Fundamentals of Permeability in Asphalt Mixtures

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ABSTRACT

Permeability is an important characteristic of asphalt mixtures. However, there is much confusion regarding the measured value of coefficient of permeability obtained from different sources. It is not uncommon that reported values for similar materials have up to 100 times difference. A study has been conducted at the Louisiana Transportation Research Center (LTRC) to investigate the drainability of five different types of asphalt mixtures that are used for pavement surface layers as well as base course layers. These mixes include: 1) a traditional design of Louisiana Type 8 dense-graded mixture, 2) 19mm Superpave wearing course mixtures, 3) a traditional open-graded Louisiana Type 501 asphalt treated base mixture and, 4) a newly developed open graded large stone asphalt mixture (LSAM). A dual mode flexible wall permeameter has been developed for the purpose of measuring the water permeability or the hydraulic conductivity of asphalt mixtures. This device works on both constant head and falling head principles. It is also capable of determining the materials' hydraulic conductivity when the common Darcy's Law is no longer valid, a situation the authors found to be true for the studied drainable asphalt mixtures (Type 501 asphalt treated base mixture and open graded LSAM). A statistical model to predict the hydraulic conductivity has been developed for the drainable asphalt mixtures in the range of materials of this study.

INTRODUCTION

Permeability or hydraulic conductivity is an important characteristic of pavement materials. A dense graded asphalt mix will prevent water from passing through the layer so that the pavement structure will not be saturated. On the other hand, an open graded asphalt treated based is designed to have the maximum drainability so that water will not stay in the pavement structure.

The common design procedures require drainability characteristics of the paving materials in terms of hydraulic conductivity and effective porosity [1]. Hydraulic conductivity is generally considered the same as the coefficient of permeability as defined in the famous Darcy's Law, in which fluid's discharge velocity is directly proportional to hydraulic gradient [2]. The validity of Darcy's Law depends on the flow condition. It is only valid when the fluid travels at a very low speed in the porous media and no turbulence should occur. Such a flow is called a laminar flow. Unfortunately,

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pavement engineers often forget to check for this important criterion when applying Darcy’s Law to characterize paving materials.

When characterizing the permeability of drainable paving materials, confusion often arises for the measured values of coefficient of permeability. According to Zhou, et al., the reported coefficient of permeability for untreated permeable base from different state DOTs varies from 0.7 mm/sec (200 ft/day) to 70 mm/sec (20,000 ft/day) [3]. One of the important factors for this variation is the different test conditions under which the coefficient of permeability being reported. Tan et al. [4] reported that for the open graded coarse mixture in their study, Darcy’s law was no longer valid.

This paper reports the results of a drainability study of several asphalt mixtures used or proposed by the Louisiana Department of Transportation and Development (LADOTD). The fundamentals of hydraulic conductivity has been reviewed and the validity of Darcy’s Law has been discussed. A dual mode permeability testing device has been developed for this study, and a statistical model to predict the hydraulic conductivity has been developed for the drainable asphalt mixtures in the range of materials of this study.

FUNDAMENTALS OF HYDRAULIC CONDUCTIVITY

Darcy’s Law

In 1856, Henry Darcy investigated the flow of water in vertical homogenous sand filters in connection with the fountains of the city of Dijon, France. He concluded that the rate of flow, Q, is (a) proportional to the cross-sectional area A, (b) proportional to water head loss, \( h_1 - h_2 \), and (c) inversely proportional to the length L. When combined, these conclusions give the famous Darcy’s Law

\[
Q = K A (h_1 - h_2) / L
\]

or

\[
v = -K i
\]

where \( K \) is the proportional factor called hydraulic conductivity (or coefficient of permeability), \( v = Q / A \) is the discharge velocity and, \( i = \partial h / \partial L \) is the hydraulic gradient.

![Figure 1. Darcy's Experiment](image)
Later researchers, having further developed Darcy's basic ideas, determined the dependence of conductivity on the parameters of the transported fluid [5]. They found that hydraulic conductivity is proportional to the ratio of specific weight ($\gamma$) and dynamic viscosity ($\mu$) of the fluid, which is the acceleration due to gravity ($g$) divided by the kinematic viscosity ($v$) of the fluid. Thus, the hydraulic conductivity as defined by Darcy's Law can further be defined as:

$$K = k (\gamma / \mu) = k (g/v)$$

where $k$ is a factor that depends only on the properties of the solid matrix of the porous medium, and is called intrinsic permeability, matrix permeability or sometimes only permeability. The dimension for $K$ is [LT$^{-1}$] and $k$, [L$^2$].

Theoretical Determination of Darcy's Hydraulic Conductivity

Having understood the basic equation of Darcy's Law as well as the definition of hydraulic conductivity and intrinsic permeability, it is not difficult to relate the hydraulic conductivity with geometric characteristics of porous media. The following derivations are excerpted from the translation of the original work of G. Kovacs [5].

**Figure 2. Symbols used For Deriving Poiseuille's Equation**

Assuming that the irregularly connected channels formed by the pores of porous medium can be simplified into a bundle of small straight pipes and assuming only two main forces influence the laminar movement (i.e. gravity and friction), their equilibrium can be expressed in a mathematical form from a model pipe with a diameter of $d_0$. Poiseuille's equation can be derived in this way. The equilibrium of a cylinder concentric about the axis of the pipe having a radius $r$ and a length of $l$, gives the following equation:

$$1 \cdot \gamma \cdot r^3 \cdot l + 2 \pi \cdot r \cdot l \eta \frac{dy}{dr} = 0$$

$$\text{(4)}$$
where $\eta$ is the viscosity of the fluid (Pa·sec).

After solving this differential equation with a boundary condition, where the velocity at the wall of the pipe is zero ($v = 0$ at $r = r_0$), the velocity at a point at a distance of $r$ from the axis can be determined by:

$$v = \frac{i\nu}{4\eta}(r_0^2 - r^2) \tag{5}$$

Integrating the product of the velocity and an elementary area ($dA$) along the total surface of the cross section, the flow-rate through one pipe with a radius of $r_0$ can be obtained by:

$$Q_0 = \int v dA = \int \frac{i\nu}{4\eta}(r_0^2 - r^2) 2\pi r dr = \frac{i\nu}{8\eta} r_0^4 \tag{6}$$

Dividing Equation (6) by the total area, we have the mean velocity,

$$v = \frac{Q_0}{A} = \frac{i\nu}{8\eta} r_0^2 \tag{7}$$

The number of pipes in the model system crossing the unit area of the sample is known, and thus, the total discharge and the virtual seepage velocity can be calculated as follows:

$$v_s = \frac{Q}{A_s} = QN = \frac{i\nu}{32\eta} n r_0^2 \tag{8}$$

where $A_s$ is the total cross-sectional area of the sample, $n$ is the porosity of the medium and $N$ is the total number of pipes which is given by:

$$N = \frac{4n}{d_0^2 \pi} \tag{9}$$

where $d_0$ is the average diameter of the model pipe ($d_0 = 2r_0$) and it is related to the effective particle diameter $D_0$ through the following equation:

$$d_0 = \frac{4n}{1-n} \frac{D_0}{\alpha} \tag{10}$$

where $\alpha$ is the coefficient of shape factor.

Substitute Equation (10) into Equation (8), the following relationship can be determined:
Hydraulic conductivity of the model pipes with constant diameter calculated from Equation (11) is greater than the actual value determined by since the actual pipe diameter is not a constant. Kovacs suggested that the right hand side of Equation (11) being multiplied by a factor of 0.4. The theoretical value of hydraulic conductivity can therefore be determined, which agrees with the dynamic analysis and includes all the effects of the influencing factors.

\[ K = \frac{1}{\eta} \frac{1}{n} \frac{3}{(1-n)^2} (\frac{D_{\text{a}}}{a})^2 \]  

(12)

From Equation (12), it can be concluded that hydraulic conductivity is determined by three factors:
- The fluid characteristics (\( \eta \)), or using the kinematic viscosity \( \nu = \eta / \rho \), the equivalent ratio is \( g(\nu) \);
- Effective grain size, shape and distribution;
- The effect of porosity, \( n^3 / (1-n)^2 \).

Range of Validity of Darcy's Law

As stated before, Darcy's Law is valid for the laminar flow condition. The fact is, Darcy's Law neglects variations in interstitial pressure associated with the inertia of pore liquid as it moves around the grains or along the convoluted pathways. If, at some point, its trajectory has a radius of curvature, \( r \), the fluid inertia sets up an additional pressure gradient \( \rho u^3 / r \), where \( u \) is the pore velocity – this provides the centripetal acceleration associated with the curved trajectory. Darcy's Law is accurate then, only when these inertial pressure gradients are small compared with the viscous stress gradients \( \mu u / d^2 \). Generally, \( r \) is approximately equal to the pore diameter \( d \). Thus, it follows that:

\[ \frac{\rho \cdot u^3}{d} \ll \frac{\mu \cdot u}{d^2} \]  

(13)

or

\[ R = \frac{\nu \cdot d}{\nu} \ll 1, \]  

(14)

where again \( \nu = \mu / \rho \) is the kinematic viscosity and \( d \) is some representative length of the porous matrix.

The term \( R \) in Equation (14) is the pore Reynolds number, a dimensionless grouping of the pore velocity, pore width, and kinematic viscosity. For the validity of Darcy's Law, the \( R \)-value must be small. Generally, when \( R \ll 1 \) a flow is called a creeping flow.

Although by analogy to the Reynolds number for pipes, \( d \) should be a length of the cross section of an elementary channel of the porous medium, it is customary to apply
for some representative length of the grains. Thus the numerical values differ when different grain sizes are chosen. Most literatures suggest using \( d_{10} \), the diameter of the 10\% passing at the gradation curve. Bear [6] suggested that for the validity of Darcy's Law, the Reynolds number should not exceed some value between 1 and 10 (Fig. 3).

![Figure 3. Schematic Curve Relating \( i \) to \( v \) (After Jacob Bear [6])](image)

When the Reynolds number \( R > 1 - 10 \), there are mainly two types of equations to approximate the relationship of hydraulic gradient and flow velocity [5]:

- Binomial form: \( i = av + bv^2 \);
- Potential form: \( i = Cv^n \); or \( v = K \cdot i^{1/m} \).

Although neither of the above forms can be applied with unified material parameters, the second potential form seems to be more accepted in the literature [2,4,5,6] when a validity zone being attached to a given value of the power.

LABORATORY TEST TO MEASURE HYDRAULIC CONDUCTIVITY

Test Methods

Laboratory tests to measure hydraulic conductivity for asphalt mixture normally adapt the test protocols of the soils/granular materials (ASTM D 5084 90, AASHTO T-215 90) [7,8]. Basically there are two types of tests: constant head method and falling head method. All the current test specifications assume the Darcy’s Law to be valid. In other words, the flows must be controlled as laminar during the test.

Testing Concerns

Short-circuiting through Side Walls

In most laboratory permeability tests, a cylindrical specimen is being tested through its vertical direction. The specimen is placed in a cell either wrapped by a flexible membrane or a rigid wall. It is very critical to prevent the short-circuiting of flow through the side of the specimen, a situation that greatly increases the measured
hydraulic conductivity. For asphalt mixture specimens, it is advisable to use flexible wall permeameters with a certain confining pressure outside the membrane to minimize the possibility of short-circuiting.

**Air Blockage**

Air bubbles in the specimens tend to block the flow of water, reducing the measured hydraulic conductivity. Unfortunately, it is sometimes nearly impossible to achieve full saturation for certain mixtures. Common ways to saturate specimens are submergence in water for a certain period of time and initial vacuum saturation.

**Non-laminar Flows**

Non-laminar flows are generally caused by excessive hydraulic gradients during the test. One way to prevent this from happening is to reduce the hydraulic gradient. ASSHTO and ASTM standards limit the upper gradient for rigid wall cell to 0.2 – 0.5, and 1 – 5 for flexible wall system. However, for drainable paving materials such as the open graded large stone asphalt mixtures considered in this study, a very small hydraulic gradient may cause turbulence due to the large air cavities present in these mixtures. In this case, it becomes impractical to simply reduce the hydraulic gradient to some very small values (like 0.01) in order to satisfy the laminar flow condition. Tan et al. [4] suggested the use of a pseudo-coefficient of permeability, the rate of specific discharge when the hydraulic gradient equals 1, as a benchmark to compare different materials hydraulic conductivity. They modified a traditional falling head permeameter and tested three asphalt mixtures under the non-laminar flow conditions [4].

**LABORATORY STUDY OF HYDRAULIC CONDUCTIVITY FOR ASPHALT MIXTURES**

**Objectives**

Realizing the problems in determining hydraulic conductivity of asphalt mixtures, a laboratory study was initiated in the Louisiana Transportation Research Center (LTRC) to investigate the water permeability characteristics of different asphalt mixtures. The main objectives of this study were to

- develop a test apparatus/procedure capable of measuring hydraulic conductivity of different asphalt mixtures;
- provide typical values of hydraulic conductivity of different mixes used in Louisiana;
- establish empirical relations of hydraulic conductivity to other physical indexes such as mix gradation and effective porosity.
Figure 4. Dual Mode Permeameter

Figure 4 is the dual mode permeameter developed and used in this study. The initial device, purchased from Virginia LAB Supply Co., and modified by LTRC is capable of measuring hydraulic conductivity of different materials from dense graded low permeable mixtures to open-graded drainable mixes under both constant and falling head modes. Two pressure transducers installed at the top and bottom of the specimen give accurate readings of the hydraulic head difference during the test. Data acquisition makes it possible to have continuous readings during a falling head test so that the test can be conducted even at very high flow rates (for drainable mixes). The specimen is placed in an aluminum cell between which and the specimen is an anti-scratch rubber membrane that is clamped tightly at both end of the cylindrical cell. A vacuum is applied between the membrane and the cell to facilitate the installation of the specimen. During the test, a confining pressure of up to 103.5 kPa (15 psi) is applied on the membrane to prevent short-circuiting from the specimen’s side. Two different top reservoir tubes have been designed for different materials. One with a diameter of 25 mm (1 inch) is used for dense graded or less permeable materials and the other with 75 mm (3 inch) diameter for highly permeable materials, both with a length of 90 mm (3 feet).

A vacuum is applied on the top of the reservoir tube before the test to saturate the specimen.

Materials
Five types of asphalt mixtures have been tested for their hydraulic conductivity and effective porosity characteristics. Figure 5 shows the gradations of these mixes. Mix LSAM is an open-graded large stone asphalt mix, D_508 is Louisiana Type 508 asphalt treated drainable base mix, Su WC is a dense-graded 19mm Superpave wearing course, C_10 and C_12 are core specimens of a dense-graded mixes taken from interstates I-10
and I-12 near Baton Rouge, Louisiana. AC content and other gradation related parameters are presented in Table 1.

![Figure 5. Gradations of the Mixtures](image)

**Table 1. Mix Asphalt Content and Other Gradation Parameters**

<table>
<thead>
<tr>
<th>Mix Symbols</th>
<th>LSAM</th>
<th>D_508</th>
<th>Su_WC</th>
<th>C_10</th>
<th>C_12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix Type</td>
<td>Open Graded Large Stone ATBC</td>
<td>Open Graded # 57 ATBC</td>
<td>Dense Graded 19mm Superpave Mix</td>
<td>SMA</td>
<td>Dense Graded</td>
</tr>
<tr>
<td>AC %</td>
<td>2 to 3</td>
<td>2.2</td>
<td>4.6</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>d_{10} (mm)</td>
<td>5</td>
<td>0.4</td>
<td>0.32</td>
<td>0.14</td>
<td>0.1</td>
</tr>
<tr>
<td>d_{50} (mm)</td>
<td>25</td>
<td>14</td>
<td>6.5</td>
<td>7.2</td>
<td>3.1</td>
</tr>
<tr>
<td>C_u \text{= d}<em>{50}/d</em>{10}</td>
<td>6</td>
<td>37.5</td>
<td>1.76</td>
<td>1.64</td>
<td>1.16</td>
</tr>
<tr>
<td>P_{38}</td>
<td>18.3</td>
<td>14</td>
<td>66</td>
<td>66</td>
<td>73</td>
</tr>
</tbody>
</table>

Note: d_{10} - Aggregate diameter of the 10% passing;  

\[ d_{50} \] - Aggregate diameter of the 50% passing;  

\[ C_u \] - Coefficient of non-uniformity;  

\[ P_{38} \] - Percent passing 9.5mm (3/8") sieve.  

ATBC - Asphalt treated base course

**Effective Porosity (n_e)**

As described earlier, porosity is one of the three main factors that influence the hydraulic conductivity of porous media. But in asphalt mixes, a portion of the air voids are trapped by asphalt and mineral fillers and are therefore water impermeable. So instead of the air voids, the index of effective porosity relates more directly to the hydraulic conductivity. By definition, effective porosity is the ratio of the volume of voids that can be drained under gravity to the total volume of mixture. The effective porosity is calculated as following:
first calculate the total air void through regular mixture bulk specific gravity \( G_{mb} \) test method using air water, SSD weight for most mixes and glass beads method for open graded, LSAMs [9];

similar to Rice specific gravity test, place the cylindrical specimen into the Rice specific gravity container and conduct the vacuum saturated specific gravity test of the briquette, \( G_{vs} \);

based on the difference between maximum theoretical specific gravity \( G_{max} \) and the vacuum saturated specific gravity of the briquette \( G_{vs} \), calculate the air voids that are undrainable;

the effective porosity is the difference between the total air void and the undrainable air void.

Test Data Processing

Both constant head and falling head tests indicate that for dense graded mixtures, Darcy’s Law is a good approximation, while for open-graded drainable mixes, linear relation between hydraulic gradient and the fluid discharge velocity no longer exist. This can be well illustrated by the following experimental curves of two very different mixes, LSAM, an open-graded large stone asphalt mixture, and, C_10, a 19mm Superpave dense-graded mixture.

Figure 6 shows hydraulic head difference vs. time curve obtained from the two pressure transducers. For the mixes tested in this study, a second order polynomial regression would give a \( R^2 \) better than 0.999.

\[
h = a_0 + a_1 t + a_2 t^2 \tag{15}
\]

where \( a_0, a_1 \) and \( a_2 \) are regression coefficients. Differentiate Equation (15), it yields:

\[
\frac{dh}{dt} = a_1 + 2a_2 t \tag{16}
\]

Therefore, the discharge velocity is expressed as:

\[
\nu = \frac{dQ}{dt} = \frac{A_1}{A_2} \frac{dh}{dt} = \frac{r_1^2}{r_2^2} \frac{dh}{dt} \tag{17}
\]

where \( A_1, A_2, r_1, r_2 \) are the cross section areas and radii of upper cylindrical reservoir and the specimen.
Plotting the discharge velocity against the corresponding hydraulic gradient and applying curve fitting of the potential form \( v = K'i^m \), one obtains two curve fitting parameters \( K' \) and \( m \) (Fig. 7). \( K' \) is defined as the pseudo-coefficient of permeability which equals the average discharge velocity when the hydraulic gradient equals 1. The factor \( m \) is a shape parameter. It is well known that laminar seepage is described with a power of \( m = 1 \). The power gradually decreases as the effect of inertia becomes stronger, achieving an \( m = 0.5 \) value in the case of turbulent flow.
Analysis of Test Results

All test data are plotted and processed similar to the analysis presented in Fig. 6 and 7 to obtain the pseudo-coefficient of permeability $K'$ and the shape factor $m$. The test results shown in Table 2 indicate that hydraulic conductivity varies greatly from different mixes. The pseudo-coefficient of permeability ($K'$) gives a good benchmark to compare the hydraulic conductivity of different mixes regardless of their conformity with Darcy's Law. The shape factor of power $m$ indicates that for dense, impermeable mixes, the values of $m$ close to 1, an indication of laminar flow. On the other hand, the values of $m$ for the drainable mixes are all much less than 1, a clear sign of turbulence.

Table 2. Hydraulic Conductivity Test Results

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>AC %</th>
<th>$n_\varepsilon$</th>
<th>$K'$ (mm/s)</th>
<th>$K'$ (ft/day)</th>
<th>$m$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSAM 2</td>
<td>3.0</td>
<td>18.5</td>
<td>14.76022</td>
<td>4184</td>
<td>0.4866</td>
<td>0.9996</td>
</tr>
<tr>
<td>LSAM 6</td>
<td>3.0</td>
<td>10.7</td>
<td>0.585611</td>
<td>166</td>
<td>0.5153</td>
<td>0.9974</td>
</tr>
<tr>
<td>LSAM 8</td>
<td>2.5</td>
<td>22.1</td>
<td>14.37922</td>
<td>4076</td>
<td>0.5356</td>
<td>0.9938</td>
</tr>
<tr>
<td>LSAM 10</td>
<td>2.5</td>
<td>22.6</td>
<td>12.65767</td>
<td>3588</td>
<td>0.3458</td>
<td>0.9998</td>
</tr>
<tr>
<td>LSAM 12</td>
<td>2.5</td>
<td>13.7</td>
<td>2.667</td>
<td>756</td>
<td>0.2856</td>
<td>0.9833</td>
</tr>
<tr>
<td>LSAM 13</td>
<td>2.0</td>
<td>18.0</td>
<td>10.02242</td>
<td>2841</td>
<td>0.5226</td>
<td>0.9968</td>
</tr>
<tr>
<td>LSAM 14</td>
<td>2.0</td>
<td>17.4</td>
<td>7.729361</td>
<td>2191</td>
<td>0.5403</td>
<td>0.9982</td>
</tr>
<tr>
<td>LSAM 16</td>
<td>2.0</td>
<td>23.2</td>
<td>10.50572</td>
<td>2978</td>
<td>0.4183</td>
<td>0.9916</td>
</tr>
<tr>
<td>LSAM 17</td>
<td>2.0</td>
<td>16.8</td>
<td>7.775222</td>
<td>2204</td>
<td>0.5253</td>
<td>0.9998</td>
</tr>
<tr>
<td>LSAM 20</td>
<td>2.5</td>
<td>20.0</td>
<td>8.011583</td>
<td>2271</td>
<td>0.3191</td>
<td>0.9978</td>
</tr>
<tr>
<td>LSAM 24</td>
<td>2.5</td>
<td>19.5</td>
<td>5.954889</td>
<td>1688</td>
<td>0.5381</td>
<td>0.9927</td>
</tr>
<tr>
<td>D 508 16</td>
<td>2.3</td>
<td>30.5</td>
<td>24.70503</td>
<td>7003</td>
<td>0.5447</td>
<td>0.9865</td>
</tr>
<tr>
<td>D 508 18</td>
<td>2.3</td>
<td>29.8</td>
<td>36.09269</td>
<td>10231</td>
<td>0.3017</td>
<td>0.9824</td>
</tr>
<tr>
<td>C 10 #15</td>
<td>5.0</td>
<td>4.7</td>
<td>0.017639</td>
<td>5</td>
<td>0.9988</td>
<td>0.9984</td>
</tr>
<tr>
<td>C 10 #16</td>
<td>5.0</td>
<td>5.0</td>
<td>0.039271</td>
<td>15</td>
<td>1.0339</td>
<td>0.9852</td>
</tr>
<tr>
<td>Su WC #2</td>
<td>4.6</td>
<td>6.0</td>
<td>0.116417</td>
<td>33</td>
<td>0.9734</td>
<td>0.8983</td>
</tr>
<tr>
<td>Su WC #12</td>
<td>4.6</td>
<td>6.1</td>
<td>0.102306</td>
<td>29</td>
<td>0.8433</td>
<td>0.9780</td>
</tr>
<tr>
<td>C 12 #1</td>
<td>5.0</td>
<td>4.1</td>
<td>0.003528</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 shows the values of the Reynolds number and $d_{10}$ for the different mixtures at the hydraulic gradient of 1. Here $d_{10}$ is used to calculate the Reynolds number.

Table 3. Reynolds Number for Different Mixes at $i = 1$

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>LSAM</th>
<th>D 508</th>
<th>Su WC</th>
<th>C 10</th>
<th>C 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>3~73</td>
<td>10~14</td>
<td>0.03</td>
<td>0.005</td>
<td>0.0004</td>
</tr>
<tr>
<td>$d_{10}$ (mm)</td>
<td>5</td>
<td>0.4</td>
<td>0.32</td>
<td>0.14</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 8 shows the relation between the hydraulic conductivity of pseudo-coefficient of permeability ($K'$) and effective porosity ($n_\varepsilon$). Mixes with similar gradation exhibit an increase in $K'$ with the increase in $n_\varepsilon$. 

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It should be pointed out that if we disregard the fact that Darcy's Law is no longer valid and still use the standard procedure to analyze the test data, very erroneous results will be expected. Figure 9 shows the curve of the ratio of discharge velocity and hydraulic gradient ($v/i$), which supposedly being the coefficient of permeability (a material constant) under the Darcy's Law, versus the hydraulic gradient. The figure clearly shows that the ratio of $v/i$ varies greatly with $i$. Therefore, it will be meaningless to compare this parameter from different sources. A standard value at $i = 1$ will be more reasonable for comparison.

**Estimation of Hydraulic Conductivity**

It is sometimes useful to estimate hydraulic conductivity from volumetric indexes of asphalt mixtures rather than perform the hydraulic conductivity testing. The FHWA
has published a widely used algorithm based on data from the literature. Most recently, Richardson published four predictive formulae based on the data from his own research and the literature [10]. Most of these empirical relations are for granular unbound materials. Hardly any of the existing predictive formulae are for asphalt mixtures. Furthermore, most of the previous test data are based on rigid wall low head variety, using either constant head or falling head procedures. There was no provision for prevention of water short-circuiting along the permeameter walls. Additionally, manometer ports were not used in many of the permeameters considered [10].

Theoretical formula (Eq. 12) indicates that fluid characteristics, effective porosity, effective grain size, shape and distribution determine hydraulic conductivity. Based on that concept, two regression formulae have been developed from the hydraulic conductivity test results considered in this study. It should be noted that the relationship presented in this study is based on a very limited test data. For more generalized empirical relations, more test data will be needed. Figure 10 shows the estimated K' values compared to the experimental test results. This figure also includes the estimation of Tan's [4] test results in which the effective porosity is assumed to be 90% of the air void since the actual test results is not available. Two linear regressive equations for K' can be expressed as

\[ K' (\text{mm/sec}) = 0.917n_v - 52.41d_{2p} + 15.45d_{10} - 175C_v + 117P_{xg} - 143.3 \quad \text{(open-graded)} \quad (r^2 = 0.8831) \]  

\[ K' (\text{mm/sec}) = 0.917n_v - 0.45d_{2p} - 0.0273d_{10} + 0.216C_v + 0.00155P_{xg} - 0.607 \quad \text{(dense-graded)} \quad (r^2 = 0.9699) \]

![Figure 10. Estimated K' vs. Measured K'](image)
Again it should be emphasized that these regressive equations are limited to the hydraulic conductivity test data in this study. More test data will be needed from different types of mixes in order to obtain predictive formulae of practical use.

CONCLUSIONS

Hydraulic conductivity is a fundamental material characteristic that is determined by the properties of the fluid, effective porosity, effective aggregate diameter, particle shape and gradations. Darcy’s Law is only valid for dense graded, low permeable asphalt mixtures under the normal test hydraulic gradients. For mixtures with high effective porosity such as the drainable asphalt mixtures used in this study, Darcy’s Law is no longer valid even for very small hydraulic gradients. A potential form of \( v = K' \) can be used for an approximation when laminar flow condition is not satisfied. A pseudo-coefficient of permeability \( K' \) can be used to compare the relative hydraulic conductivity of different materials.

A flexible wall, dual mode permeameter is developed in LTRC through the modification of Virginia LAB Supply Co.’s flexible wall permeameter cell for the hydraulic conductivity test of asphalt mixtures. The device has been validated through the hydraulic conductivity tests of five different asphalt mixtures used or proposed by the LADOTD.

The typical values of pseudo-coefficient of permeability \( K' \) for the mixtures in this study are: for open-graded large stone asphalt mixture, 2.7 mm/sec (765 ft/day) to 14.8 mm/sec (4190 ft/day), for LA Type 508 open graded drainable base, 24.7 mm/sec (7000 ft/day) to 36.1 mm/sec (10200 ft/day). The coefficient of permeability for dense mixtures varies from 0.003 mm/sec (1 ft/day) to 0.116 mm/sec (33 ftf/day).

Statistical models to predict the hydraulic conductivity have been developed for the asphalt mixtures in the range of materials of this study.

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