location of minimum effective porosities. In order to investigate the effect of these constrictions on flow, minimum effective porosities in each direction were plotted against the hydraulic conductivity in the same direction in figure 12(d)–(f). It can be seen that the degree of relationship between the minimum effective porosity and hydraulic conductivity varies in different directions. A relatively good relationship was observed ($R^2 = 0.89$) when the minimum effective porosity in the $z$-direction ($n_{eff-min}$) was plotted against the hydraulic conductivity in the same direction. However, the coefficients of determination between the horizontal hydraulic conductivities (i.e. $k_{xx}$ and $k_{yy}$) and the minimum effective porosities in their corresponding

![Figure 9. Streamlines computed at the end of LB simulation for specimen 25C75.](image)

![Figure 10. Change in (a) mean velocity, (b) pressure, and (c) pore cross sectional area with depth for specimen 25C75.](image)

![Figure 11. (a) The relationship between (a) vertical (i.e. $k_z$) and horizontal (i.e. $k_{xx}$ and $k_{yy}$) hydraulic conductivities, and (b) two horizontal hydraulic conductivities (i.e. $k_{xx}$ vs. $k_{yy}$).](image)
### Table 3. Hydraulic conductivity anisotropy of the asphalt specimens tested.

<table>
<thead>
<tr>
<th>Sample No</th>
<th>ID</th>
<th>Sample</th>
<th>$k_{x}/k_{zz}$</th>
<th>$k_{y}/k_{zz}$</th>
<th>$k_{y}/k_{xx}$</th>
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<td>24.75 12.81 0.52</td>
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Figure 12. The variation in effective porosities in specimen 25C75 along three different directions: (a) z-, (b) x- and (c) y-directions, and the relationship between the minimum porosity and the hydraulic conductivity in (d) z-, (e) x-, and (f) y-direction.
5.4 Relationship between the normal and shear components of the hydraulic conductivity tensor

Physical meaning of the hydraulic conductivity of a porous medium is that it relates the pore water pressure gradient to the resulting fluid velocity in the voids. For example, equation (7) simply implies that \( k_{zz} \) (herein called “normal component” in \( z \)-direction) is a ratio of the average velocity to the applied pressure gradient in \( z \)-direction. Similarly, the “shear components” (i.e. \( k_{xz} \) and \( k_{yz} \)) of the hydraulic conductivity tensor in \( z \)-direction relate the pressure gradient in \( z \)-direction to the velocities in the other two directions (figure 2). Three commonly observed field cases where shear components of the hydraulic conductivity tensor can be used to calculate the fluid velocities are presented in figure 13. Case-1 illustrates a pavement laying on a flat surface. In this case, the flow can be triggered by a rain event creating a pressure gradient in the \( z \)-direction. The velocities in different directions can easily be computed by using the three components of the hydraulic conductivity tensor. Case-2 illustrates a pavement on a slope. In this case, the pressure gradients are present in two directions and, thus, six components of the hydraulic conductivity tensor are required to calculate the fluid velocities. Case-3 illustrates a pavement on a curvature and going downhill, which may experience pressure gradients in all three directions. In this case, all nine components of the hydraulic conductivity tensor are needed to compute the velocities. These three cases illustrate the significance of the components of the hydraulic conductivity tensor to calculate the fluid velocities in the pore structure of asphalt pavements.

Figure 14 shows the relationship between the normal and shear components of the hydraulic conductivity tensor in three different directions. In all three directions, the shear components of the hydraulic conductivity are 1–3 orders of magnitude lower than the normal components (e.g. \( k_{xz} \) and \( k_{yz} \) vs. \( k_{zz} \) for \( z \)-direction). A careful observation indicates that the data in \( z \)-direction (figure 14(a)) are closer to the line of equality than the data in \( x \)- and \( y \)-directions. This is attributed to the fact that the presence of smaller constrictions in \( z \)-direction (figure 12(a)) diverted the flow towards the other two directions (i.e. \( x \) and \( y \)) when a pressure gradient was applied in that direction (e.g. Case-1 in figure 13). This was further evident in the observations made for the shear components of hydraulic conductivity in the \( x \)- and \( y \)-directions.
Figure 14(b) and (c) show that the shear components pointing in the $z$-direction (i.e. $k_{xz}$ and $k_{zy}$) are, in general, lower than the shear components pointing the other two directions (i.e. $k_{yx}$ and $k_{zx}$), indicating that the flow is prevented in the $z$-direction and is diverted towards the other two directions. These results, along with the data presented in table 3, suggest that the asphalt specimens exhibited anisotropic hydraulic performance.

6. Summary and conclusions

Understanding fluid flow characteristics of asphalt pavements is critical in the design and performance prediction of these structures. The fluid penetrating into the pores of an asphalt pavement can quickly cause distresses such as cracks and permanent deformation due to the damage of the adhesive bond between the aggregates and the binders. An algorithm was developed for conducting three-dimensional fluid flow simulations through the pores of the asphalt pavements using the LB technique. In a previous study, the accuracy of these simulations was verified with well known analytical and theoretical solutions of fluid flow and hydraulic conductivity of simple geometries. It was shown that the LB model was able to simulate fluid flow accurately, even at very low resolutions (low number of lattice sites).

X-ray CT and mathematical morphology-based techniques were used to capture the three-dimensional pore structure of asphalt specimens prepared using different materials, aggregate size distribution, and compaction levels. These pore structures were input into the LB model, and a very good agreement was observed between the model predictions and the laboratory measurements of hydraulic conductivity.

Analysis of hydraulic conductivity tensor revealed that the horizontal hydraulic conductivities (i.e. $k_{xx}$ and $k_{yy}$) were up to two orders of magnitude higher than the vertical hydraulic conductivity (i.e. $k_{zz}$) for the asphalt pavements tested. On the other hand, the hydraulic conductivities in two horizontal directions (i.e. $k_{yx}$ and $k_{zx}$) were comparable within a 50% confidence interval. This phenomenon was observed for both coarse-graded gyratory specimens and SMA mixtures. In all three directions, the shear components of the hydraulic conductivity were 1–3 orders of magnitude lower than the normal components (e.g. $k_{xz}$ vs. $k_{zz}$ for $z$-direction).

Analysis of X-ray CT images indicated that the pore pressures and velocities varied nonlinearly along the depth due to the heterogeneous nature of the asphalt specimens. The maximum values of pore pressures and velocities consistently occurred at the constriction zones (within the zones that minimum effective porosities were located). The results also indicated that constrictions of flow channels rather than the average effective porosity of the entire channel are likely to be responsible for hydraulic conductivities.

The findings of the research study suggest that caution should be exercised when interpreting the field and laboratory measurements of asphalt hydraulic conductivity. The lack of proper confinement in the current field test procedures causes inaccurate measurements of the vertical hydraulic conductivity. In addition, both laboratory and field methods do not allow for measuring lateral hydraulic conductivity, which is needed for accurate predictions of fluid flow in pavements.

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References


