A New Simplistic Model for Dynamic Modulus Predictions of Asphalt Paving Mixtures

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Abstract

This paper presents a new mechanistic empirical model for predicting dynamic modulus of asphalt paving mixtures at a wider range of temperatures and loading frequencies, which can be shifted into a master curve for characterizing asphalt concrete. Available predictive models seem to be not capable of predicting dynamic modulus of asphalt mixtures at higher temperatures and lower loading frequencies; these models over-predict dynamic modulus by a significant deviation from laboratory-measured values. The new model is capable of accurately predicting measured dynamic modulus at a broader range of temperatures and loading frequencies.

The proposed new model was derived from the law of mixtures where composite materials are modeled in a combination of parallel and series phases. For a system of purely parallel phases, the combined mechanical behavior is simply the addition of the responses from these phases.

To develop the new model, asphalt mixtures with different performance grades covering highly modified and unmodified asphalt binders were tested in one of the marketed simple performance test (SPT) devices to measure dynamic modulus.

The new model is simple in its formulation, and needs no more than one input from the asphalt binder; the dynamic shear modulus

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(\(|G^*|\)), and one input from the mixture; the voids in mineral aggregate (VMA).

**Key Words:** Dynamic Modulus, Simple Performance Test, Composite Materials, Repeated Loading, Mechanistic Models, Asphalt Concrete, Asphalt Mixtures, Asphalt Binder, Asphalt.

**Introduction**

Dynamic load testing of asphalt concrete became more commonly used to predict pavement performance due to the fact that this type of testing better simulate field conditions as pavements are subjected to repeated traffic loading. Test conditions in dynamic loading including stress level, rate of loading (loading frequency), and test temperature can be changed to measure a broader range of mechanical behavior of asphalt mixtures to predict the variety in traffic loading, speeds, and environmental conditions.

Dynamic modulus is the response of the material under dynamic loading determined in the linear elastic or viscoelastic range by dividing the loading stress amplitude by the peak-to-peak recoverable strain. Two types of dynamic moduli are commonly used in asphalt testing: the extensional (axial) dynamic modulus \((E^*)\) measured from uniaxial or triaxial loading under compression or tension, and the complex shear modulus \((G^*)\) measured from the frequency sweep at constant height (FSCH) test for asphalt mixtures or the dynamic shear rheometer (DSR) sweep test for asphalt binders.

The Strategic Highway Research Program (SHRP) focused on providing simple tools and methods for obtaining fundamental properties of asphalt mixtures that would highly correlate to pavement performance through mechanistic models. One of the simple performance testers that were developed during the SHRP was the Superpave Shear Tester (SST) (1). In the SST frequency sweep at constant height (FSCH) test, a sinusoidal shear strain is applied at a sweep of frequencies to a 50-mm thick specimen glued at both ends and sandwiched between two top and bottom platens applying a variable vertical load to keep the height of the specimen
constant. The shear strain is applied for a specified number of cycles at each frequency. The axial and shear deformations and loads are measured for the number of cycles specified for each frequency. The SST is not portable, and the preparation of the test specimen takes a considerable amount of time and effort. Therefore, the focus was directed towards another simple performance tester that might have advantages over the SST in terms of simplicity and portability.

The National Cooperative Highway Research Program (NCHRP) under NCHRP projects 9-19 and 9-29 developed a Simple Performance Tester (SPT) [2], which can provide fundamental mechanical properties of asphalt mixtures with low cost and simple methods. The advantages of the SPT developed under NCHRP program over the SST are: its simplicity of running the test, less expensive, portable and compact, and less time and effort to prepare the test specimen. Using the SPT, both dynamic modulus and flow number tests can be conducted.

In a dynamic modulus test, a continuous haversine cyclic loading is applied to the specimen at the expected pavement temperature and at a wide frequency range that covers 0.01 to 25 Hz. The dynamic modulus is determined as the peak-to-peak loading stress amplitude divided by the peak-to-peak recoverable resulting strain. In a flow number test, a haversine pulsed loading with a 0.9 second rest period is applied to the specimen at a loading frequency of 10 Hz, at the effective pavement temperature, and at the design stress level (covers the range of 69 to 207 kPa for the unconfined tests, and 483 to 966 kPa for the confined tests). The cyclic loading in the flow number test is continued until 10,000 cycles or until the specimen reaches the tertiary stage, an indication of excessive deformation or failure. The flow number is the number of cycles at the lowest point (zero slope) on the change rate in axial strain versus number of loading cycles curve.

Dynamic modulus is one of the main inputs required for high reliability (level 1) pavement designs in the AASHTO design guide being developed under NCHRP project 1-37A. Currently, the SPT is the leading simple performance tester that provides such fundamental mechanical property (dynamic modulus) for the AASHTO design guide. The SPT is currently used at the Federal Highway Administration’s research centers and by various Departments of Transportation (DOTs).
Other efforts were devoted to develop other simple performance devices capable of providing fundamental mechanical properties including work done at the University of Illinois at Urbana-Champaign on a Hollow-Cylinder Tensile Tester (HCT) (3,4). The HCT showed good potential to serve as a practical method to satisfy testing requirements for level 1 high reliability pavement designs in the AASHTO design guide. The HCT was used to obtain dynamic modulus at temperatures of 0 and 20°C and at loading frequencies of 1 and 5 Hz (5).

The need for dynamic modulus measurement at effective pavement temperatures and design stress levels, therefore, is vital for pavement design and analysis. For this reason, some researchers in the asphalt area focused on developing new effective and robust predictive models for estimating dynamic modulus using available asphalt binder and mixture data, particularly knowing that dynamic modulus measurements at extreme conditions of temperatures and loading frequencies are hard to obtain in laboratory.

Researchers including Christensen, Pellinen, and Bonaquist presented a modified Hirsch model for predicting dynamic modulus of asphalt concrete based on the law of mixtures (6). These researchers modified the original Hirsch model (7) to a relatively simple version for estimating complex modulus and phase angle of asphalt concrete under shear and compression loading.

Witczak and his associates (8,9) developed a predictive equation for estimating dynamic modulus of asphalt concrete as a function of mix design inputs and asphalt binder properties. The original version of the model was developed by Shook and Kallas (10) in the late 60s. Witczak and his associates further modified and refined this model over many years of work and using a large database developed with hundreds of measurements and mix designs. The Witczak model uses the conventional viscosity instead of the complex shear modulus value of the asphalt binder, which requires a middle step of conversion from complex shear modulus (that current Superpave asphalt binder tests provide) to viscosity. It also requires many inputs from the asphalt mixture design part, which makes dealing with this model laborious.

Both the Hirsch model and the Witczak model seem to have reasonable capability of predicting dynamic modulus of asphalt
concrete. The Hirsch model, however, is valid over a wide range of dynamic modulus values as stated by Dongre et al. (11). Both provide reasonable predictions of dynamic modulus until a certain lower limit of asphalt binder modulus. Below this lower limit, predictions from these models seem to have high deviation from measured dynamic modulus values. In other words, both models lack the ability to predict dynamic modulus at higher temperatures and lower loading frequencies. The limitations of these models will be discussed in more details in the coming sections.

In this study, a new simple predictive model was developed based on the law of mixtures for estimating dynamic modulus of asphalt concrete at a broader range of temperatures and loading frequencies with good accuracy and reliability.

**Background on Hirsch Model Formulation**

Christensen, Pellinen, and Bonaquist (6) presented four alternative versions of a modified Hirsch model with different formulations: 1) series formulation; 2) parallel formulation; 3) dispersed formulation; and 4) alternate formulation. Their refinement and analysis showed that the first three versions of the Hirsch model did not provide good accuracy, but the fourth formulation (the alternate one), which is a generalization of parallel and series formulation, provided consistently better accuracy on their data. It was also found in their study that this version of the Hirsch model produced the best results and had the advantage over the other versions of the simplicity and the similarity to the original formulation of the Hirsch model.

What was common in the first three formulations presented in Christensen et al. (6) is the use of what is called the aggregate contact volume (Vc) and the use of the asphalt mastic (asphalt binder + mineral filler) phase instead of the asphalt binder phase alone. The fourth formulation of the Hirsch model was further simplified by treating asphalt concrete as a three-phase system of aggregate, asphalt binder, and air voids. The use of what is called the contact factor (Pc) was also introduced to represent the proportion of parallel to total phase volume. The effective asphalt binder modulus was then substituted for the true asphalt binder
modulus by assuming that the asphalt binder modulus at the aggregate surface is equivalent to the glassy modulus, and then decreases to the true asphalt binder modulus over a transitional distance between the aggregate and the asphalt binder.

One of the main conclusions of their study was that the most effective version of the Hirsch model is the relative simple version, which can be given in terms of the asphalt binder complex shear modulus value, $G^{*}_b$, and voids filled with asphalt (VFA) and VMA of the mixture.

**Objectives**

The main objectives of this study are:
1. To present a new simple mechanistic empirical model for predicting dynamic modulus of asphalt concrete at a wider range of temperatures and loading frequencies;
2. To adjust the high deviation between measured and predicted dynamic modulus from available models; and
3. To discuss the limitations of the available predictive models of dynamic modulus.

**Materials, Experimental Plan and Methodology**

Plant-produced lab-compacted (PPLC), lab-produced lab-compacted (LPLC) asphalt mixtures and field cores taken from the Federal Highway Administration’s Accelerated Loading Facility (ALF) pavements constructed in the summer of 2002 were tested in the SPT for dynamic modulus. Below is a detailed description of the materials used in this study and the experimental plan followed to achieve the goals of the study.

**Asphalt Binders**

Six asphalt binders were used in the preparation of the LPLC asphalt mixtures. These binders consisted of an unmodified PG 70-22 asphalt binder, an air-blown asphalt binder, and the following
four polymer-modified asphalt binders: Styrene-Butadiene-Styrene Linear-Grafted (SBS LG), a crumb rubber asphalt binder blended at the terminal (CR-TB), an Ethylene Terpolymer binder (Terpolymer), and a binder containing a blend of SB and SBS, hereafter called SBS 64-40. The performance grade of these asphalt binders is given in Table1.

<table>
<thead>
<tr>
<th>Asphalt Binder</th>
<th>PG 70-22</th>
<th>Air-Blown</th>
<th>SBS LG</th>
<th>CR-TB</th>
<th>Terpolymer</th>
<th>SBS 64-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>70-22</td>
<td>70-28</td>
<td>70-28</td>
<td>76-28</td>
<td>70-28</td>
<td>70-34</td>
</tr>
<tr>
<td>Continuous PG</td>
<td>72-23</td>
<td>74-28</td>
<td>71-29</td>
<td>79-28</td>
<td>74-31</td>
<td>71-38</td>
</tr>
</tbody>
</table>

**Aggregates**

The aggregate gradation that was used for these asphalt mixtures is shown in Table 2 and Figure 1. It consisted of 100-percent crushed diabase stone with a 12.5-mm (0.5-in) nominal maximum aggregate size (NMAS), the Los Angeles abrasion of the coarse aggregate was 19 and the sand equivalent was 75. The material called “sand” is a Grade F and G sand-sized crushed diabase aggregate. All of the aggregates were from the Loudoun Quarry, Herndon, VA, except for the sand, which was from Luck Stone, Leesburg, VA.
### Table 2 Aggregate Gradations

<table>
<thead>
<tr>
<th>Sieve Size (mm)</th>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.5</td>
<td>100.0</td>
</tr>
<tr>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>12.5</td>
<td>93.6</td>
</tr>
<tr>
<td>9.5</td>
<td>84.6</td>
</tr>
<tr>
<td>6.3</td>
<td>-</td>
</tr>
<tr>
<td>4.75</td>
<td>56.7</td>
</tr>
<tr>
<td>2.36</td>
<td>34.9</td>
</tr>
<tr>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>1.18</td>
<td>24.8</td>
</tr>
<tr>
<td>0.600</td>
<td>18.2</td>
</tr>
<tr>
<td>0.425</td>
<td></td>
</tr>
<tr>
<td>0.300</td>
<td>13.1</td>
</tr>
<tr>
<td>0.150</td>
<td>9.3</td>
</tr>
<tr>
<td>0.075</td>
<td>6.7</td>
</tr>
</tbody>
</table>

### Specific Gravity and Percent Absorption

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Dry SG&lt;sup&gt;1&lt;/sup&gt;</td>
<td>2.947</td>
</tr>
<tr>
<td>Bulk SSD&lt;sup&gt;2&lt;/sup&gt;</td>
<td>2.965</td>
</tr>
<tr>
<td>Apparent SG&lt;sup&gt;1&lt;/sup&gt;</td>
<td>3.001</td>
</tr>
<tr>
<td>% Absorption</td>
<td>0.60</td>
</tr>
<tr>
<td>Los Angeles Abrasion</td>
<td>19</td>
</tr>
<tr>
<td>Sand Equivalent</td>
<td>75</td>
</tr>
</tbody>
</table>

<sup>1</sup> Specific Gravity  
<sup>2</sup> Saturated Surface Dry  
<sup>3</sup> Not Applicable
SPT Specimen Preparation

The asphalt binders were heated to 163°C and mixed with the heated aggregates in proportion to achieve a binder content of 5.3 percent by the total mass of the mixture.

All the asphalt mixtures were short-term oven aged for 4 hours at 135°C according to AASHTO provisional practice PP2-00 (12), and compacted using a Superpave gyratory compactor as prescribed in AASHTO TP4 (13). The compacted gyratory specimen is 165 mm in height and 150 mm in diameter. Final SPT specimens were cored from the gyratory specimens to 100 mm in diameter and sawed at both ends to 150 mm in height with smooth parallel cut faces as prescribed in NCHRP Report 465 (14). The target air-void level was 7.0 ± 0.5 percent. The air-void content of the final test specimen was determined according to AASHTO T269-97 (15).

Gyratory-compacted specimens were also obtained from the plant-produced loose asphalt mixtures in the same manner that was used to produce gyratory specimens from the lab-produced asphalt mixtures. Standard SPT specimens were then fabricated from these
gyratory specimens in the same way described above. Field cores were also taken from the ALF pavements; they were sawed at both ends to create smooth parallel cut faces according to the specifications. In this sense, three different SPT specimen groups were obtained: LCLP, PPLC, and field cores (FC).

Three axial LVDTs were mounted on studs attached to the sides of the SPT specimen with epoxy cement as shown in Figure 2. The gauge length between the stud centers is 75 mm.

![Figure 2. SPT Specimen with Mounted LVDTs](image)

**Testing Procedure**

The SPT specimens were placed in an environmental chamber in order to equilibrate to the testing temperature. Prior to testing, a friction reducing Teflon disc was placed on the platen at the bottom of the loading frame beneath the specimen. Another Teflon disc was placed on top of the specimen with the top platen. The specimen was then centered visually with the load actuator.

The SPT dynamic modulus tests were conducted according to the procedures described in NCHRP Report 465 (14). A contact load was applied to the specimen that is equal to 5 percent of the dynamic load. A haversine dynamic loading was then applied to the specimen as shown in Figure 3. The dynamic load was selected to obtain axial strains in the range of 75 to 125 microstrains. It is
varied from mixture to mixture depending on the stiffness and temperature. The haversine dynamic loading was applied for the specified number of cycles at each specified frequency as shown in Table 3. The dynamic modulus testing was conducted at temperatures of 4, 19, 31, 46, and 58°C (the temperatures of interest in the ALF program). Specimen preparation and testing were conducted at the bituminous mixture and binder rheology laboratories of the Federal Highway Administration’s Turner-Fairbank Highway Research Center in McLean, Virginia.

Table 3 Number of Cycles for Each Frequency

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Number of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>0.5</td>
<td>6</td>
</tr>
<tr>
<td>0.1</td>
<td>6</td>
</tr>
</tbody>
</table>
The full data of the waveform load and deformation were acquired in the last six loading cycles for each transducer. These cycles are used to determine dynamic modulus, $|E^*|$ and phase angle, and $\phi$ as per NCHRP Report 465 (14) procedures summarized below:

The loading stress was calculated using the following formula:

$$\sigma_0 = \frac{\overline{P}}{A}$$  \hspace{1cm} (1)

where:
- $\sigma_0$ = loading stress amplitude;
- $\overline{P}$ = average load amplitude (from best-fit sinusoid function); and
- $A$ = cross-sectional area of specimen.

And the recoverable axial strain was computed using the equation below:

$$\varepsilon_0 = \frac{\overline{\Delta}}{GL}$$  \hspace{1cm} (2)

where:
- $\varepsilon_0$ = strain;
- $\overline{\Delta}$ = average deformation amplitude (from best-fit sinusoid function, computed after removal of the underlying baseline drift deformation); and
- $GL$ = gauge length.

The dynamic modulus, $|E^*|$, was then calculated using the following equation:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$  \hspace{1cm} (3)

The phase angle, $\phi$, was computed using the equation below:
\[ \phi = 360 \times \frac{t_i}{t_p} \]  

(4)

where:
- \( \phi \) = phase angle (in degrees);
- \( t_i \) = average time lag between the peak stress and the peak strain in seconds (computed as the difference between the best-fit load and deformation sinusoid functions); and
- \( t_p \) = average time for a loading stress cycle in seconds.

**Measured Dynamic Modulus Analysis**

The dynamic modulus and the phase angle were determined for all materials in the three sets of data (LPLC, PPLC, and FC data) at all frequencies and temperatures. Dynamic modulus master curves were constructed for each asphalt mixture in the three sets using a sigmoid function in the form shown below:

\[
\log[E^*]_m = a + \frac{b}{1 + e^{c \log f_R + d}}
\]  

(5)

where:
- \([E^*]_m\) = asphalt mixture dynamic modulus;
- \(a, b, c, \) and \(d\) = function coefficients; and
- \(f_R\) = reduced frequency, Hz.

The reference temperature for the master curves was selected to be 19°C. The temperature shift factors and the coefficients of the sigmoid function that best fit the measured dynamic modulus data were determined using “Solver” technique optimization in Excel by minimizing the sum of the errors between the measured data and the sigmoid-fitted data (16). This was done for each asphalt mixture in the three sets. The master curves were created outside of the SPT software environment.
The shift factors were used to calculate the reduced frequency from the loading frequency for a given temperature using the following equation:

\[ f_R = f \times a_T \]  \hspace{1cm} (6)

where:
- \( f_R \) = reduced frequency;
- \( f \) = loading frequency; and
- \( a_T \) = shift factor at a given temperature, T.

The relationship between a temperature and the shift factor at that temperature is given in the form of a binomial function as shown in the following equation:

\[ \log a_T = AT + BT^2 + CT^3 \]  \hspace{1cm} (7)

where:
- \( A, B, \) and \( C \) = function fitting coefficients.

Bonaquist procedure developed under NCHRP project 9-29 is normally used to generate the low-temperature part of the master curve (higher dynamic modulus values) because of the testing limitations in measuring dynamic modulus at low temperatures. An assumed asphalt binder shear glassy modulus of 1 GPa is used to predict the dynamic modulus at low temperatures using the Hirsch model (6,7). At low temperatures or very high reduced frequencies, the limiting value of \( \log \left| E^* \right|_m \) in the sigmoid function is \( a \). Using the Hirsch model-predicted \( \left| E^* \right|_m \) value at the glassy modulus of the asphalt binder, 1 GPa, \( a \) can be found as \( \log \left| E^* \right|_m \). Therefore, \( a \) was fixed when Excel “solver” tool was used to solve for the coefficients of the sigmoid function \( b, c, \) and \( d \). By doing this, the low-temperature asymptote of the master curve was obtained.

Each asphalt mixture master curve represents the measured dynamic modulus of the mixture at the reference temperature. One can obtain the dynamic modulus at any given frequency and temperature knowing the temperature shift factor function and using the master curve.
Figure 4 shows the sigmoidal dynamic modulus master curve; measured data and Hirsch-model predictions for the Terpolymer modified mixture.

![Figure 4. Master Curve of Measured Dynamic Modulus Values for Terpolymer Asphalt Mixture](image)

**Development of the New Model**

There are two forms of the new model as will be shown in the sections below. There was small difference between the developments of the two forms. The factor, $F_c$ in the first formulation is a function of VMA and $|G^*|_b$, and in the second formulation, it is a function of $|G^*|_b$ only.
Derivation of the First Form of the New Model

A simple three-phase system of the composite material was used to formulate the new predictive model developed in this study for estimating dynamic modulus of asphalt concrete as shown in Figure 5.

![Figure 5. Schematic Representation of the New Model](image)

where:
- $V_s$ = volume fraction of aggregate (solids);
- $V_b$ = volume fraction of asphalt binder; and
- $V_a$ = volume fraction of air voids.

$V_s + V_b + V_a = 1.0$.

In this three-phase system, the aggregate, the asphalt binder, the air voids phases are in parallel arrangement with each other. The mechanical response of three simple phases arranged in a composite system in parallel or series can be derived from the law of mixtures, which formulates the combined response of these phases in the system. Based on the laws of mixtures (17), the combined mechanical response of three phases in parallel is given in the following equation:

\[
(V_1 + V_2 + V_3)E_m = V_1 E_1 + V_2 E_2 + V_3 E_3
\]  \hspace{1cm} (8)

And for three phases in series, the equivalent response is represented as shown in the equation below:

\[
\frac{(V_1 + V_2 + V_3)}{E_m} = \frac{V_1}{E_1} + \frac{V_2}{E_2} + \frac{V_3}{E_3}
\]  \hspace{1cm} (9)
where:
\( E_m \) = equivalent mixture extensional dynamic modulus value;
\( V_1 \) = volume fraction of phase 1;
\( E_1 \) = extensional modulus value of phase 1;
\( V_2 \) = volume fraction of phase 2;
\( E_2 \) = extensional modulus value of phase 2.
\( V_3 \) = volume fraction of phase 3; and
\( E_3 \) = extensional modulus value of phase 3.

Note that \( V_1 + V_2 + V_3 = 1.0 \) in this case.

Therefore, using the law of mixtures, the combined behavior of the three-phase system of the new model shown in Figure 5 can be formulated in the following equation:

\[
E_m = V_1 E_1 + V_2 E_2 + V_3 E_3
\]

where:
\( E_1 \) = extensional modulus value of aggregate;
\( E_2 \) = extensional modulus value of asphalt binder; and
\( E_3 \) = extensional modulus value of air voids = 0;

The extensional modulus value of the aggregate is assumed to be equivalent to the glassy modulus of the asphalt binder \( (E_g) \) multiplied by some function of the VMA:

\[
E_s = K_1 E_g
\]

The volume of the aggregate in the compacted asphalt mixture (the composite system in this case) is equal to the total volume minus the volume of voids in mineral aggregate as a percentage of the total volume. Therefore, the volume fraction of the aggregate with respect to the total volume of the system (equals 1.0) can be written in the following equation:

\[
V_s = \frac{100 - VMA}{100}
\]
The volume fraction of the asphalt binder in the system can be represented as a fraction of the volume of the aggregate in the system, and therefore can be formulated as shown below:

\[ V_b = K_2 \frac{100 - VMA}{100} \]  \hspace{1cm} (13)

where:
- \( K_2 \) = coefficient of less than 1.0.

By substituting equations 11, 12, and 13 into equation 10, the following form can be obtained:

\[ E_m = \frac{100 - VMA}{100} K_1 E_g + K_2 \frac{100 - VMA}{100} E_b \]  \hspace{1cm} (14)

By rearranging equation 14:

\[ E_m = \left( \frac{100 - VMA}{100} \right) \left( K_1 E_g + K_2 E_b \right) \]  \hspace{1cm} (15)

The extensional modulus value and the complex shear modulus value are correlated according to the following formula:

\[ G_b = \frac{E_b}{2(1 + \nu)} \]  \hspace{1cm} (16)

where:
- \( G_b \) = complex shear modulus value of asphalt binder;
- \( E_b \) = extensional modulus value of asphalt binder; and
- \( \nu \) = Poisson’s ratio.

Assuming that the Poisson’s ratio of the asphalt binder is 0.5 (incompressible material), then the absolute value of the extensional modulus of the asphalt binder, \( |E_b^*| \), is \( 3 |G_b^*| \), the absolute value of the complex shear modulus of the asphalt.
binder). By substituting into equation 15, the following formulation is obtained:

$$[E^*]_m = \left(\frac{100 - VMA}{100}\right)\left(3K_1[G^*_b]_g + 3K_2[G^*_g]_b\right)$$  \(17\)

The term \(3K_1[G^*_b]_g + 3K_2[G^*_g]_b\) can be reformed as follows:

$$3K_1[G^*_b]_g + 3K_2[G^*_g]_b = 3G^*_g G_{MA}(G^*_b)$$  \(18\)

where:

\[F_c = \text{some function of VMA and asphalt binder complex shear modulus value, which can be formulated in the following form:}\]

$$F_c = \left(\frac{A_1 + A_2}{VMA}\right)^{A_3}$$  \(19\)

This form is derived from the form of the contact volume \((P_c)\) in Christensen et al. \((6)\). \(A_1, A_2, A_3, A_4, A_5\) above are function constants determined from model calibration.

Therefore, the final formulation of the new model is as below:

$$[E^*]_m = 3\left(\frac{100 - VMA}{100}\right)\left(\frac{A_1 + A_2}{VMA}\right)^{A_3} G^*_g$$  \(20a\)

Another alternative approach for the derivation of the new model is based on differences between the modulus of the asphalt binder of the thin asphalt shell covering the surface of the aggregate and the true modulus of the asphalt binder (see Figure 6). The modulus of
the asphalt binder at the aggregate surface is equal to the glassy modulus, but then decreases to the true asphalt binder modulus value over a transitional zone between the aggregate and the asphalt binder as stated by Christensen et al. (6). Based on this fact, equation 10 can be rearranged as follows:

$$E_m = V_s E_s + V'_b E_g + (V_b - V'_b)E_b$$

where:

- $V'_b$ = volume fraction of that zone near the aggregate surface where the modulus of the binder is equivalent to the glassy modulus.

$$E_b = T_i E_g$$

where:

- $T_i$ = variable with a value between 0 and 1.
$T_t \approx 0$ at higher temperatures and lower frequencies; and $T_t = 1$ at lower temperatures and higher frequencies when the modulus of the asphalt binder equals the glassy modulus. By substituting equations 11 and 22 into equation 21 and rearranging:

$$E_m = K_1 V'_g E_g + (V'_b - T_t V'_b) E_b + V'_b E_b$$

(23)

By substituting equations 12 and 13 into equation 23, and knowing that the term $(V'_b - T_t V'_b)$ is equal to zero at lower temperatures and higher frequencies when term $T_t = 1$, equation 23 can be reformed as:

$$E_m = \left(\frac{100 - VMA}{100}\right) (K_1 E_g + K_2 E_b)$$

(15)

This equation is equation 15 derived earlier. The term $(V'_b - T_t V'_b)$ is equal to $V'_b$ at higher temperatures and lower frequencies when term $T_t = 0$, therefore using this term and by substituting equations 12 and 13 into equation 23, equation 23 can be reformed as:

$$E_m = \left(\frac{100 - VMA}{100}\right) (K_1 E_g + K_2 E_b) + V'_b E_g$$

(24)

Since $V'_b$ represents the volume fraction of the very thin layer of the asphalt binder at the surface of the aggregate and due to the fact that the asphalt binder is in flow state at higher temperatures and lower frequencies, $V'_b \approx 0$, concluding that equation 24 becomes similar to equation 15 as follows:

$$E_m = \left(\frac{100 - VMA}{100}\right) (K_1 E_g + K_2 E_b)$$

(15)

From this point further, the same steps can be followed to reach the final formulation of the model shown in equation 25a:
The coefficients, $A_1, A_2, A_3, A_4$, and $A_5$ of the function, $f_c$, were obtained using the Excel “solver” tool. Error minimization technique to minimize the error between the model-predicted dynamic modulus and the measured dynamic modulus was used. The following values for these coefficients were obtained:

- $A_1 = 90$;
- $A_2 = 10000$;
- $A_3 = 0.66$;
- $A_4 = 1100$; and
- $A_5 = 900$.

Therefore, the final mathematical formulation of the new model is shown in the following equation:

$$
|E^*|_m = 3 \left( \frac{100 - VMA}{100} \right) \left( \frac{A_1 + A_2 \left| \frac{G^*_b}{VMA} \right|^{A_3}}{A_4 + \left( \frac{A_5 \left| \frac{G^*_b}{VMA} \right|^{A_3}}{\left| G^*_g \right|} \right)^{A_3}} \right) \left| G^*_g \right|^{0.66}
$$

(20a)

The following equation shows the mathematical formulation with new coefficients when the units of $|G^*_b|$, $|G^*_g|$, and $|E^*|_m$ are in psi. The following equation shows the mathematical formulation with new coefficients when the units of $|G^*_b|$, $|G^*_g|$, and $|E^*|_m$ are in Pa.

$$
|E^*|_m = 3 \left( \frac{100 - VMA}{100} \right) \left( \frac{90 + 10000 \left| \frac{G^*_b}{VMA} \right|^{0.66}}{1100 + \left( 900 \left| \frac{G^*_b}{VMA} \right|^{0.66} \right)^{0.66}} \right) \left| G^*_g \right|^{0.66}
$$

(20b)
A second form was used for the new model development by following a slightly different approach. Starting from equation 17:

\[ |E^*|_w = 3 \left( \frac{100 - VMA}{100} \right) \left( 90 + 1.45 \frac{G^*_b}{VMA} \right)^{0.66} \left( \begin{array}{c} G^*_e \\ G^*_b \end{array} \right) \]  

(20c)

**Derivation of the Second Form of the New Model**

The term \( \left( 3K_1|G^*_e| + 3K_2|G^*_b| \right) \) is now reformed as follows:

\[ \left( 3K_1|G^*_e| + 3K_2|G^*_b| \right) = 3|G^*_e| F_c \left( |G^*_b| \right) \]  

where:

\( F_c \) = some function of complex shear modulus value of asphalt binder, which can be formulated in the following form:

\[ F_c = \left( \frac{A_1 + A_2|G^*_b|}{A_4 + (|G^*_b|)} \right)^{a_1} \]  

(26)

Therefore, the final formulation of the new model becomes as shown in the equation below:
Another alternative approach for the derivation of the second form of the model is again based on differences between the modulus of the asphalt binder of the thin asphalt shell covering the surface of the aggregate and the true modulus of the asphalt binder as discussed earlier. Therefore equation 21 (shown earlier) is used:

$$E_m = V_s E_s + V_b' E_g (V_b - V_b') E_b$$  \hspace{1cm} (21)$$

By substituting equations 11 and 22 into equation 21 and rearranging:

$$E_m = K_1 V_s E_g + (V_b' - T_b V_b') E_g + V_b E_b$$ \hspace{1cm} (23)$$

By substituting equations 12 and 13 into equation 23, and knowing that the term $(V_b' - T_b V_b')$ is equal to zero at lower temperatures and higher frequencies when term $T_b = 1$, equation 23 can be reformed as:

$$E_m = \left(100 - V_{MA}\right) \left(K_1 E_g + K_2 E_b \right)$$ \hspace{1cm} (15)$$

This equation is actually equation 15 derived in the first derivation. The term $(V_b' - T_b V_b')$ is equal to $V_b'$ at higher temperatures and lower frequencies when term $T_b = 0$, therefore using this term and by substituting equations 12 and 13 into equation 23, equation 23 can be reformed as:

$$E_m = \left(100 - V_{MA}\right) \left(K_1 E_g + K_2 E_b \right) + V_b' E_g$$ \hspace{1cm} (24)$$

Since $V_b'$ represents the volume fraction of the very thin layer of the asphalt binder at the surface of the aggregate and due to the fact that the asphalt binder is in flow state at higher temperatures
and lower frequencies, $V'_b \approx 0$, concluding that equation 24 becomes similar to equation 15 as follows:

$$E_m = \left(100 - VMA\right)\left(K_1E_g + K_2E_b\right) \quad (15)$$

From this point further, the same steps can be followed to reach the final formulation of the model shown in equation 20a:

$$\left|E^*_m\right| = 3\left(100 - VMA\right)\left(\frac{A_1 + A_2\left(G^*_b\right)^{\frac{1}{2}}}{A_4 + \left(G^*_b\right)^{\frac{1}{2}}}\right)\left|G^*_g\right| \quad (27a)$$

The coefficients, $A_1$, $A_2$, $A_3$, and $A_4$ of the function, $f_c$ were obtained using the Excel “solver” tool. Error minimization technique to minimize the error between the model-predicted dynamic modulus and the measured dynamic modulus was used. The following values for these coefficients were obtained:

- $A_1 = 1.0$,
- $A_2 = 225$,
- $A_3 = 0.5$; and
- $A_4 = 150$.

Therefore, the final mathematical formulation of the new model is shown in the following equation:

$$\left|E^*_m\right| = 3\left(100 - VMA\right)\left(\frac{1 + 225\left(G^*_b\right)^{0.5}}{150 + \left(G^*_b\right)^{0.5}}\right)\left|G^*_g\right| \quad (27b)$$

Note that the units of $\left|G^*_b\right|$ and $\left|E^*_m\right|$ are in psi. The following equation shows the mathematical formulation with new coefficients when the units of $\left|G^*_b\right|$ and $\left|E^*_m\right|$ are in Pa.
\[ |E^*|_m = 3 \left( \frac{100 - VMA}{100} \right) \left( \frac{1 + 0.0326 |G^*_b|^{0.5}}{150 + 0.0120 |G^*_b|^{0.5}} \right) |G^*_b|_g \]  

The two forms of the new model were calibrated with four polymer-modified mixtures and one neat mixture of the plant-produced asphalt mixtures, which had a wide range of stiffnesses even at higher temperatures/lower loading frequencies. It should be recognized that a single volumetric state was considered. Nevertheless, the improvement this model offers on the high temperature/low frequency area is significant. Then the model was validated using the other mixtures in the plant-produced lab-compacted set and the mixtures from the lab-produced lab-compacted set and the field cores.

**Dynamic Modulus Predictions**

**Hirsch Model Sensitivity Analysis**

A sensitivity analysis of the different properties (inputs) in the Hirsch model was conducted. The effect of \[ |G^*_b|_b, VMA, \] and VFA on the mixture dynamic modulus, \[ |E^*|_m \] computation was investigated. The effect of \[ |G^*_b|_b \] was found to be significant to a certain lower limit. The asphalt binder phase composes a main part of the composite system of the asphalt mixture regardless of the arrangement of the different phases in the system. On the other hand, the Hirsch model was found insensitive to changes in VMA or VFA as they were investigated at their extreme values. This does not conclude, however, that VMA has insignificant impact on \[ |E^*|_m \], but rather, it means that VMA in the current formulation of the Hirsch model has negligible impact on \[ |E^*|_m \]. Therefore, this fact suggests that the arrangement of phases in the composite system for this version of the Hirsch model is not accurately appropriate.
Similarly, the effect of VFA on $E^*$ predictions was found inconsiderable using the current formulation of the Hirsch model. Because of the inter-correlation between VMA and VFA as shown in equation 31, one of these mixture properties could be eliminated from the Hirsch model and replaced with an appropriate formulation of the other.

**Hirsch Model Predictions**

The Hirsch model was used to predict the dynamic modulus of all the asphalt mixtures tested in this study. The Hirsch model is a semi-empirical model that requires three material property inputs: the absolute value of the complex shear modulus of the asphalt binder ($G^*$), and the voids in mineral aggregate (VMA) and the voids filled with asphalt (VFA) of the compacted asphalt mixture. The formulation of the Hirsch model is shown mathematically in the following equation:

$$
|E^*|_m = P_c \left[ 4,200,000 \left( 1 - \frac{VMA}{100} \right) + 3G^*_b \left( \frac{(VFA)(VMA)}{10,000} \right) \right] + \\
1 - P_c \left[ \frac{1 - VMA}{100} \right] + \frac{VMA}{4,200,000} + \frac{3G^*_b (VFA)}{3G^*_b (VMA)}
$$

where:

$$
|E^*|_w = \text{absolute value of asphalt mixture dynamic modulus in psi};
$$

$$
P_c = \frac{20 + \left[ \frac{3G^*_b (VFA)}{VMA} \right]^{0.58}}{650 + \left[ \frac{3G^*_b (VFA)}{VMA} \right]^{0.58}}
$$
$|G^*_b|$ = absolute value of asphalt binder complex shear modulus in psi;  
$VMA$ = voids in mineral aggregate in compacted mixture, %; and  
$VFA$ = voids filled with asphalt in compacted mixture, %.

Master curves were constructed again using the Hirsch model-predicted dynamic modulus values of all mixtures in the three sets (LPLC, PPLC, and FC). The same method used for the lab-measured dynamic modulus master curve generation was followed. The shift factors and the coefficients of the sigmoid function were determined for each asphalt mixture.

The mixture volumetric properties (VMA, VFA) needed for estimating the dynamic modulus from the Hirsch model were calculated using the following formulas (18):

$$VMA = 100\left(1 - \frac{G_{mb}(1 - P_b)}{G_{sb}}\right)$$  \hspace{1cm} (30) 

$$VFA = 100\left(\frac{VMA - VTM}{VMA}\right)$$  \hspace{1cm} (31) 

where:

$G_{mb}$ = bulk specific gravity of compacted asphalt mixture;  
$P_b$ = asphalt binder content;  
$G_{sb}$ = dry bulk specific gravity of aggregate; and  
$VTM$ = voids in total mixture.

These computations were performed for each compacted specimen of the LPLC and PPLC final SPT specimens, and for each specimen of the field cores final SPT specimens.

The complex shear modulus value, $|G^*_b|$ of the asphalt binder was determined from the frequency sweep tests conducted on all asphalt binders at a sweep of frequencies and wide range of temperatures using the dynamic shear rheometer (DSR) (19).

The master curves of the Hirsch model-predicted dynamic modulus were compared to those of the lab-measured dynamic modulus. The Hirsch model seemed to predict the measured
dynamic modulus well at lower temperatures and higher loading frequencies into the intermediate range. The Hirsch model, however, over-predicted the measured dynamic modulus at higher temperatures and lower loading frequencies as shown in Figures 4, 7, and 8.

The Witczak model (8,9) for predicting dynamic modulus was not used in this study for three reasons: 1) the Hirsch model requires fewer inputs than what the Witczak model requires; 2) the Hirsch model is simpler to use because of the direct use of $G\ast$, while the Witczak model requires a transitional step to convert $G\ast$ to viscosity of asphalt binder that is needed in the model; and 3) both the Hirsch model and the Witczak model provides reasonable predictions of dynamic modulus, but the Hirsch model is valid over a wide range of $E\ast$ values as stated by Dongre et al. (11).

**Comparison between Hirsch and New Model Predictions**

The Hirsch model as shown earlier predicts the measured dynamic modulus values within a relatively reasonable accuracy. However, the Hirsch model lacks the accuracy at higher temperatures and lower loading frequencies when the measured dynamic modulus values are lower as shown in Figure 9. There is a good agreement between the measured and the Hirsch model-predicted dynamic modulus at higher values. The deviation from the equality line increases as the dynamic modulus values decrease. It is clear that the Hirsch model over-predicts the measured dynamic modulus values beyond a certain level of dynamic modulus.
Figure 7. Measured versus Hirsch-Predicted Dynamic Modulus Values for PG 70-22 Asphalt Mixture

Figure 8. Measured versus Hirsch-Predicted Dynamic Modulus Values for SBS LG Asphalt Mixture
When the asphalt binder at high temperatures and low loading frequencies is in flow state and having low measured complex shear modulus value, $|G^*|_b$, the modulus of the asphalt mixture, $|E^*|_m$, is highly controlled by the aggregate and less sensitive to the modulus of the asphalt binder. Therefore, predictive models should take this fact into consideration to accurately capture the behavior of asphalt mixtures at lower $|G^*|_b$ values. The Hirsch model is not capable of capturing the $|E^*|_m$ values at lower $|G^*|_b$ values and seems to fall into this caution. This fact is illustrated in Figure 10. The Hirsch model predictions tend to stabilize as the $|G^*|_b$ values decrease as shown in the sudden change in the slope of the curve to nearly zero slope (flat line). The reader should note here that this is happening before the high-temperature asymptote of the master curve. The reader should not get confused of this asymptote and the low sensitivity of the Hirsch model at relatively low $|G^*|_b$ values. All the master curves of the measured $|E^*|_m$ values show that the high-temperature asymptote is occurring after the
point where the Hirsch model predictions start to flatten as shown in Figures 7 and 8.

The new model developed in this study seems to be capable of predicting the measured dynamic modulus values of all the asphalt mixtures in this study with high accuracy. The new model can capture the behavior of asphalt concrete at a broader range of temperatures and loading frequencies with good accuracy. The deviation between the measured and the predicted dynamic modulus values seen in the Hirsch model at higher temperatures and lower loading frequencies seems to be fixed using the new model. Figure 11 below shows new model predictions as compared to measured values of dynamic modulus.

The new model is found to be more sensitive than the Hirsch model to changes in $G^*$ when $G^*$ is relatively low (Figure 12), which indicates that the model is using correct property inputs of the constituents in the asphalt concrete system. For this reason, it has the ability to capture the behavior of the asphalt concrete at higher temperatures and lower loading frequencies with an acceptable amount of error.
Figure 11. Measured versus New Model-Predicted Dynamic Modulus Values for CR-TB Asphalt Mixture

Figure 12. Measured $G^*$ Values versus New Model-Predicted $E^*$ Values
Dynamic modulus measured values are plotted against new model-predicted values in Figure 13. As shown in this figure, the over-prediction from the Hirsch model (Figure 9) is adjusted for the new model. The measured and the predicted values agree well with each other as noticed from the deviation of the points in Figure 13 from the equality line. The new model seems to be capable of reducing the percentage error in the dynamic modulus predictions as compared to the error associated with the Hirsch model predictions as shown in Table 4. It is clear that the effectiveness of the new model increases at lower measured $|G^*|_b$ values when the Hirsch model lacks from accuracy. At High measured $|G^*|_b$ values, the new model also tends to decrease the amount of error in predictions compared to the Hirsch model but not as significant as at lower $|G^*|_b$ values. The percentage error obtained from the Hirsch model predictions increased significantly below a certain lower limit of $|G^*|_b$ value as shown in Table 4. This limit is lower than what was reported by Dongre et al. (11). The new model is still capable of reducing this percentage error beyond this lower limit.
Table 4 Hirsch vs. New Model Predictions and the Associated Percentage Error

<table>
<thead>
<tr>
<th>Measured G* Values (Pa)</th>
<th>Measured E* values (MPa)</th>
<th>Predicted E* Values (MPa)</th>
<th>Prediction Error, %</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td>Hirsch Model</td>
<td>New Model</td>
</tr>
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</tr>
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</tr>
<tr>
<td>5773</td>
<td>128</td>
<td>250</td>
<td>137</td>
</tr>
</tbody>
</table>

Limitations of the Hirsch Model Predictions

The Hirsch model was developed using data of asphalt mixtures produced using primarily unmodified asphalt binders. Although some researchers like Dongre et al. (11) do not consider this necessarily a limitation because of the $G^*$ input in the model, it is considered a limitation in this study because of the significant difference in mechanical behavior between modified and unmodified asphalt mixtures. Some asphalt modifiers tend to have elastic properties; such modifiers are called “elastomers”. Others, however, have plastic properties and so they are called “plastomers”. And some others are called “elasto-plastomers” due to their tendency of having both elastic and plastic properties. Therefore, despite the fact that $G^*$ is an input in the Hirsch model that would take care of the increase in the asphalt binder modulus in case of the use of asphalt modifiers, the “elasto-plastic” behavior of some modified asphalt binders was not considered in the development of the model.

The Hirsch model over-predicted the dynamic modulus of asphalt mixtures at high temperatures and low loading frequencies. The model is not capable of capturing the mechanical response of asphalt mixtures under these testing conditions.

The error in the Hirsch model predictions in this study was found to be dependent on the type and stiffness of the asphalt binder. Dongre et al. (11) reported an error of less than 15 percent in the Hirsch model predictions when the asphalt binder modulus was above a lower limit, and beyond this limit the error increased...
significantly as they stated. Christensen (20) also reported an average error of 41 percent for the Hirsch model predictions.

The Hirsch model predicted some asphalt mixtures produced with asphalt binders modified with an elastomer like SBS 64-40 with a higher amount of error. This seems rational because the contribution of the elastic behavior from an elastomer-modified asphalt binder into the Hirsch model was not included in the Hirsch model formulation or system phase arrangement. However, for elasto-plastomer-modified asphalt binders like Terpolymer, the Hirsch model predicted the measured dynamic modulus of the mixture well of course except at higher temperatures and lower loading frequencies as shown in Figures 4, 7, and 8.

In all cases, the error in the Hirsch model predictions in this study increased significantly when the asphalt binder modulus was below a certain lower limit.

Comparison between the Hirsch model dynamic modulus predictions from the LPLC specimens versus the PPLC specimens versus the FC specimens was conducted. In the three cases, it was found that the Hirsch model predicted the measured dynamic modulus well for PG 70-22, Terpolymer, SBS LG, and CR-TB with a minimized error when predicting above the lower limit of the asphalt binder modulus. The Hirsch model predictions for Air-Blown from the FC specimens were more accurate than those from the LPLC or PPLC specimens. Also the Hirsch model predictions for SBS 64-40 appeared more precise from the PPLC specimens than those from the LPLC or FC specimens. In general, the three sets show relatively similar predictions using the Hirsch model.

**Findings and Conclusions**

The Hirsch model over-predicted the measured dynamic modulus values by a significant amount of error at higher temperatures and lower frequencies. The Hirsch model was found to be insensitive to changes in \( G^* \) at relatively lower values. It was not able to capture the decrease in the measured values of \( E^* \). The percentage error associated with the Hirsch model
predictions was significantly high beyond a certain lower limit of $|G^*|_b$ values.

Using the current formulation of the Hirsch model, the effect of both VFA and VMA on $|E^*|_m$ predictions was found to be not significant. Because of the inter-correlation between VMA and VFA, one of these mixture properties could be eliminated from the Hirsch model and replaced with an appropriate formulation of the other.

The new model is capable of predicting dynamic modulus of asphalt concrete at broader range of temperatures and loading frequencies. Due to the fact that the model was refined and verified using asphalt mixtures produced with modified and unmodified asphalt binders, it has the advantage over the other available predictive models of estimating dynamic modulus of modified asphalt mixtures. Normally dynamic modulus of modified asphalt mixtures at higher temperatures and lower frequencies need more reduced time before it starts to stabilize into the lower asymptote of the master curve especially for asphalt binders modified with elastomers or elasto-plastomers. This model is having the capability of capturing this behavior.

The new model reduced the percentage error of the dynamic modulus predictions significantly particularly at higher temperatures and lower frequencies beyond a certain lower limit of $|G^*|_b$.

The model was derived from the law of mixtures concluding that its derivation is based on fundamental engineering and combined behavior of composite materials. The mathematical formulation of the new model is simple, logical, and easy to use. Besides, the model is effective and provides accurate dynamic modulus predictions within acceptable amount of error.

The model requires no more than two inputs: the asphalt binder complex shear modulus value, $|G^*|_b$, and the voids in mineral aggregates (VMA) of the compacted asphalt mixture. The glassy shear modulus of the asphalt binder is also used in the model, which is equivalent to 1 GPa. The model has upper and lower limiting values at very high and low $|G^*|_b$ values, respectively, which characterize the upper and lower asymptotes of the dynamic
modulus master curve. At higher temperatures and lower frequencies, the asphalt mixture tends to have more viscous than elastic properties and the asphalt binder is in flow state. Therefore, the predominant constituent in the system is the aggregate in this case, and the lower limiting value of the dynamic modulus is highly controlled by the aggregate. On the other hand, at lower temperatures and higher frequencies, the asphalt mixture behaves as an elastic material, and the asphalt binder is in glassy state. Therefore, the behavior of the system is controlled by the aggregates covered by the asphalt binder in its glassy state.

The new model provides good predictions for lab-produced lab-compacted and plant-produced lab-compacted asphalt mixtures as well as field cores taken from the FHWA’s ALF pavements with a standard error within the acceptable range.

Acknowledgments

The authors of this paper are grateful to Mr. Scott Parobeck, Mr. Frank Davis, and Mrs. Susan Needham for preparing the specimens and conducting the lab testing. The authors would like to thank each of Dr. Imad Basheer, Mr. Terry Arnold, and Dr. Ala Abbas for their valuable comments. The authors are also grateful to Mrs. Haleh Azari for summarizing the dynamic modulus data.

References


