# RESILIENT RESPONSE CHARACTERISATION OF HOT-MIX ASPHALT MIXES FOR A NEW SOUTH AFRICAN PAVEMENT DESIGN METHOD

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**Abstract**

The South Africa National Road Agency Ltd (SANRAL) is in the process of revising the South African Pavement Design Method (SAPDM). A necessary part of this programme is to develop resilient response models. Dynamic (complex) modulus has been used as the resilient response property to characterise five selected South African hot-mix asphalt (HMA) mixes. The objective of this paper is to present dynamic modulus models which were investigated for implementation in the SAPDM. These models include sigmoidal master curves developed for the five mixes based on dynamic modulus laboratory data and two dynamic modulus predictive equations, namely Witczak and Hirsch models. The two predictive equations were evaluated against the dynamic modulus values obtained from the laboratory testing. Based on the results obtained from this study, the Hirsch predictive model was found to be more promising in terms of predictive performance than the Witczak model.

## 1. INTRODUCTION

The existing South African mechanistic design method (SAMDM) for flexible pavements uses resilient modulus to characterise the resilient response behaviour of HMA mixes (Theyse et al., 1996). In the SAMDM, default resilient modulus values are provided based on tests at a single loading frequency and two test temperatures. This is similar to the American Association of State Highway and Transportation Officials (AASHTO), pavement design guidelines, in which HMA is characterised in terms of resilient modulus (AASHTO, 1986). In the new United States mechanistic-empirical pavement design guide (MEPDG) proposed by the National Cooperative Highway Research Project 1-37A however, resilient modulus was replaced by the dynamic modulus (NCHRP 1-37A, 2004).

The South African National Road Agency Limited (SANRAL) is developing a new mechanistic-empirical pavement design guide for road pavements referred to as South African Pavement Design Method (SAPDM). The revision of the SAPDM requires advanced characterisation of the material properties of typical South African HMA mixes including mixes for surfacing and base courses. In this regard, the SAPDM Project B-1b requires the development of new resilient response models based on dynamic modulus to characterise HMA mixes (SANRAL PB/2006/B-

1B, 2007). The resilient response models will be incorporated in the revised ME design component of the SAPDM by providing data to the materials design input information system developed under Project B-4 (SANRAL PB/2006/B-4, 2007).

The objective of this paper is to present resilient response models evaluated during the characterisation of asphalt mixes in the SAPDM project using five selected asphalt mixes. A comprehensive laboratory testing programme was conducted to establish a dynamic modulus database for the asphalt samples studied. This data was used to construct master curves which would enable the resilient response of selected mixes to be characterised at any test temperature and time of loading (frequency). Another objective of the paper is to present an evaluation of two resilient response equations commonly used for the prediction of dynamic modulus in ME pavement analysis. These models, namely Witczak and Hirsch dynamic modulus predictive equations were evaluated against the dynamic modulus values obtained from the laboratory testing conducted on the five asphalt mixes. The Witczak and Hirsch models are among the resilient response models used to predict dynamic modulus values of HMA (Witczak and Fonseca, 1996; Andrei and Witczak, 1999; Christensen et al, 2003).

## 2. RESILIENT RESPONSE AND HIERARCHICAL APPROACH TO DESIGN

The modulus properties of HMA materials are known to be a affected by temperature, rate of loading (frequency), ageing, and mix characteristics including binder stiffness, aggregate grading, binder content and air voids. MEPDG has a hierarchical approach with regards to the input requirements for ME design (NCHRP 1-37A, 2004). The modulus of the HMA at all analysis levels are determined from master curve constructed at a reference temperature.

It is assumed that the revised SAPDM would have a similar approach as presented below:

- Level 1 analysis: Design inputs at this level would have the highest level of certainty, requiring comprehensive laboratory testing to obtain dynamic modulus values at different loading frequencies and temperatures of interest for the mix. It is believed that this level of analysis would apply to high volume roads such as national highways and freeways, and in general to roads where high design certainty is required.
- Level 2 analysis: Design inputs at this level would have an intermediate level of certainty, requiring no laboratory testing for dynamic modulus. Binder test results would be used as input values for resilient response predictive equations (models) to obtain dynamic modulus values. This level of analysis requires construction of a master curve using actual bituminous binder test data based on the relationship between binder viscosity and temperature.
- Level 3 analysis: Similar to Level 2 analysis, this level would have no dynamic modulus laboratory testing, and will use the resilient response predictive equations to obtain dynamic modulus values. Estimated material properties for design inputs would be based on typical values obtained from tabulated historical data. Master curves are also required at this level.

## 3. DYNAMIC MODULUS TESTING PROGRAMME FOR SAPDM

### 3.1. Materials and sample preparation

Five commonly used asphalt mixes in South Africa were selected for the SAPDM project. These are:

- Bitumen-Treated Base (BTB) mix with a 40/50 binder.
- Coarse continuously graded mixes with A-E2 modified binder.
- Medium continuously graded mixes with A-E2 modified binder.
- Medium continuously graded mix with a 60/70 penetration grade binder, and
- Semi-open graded asphalt mix with a bitumen-rubber binder (BRASO).

All the five mixes were designed by Much Asphalt. The mix designs were reproduced and tested in the CSIR pavement materials laboratory in accordance to Technical Methods of Highways (TMH1) Method C2 (TMH1, 1986).

The HMA samples were aged after mixing to simulate the ageing that takes place during the production process in an asphalt plant and during transportation to site, using the Superpave short-term ageing procedure. The procedure is described by Von Quintus et al. (1991) and Bell et al. (1994). Short-term ageing conditioning is achieved by ageing the loose mix in an oven at compaction temperature of 135°C for four hours before compaction. An adjustment to this method has been made as part of the CSIR test protocol development for SAPDM (Anochie-Boateng et al., 2010). The short-term ageing temperature of 135°C is replaced by the actual compaction temperature of the mix. For instance, the BRASO mix was aged at 145°C for 4 hours instead of 135°C. It should be mentioned that both short-term and long-term aged samples were prepared and tested for the SAPDM project. However, this paper presents results that are based on only short-term ageing prepared samples.

An Industrial Process Controls Ltd (IPC) servopac gyratory compactor was used to prepare cylindrical samples for the dynamic modulus testing. All the samples were compacted to the voids necessary to obtain the target design voids for a cored cylindrical specimen (100 mm diameter x 150 mm height) from the original gyratory sample (150 mm diameter x 170 mm height). A trial and error method was used to obtain the designed voids. In the dynamic modulus test protocol for SAPDM, prepared samples with voids content more than 0.5% of the design air voids are discarded (Anochie-Boateng et al., 2010).

### 3.2. Dynamic modulus as design parameter

Modern pavement design methods have adopted the dynamic (complex) modulus as the most appropriate input parameter of HMA modulus for flexible pavement design (SANRAL PB/2007/HPS, 2008; NCHRP 1-37A, 2004). Regardless of the analysis level, dynamic modulus will be used in the SAPDM for resilient response characterisation of the HMAs. As mentioned earlier, Level 1 analysis requires actual dynamic modulus test data obtained from laboratory to develop master curves and shift factors, whereas Levels 2 and 3 analyses do not require laboratory testing, rather predictive equations are used to obtain the dynamic modulus values.

### 3.3. Dynamic modulus testing

The recently developed CSIR dynamic modulus test protocol for SAPDM was used for testing the five HMA samples (Anochie-Boateng et al., 2010). The CSIR test protocol is similar to the one contained in the AASHTO TP62 protocol (AASHTO 2009), except that some modifications were made to suit South African road pavement conditions. The CSIR test protocol for SAPDM uses a commercially available servo-hydraulic universal testing machine with load capacity 25kN (UTM-25). The UTM-25 system has been widely used in major pavement design projects for dynamic modulus testing of hot-mix asphalt mixes, and complies with several international standards (AASHTO TP 62, 2009; NCHRP 9-29, 1999; BSI EN 12697-26, 2004). The test setup includes a temperature chamber, capable of maintaining the test temperatures of the samples.

During testing, a haversine load pulse was applied to the gyratory compacted cylindrical samples (100 mm x 150 mm) at five test temperatures (-5, 5, 20, 40, and 55°C ) and six loading frequencies (25, 10, 5, 1, 0.5, and 0.1Hz). That is, a total of 30 tests were conducted on the mix to complete a full factorial dynamic modulus test matrix. The specimen's vertical deformation was determined by averaging the readings of three axial linear variable displacement transducers (LVDTs). Axial stresses and the corresponding axial strains were recorded for five load cycles for each test to compute the dynamic modulus of the HMA samples. Five replicate specimens were tested for each asphalt mix in accordance with the CSIR protocol, so that reliability can be established. Figure 1 shows the dynamic modulus test specimens for a medium 60/70 mix for example, and the UTM-25 setup at CSIR pavement materials laboratory.

(a) Gyratory compacted samples – 150 mm x 170 mm

(b) Cored samples from (a) – 100 mm x 150 mm


(c) UTM-25 Test set-up at CSIR

**Figure 1. Dynamic modulus samples and testing equipment**

## 4. ANALYSIS OF DYNAMIC MODULUS RESULTS

The test data used for the dynamic modulus analyses include the loading frequency (time of loading), applied stresses and strains. For visco-elastic materials, the stress-strain relationship under a continuous sinusoidal loading is defined by the complex modulus E* (ASTM D 3497, 2003; NCHRP 1-37A, 2004; AASHTO TP 62, 2009). The complex modulus has real and imaginary components that define the elastic and viscous behaviour of linear visco-elastic materials. The absolute value of the complex modulus is defined as the material's dynamic modulus ($|E^*|$). For one-dimensional case of a sinusoidal loading, the applied stress and the corresponding strain can be expressed in a complex form by Equations 1a and 1b, respectively.

$$\sigma^* = \sigma_0 e^{i\omega t} \quad \text{(Eq.1a)}$$

$$\varepsilon^* = \varepsilon_0 e^{i(\omega t - \delta)} \quad \text{(Eq.1b)}$$

where $\sigma$ is the applied stress, $\sigma_0$ is the stress amplitude; $\varepsilon$ is the strain response, $\varepsilon_0$ is the strain amplitude; $\omega$ is angular frequency, which is related to frequency by $\omega = 2\pi f$ ; $f = 1/\mathrm{T}$ ; $t$ is time, and T is period; δ is the phase angle related to the time the strain lags behind the stress. Phase angle is an indicator of the viscous (or elastic) properties of the visco-elastic material. For a pure elastic material, δ = 0°, and for a pure viscous material, δ = 90° Mathematically, dynamic modulus is defined as the maximum dynamic stress divided by the recoverable maximum axial strain.

From Equations 1a and 1b the complex modulus, $E^*(i\omega)$ is defined as the complex quantity in Equation 2.

$$E^*(i\omega) = \frac{\sigma^*}{\varepsilon^*} = \frac{\sigma_0}{\varepsilon_0} e^{i\delta} = E' + iE'' \quad \text{(Eq.2)}$$

The real part of the complex modulus is the storage modulus ($E'$) and the imaginary part is the loss modulus ($E''$). The dynamic modulus $|E^*|$ is the absolute value of the complex modulus, which is defined mathematically in Equation 3.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad \text{(Eq.3)}$$

### 4.1. Construction of dynamic modulus master curves

The master curve-sigmoidal function analytical approach for estimating dynamic modulus of HMA materials was used to analyse the five asphalt materials. The importance of master curves is supported by the fact that they are required at all three levels of analysis in the MEPDG and the SAPDM (SANRAL PB/2007/HPS, 2008; NCHRP 1-37A, 2004). Master curves are generated using time-temperature superposition principle. This principle allows for test data collected at different temperatures and frequencies to be shifted along the frequency axis relative to a reference temperature to form single characteristic master curve. Thus, master curve of an asphalt mix allows comparisons to be made over extended ranges of test temperatures and frequencies. In this paper, five master curves were constructed to represent the five asphalt mixes tested. Detailed step- by- step construction of master curves for South Africa HMA materials is described in the CSIR HMA test protocol (Anochie-Boateng et al., 2010).

During the construction of the master curves, a non-linear least square regression technique was used to fit the dynamic modulus data with a sigmoidal function defined in Equation 4. Using the time-temperature superposition principle, the dynamic modulus test data were then shifted horizontally relative to a reference temperature of 20°C. The master curve relationship is presented as follows:

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma\left\{\log(f) + c\left[10^{A+VTS\log T} - 10^{A+VTS\log(527.67)}\right]\right\}}} \qquad \text{(Eq.4)}$$

where

| | |
|---|---|
| $\lvert E^*\rvert$ | = dynamic modulus |
| $\delta$ | = minimum value of \|E*\| |
| $\delta+\alpha$ | = maximum value of \|E*\| |
| $\beta$, $\gamma$ | = shape parameters of the model |

The fitting parameters ($\alpha$, $\beta$, $\delta$, $\gamma$, and $c$) were determined through numerical optimization of Equation 4 using the dynamic modulus values of the five mixes obtained from laboratory testing.

The temperature dependency of the dynamic modulus is incorporated in a reduced frequency parameter, $f_r$ in Equations 5a and 5b. The reduced frequency is defined as the actual loading frequency multiplied by the time-temperature shift factor, *a(T).*

$$f_r = a(T) \times f \qquad \text{(Eq.5a)}$$

$$\log f_r = \log f + \log a(T) \qquad \text{(Eq.5b)}$$

where

| | |
|---|---|
| $f$ | = frequency, Hz |
| $a\ (T)$ | = shift factor as a function of temperature |
| $T$ | = temperature |

In the MEPDG, the shift factors are expressed as a function of the binder viscosity to allow ageing over the life of the pavement to be considered using the Global Ageing Model developed by Mirza and Witczak (1995). Equation 6 presents the shift factor -viscosity relationship used in the MEPDG (NCHRP 1-37A, 2004), and followed for all the five mixes tested for SAPDM.

$$\log a(T) = c\,(\log \eta - \log \eta_{70_{\mathrm{RTFO}}}) \qquad \text{(Eq.6)}$$

where

| | |
|---|---|
| $\eta$ | = viscosity at the age and temperature of interest |
| $\eta_{70_{RTFO}}$ | = viscosity at the reference temperature and short-term ageing |
| $c$ | = fitting parameter |

The American Society for Testing and Materials (ASTM) viscosity-temperature relationship given in Equation 7 provides the rolling thin film oven test (RTFOT) ageing values of A and VTS used for the construction of HMA master curves (ASTM D2493, 1998). This relationship is used in the MEPDG, and recommended for construction of dynamic modulus master curves in SAPDM. The MEPDG recommends that A and VTS parameters could be obtained from several test procedures for the bituminous binder including dynamic shear rheometer, Brookfield viscosity, penetration and softening point (NCHRP 1-37A , 2004). The A/VTS parameters used in this study were obtained from a combination of the consistency tests mentioned above.

$$\log \log \eta = A + VTS \log T_R \quad \text{(Eq.7)}$$

where:

$\eta$ = viscosity (Pa.s)
$T_R$ = temperature (R)
$A$ = regression intercept
$VTS$ = regression slope of viscosity temperature susceptibility

By substituting Equation 7 in Equation 6, the shift factors can be obtained as a function of *A* and *VTS* parameters as presented in Equation 8.

$$\log a(T) = c\left(10^{A+VTS\log T} - 10^{A+VTS\log(527.67)}\right) \quad \text{(Eq.8)}$$

Where, $c$ = fitting parameter

Note that the reference temperature adopted for the SAPDM protocol is 20°C instead of 21.1°C used by the MEPDG.

Figure 2 presents the detailed master curve at five temperatures produced for a medium continuous asphalt mix (as an example) tested for SAPDM using the average dynamic modulus values of the five replicate specimens tested. It can be seen that the test data obtained at the low test temperatures (-5°C and 5°C) were shifted to the right whereas the high test temperatures (40°C and 55°C) data were shifted to the left to meet the master curve.

Next, direct comparison was made for the average dynamic modulus values for all the five asphalt mixes tested for the SAPDM project. Figure 3 compares five dynamic modulus master curves constructed for all the mixes. The figure shows that at the high frequency regimes, the dynamic modulus of the BTB 40/50 and medium 60/70 mixes were high when compared to the other three mixes. It is well known that high modulus values are desirable for HMA wearing courses to effectively resist permanent deformation, whereas relatively low modulus is desired to avoid excessive cracking. Also, it is important to note that the BRASO mix had low modulus values compared to the four asphalt mixes tested. The bitumen rubber in the BRASO is relatively soft compare to the binders used in the other mixes. There is a possibility that the recoverability of deformation is far greater in BRASO than for the other mixes.

Table 1 presents the average dynamic modulus values for all the five HMA samples at different test temperatures and loading frequencies, and Table 2 shows the sigmoidal model parameters developed for the five mixes. Note that each result represents an average dynamic modulus value of five specimens. The parameters will need to be calibrated/validated using additional laboratory tests. With known A/VTS, frequency and temperature values, the dynamic modulus values could be estimated from Equation 4.

**Table 1: Dynamic modulus results of the five asphalt mixes tested**

| Temperature (°C) | Frequency (Hz) | BTB 40/50 | Coarse AE2 | Medium AE2 | Medium 60/70 | BRASO |
|---|---|---|---|---|---|---|
| -5 | 25 | 31 802 | 24 037 | 23 862 | 32 894 | 15 994 |
| | 10 | 30 941 | 22 681 | 22 386 | 31 412 | 14 855 |
| | 5 | 29 842 | 21 533 | 21 237 | 30 270 | 13 907 |
| | 1 | 27 212 | 18 513 | 18 442 | 27 387 | 11 648 |
| | 0.5 | 26 003 | 17 222 | 17 226 | 26 044 | 10 649 |
| | 0.1 | 22 972 | 14 120 | 14 436 | 22 709 | 8472 |
| 5 | 25 | 26 342 | 20 314 | 17 606 | 26 888 | 12 093 |
| | 10 | 24 731 | 18 688 | 15 898 | 24 905 | 10 775 |
| | 5 | 23 311 | 17 369 | 14 579 | 23 324 | 9772 |
| | 1 | 19 831 | 14 097 | 11 586 | 19 503 | 7557 |
| | 0.5 | 18 282 | 12 729 | 10342 | 17 759 | 6677 |
| | 0.1 | 14 765 | 9525 | 7731 | 13 801 | 4822 |
| 20 | 25 | 16 877 | 9966 | 8938 | 14 601 | 5616 |
| | 10 | 15 476 | 8220 | 7394 | 12 221 | 4571 |
| | 5 | 12 862 | 6980 | 6342 | 10 512 | 3863 |
| | 1 | 7981 | 4431 | 4206 | 6952 | 2458 |
| | 0.5 | 6459 | 3601 | 3513 | 5644 | 2028 |
| | 0.1 | 3590 | 2038 | 2154 | 3132 | 1206 |
| 40 | 25 | 3384 | 2159 | 2151 | 3246 | 1279 |
| | 10 | 2183 | 1458 | 1533 | 2130 | 884 |
| | 5 | 1517 | 1081 | 1181 | 1492 | 671 |
| | 1 | 613 | 506 | 616 | 603 | 330 |
| | 0.5 | 430 | 393 | 492 | 420 | 266 |
| | 0.1 | 216 | 224 | 290 | 205 | 158 |
| 55 | 25 | 777 | 798 | 859 | 907 | 534 |
| | 10 | 448 | 486 | 557 | 529 | 342 |
| | 5 | 318 | 360 | 416 | 373 | 259 |
| | 1 | 154 | 188 | 223 | 172 | 127 |
| | 0.5 | 131 | 165 | 192 | 143 | 111 |
| | 0.1 | 100 | 126 | 138 | 104 | 80 |

**Table 2: Master curve-sigmoidal model parameters for the HMA studied**

| Mix type | $\delta$ | $\alpha$ | $\beta$ | $\gamma$ | c |
|---|---|---|---|---|---|
| BTB 40/50 | 1.612 | 2.848 | -1.407 | -0.742 | 1.196 |
| Coarse AE2 | 1.721 | 2.656 | -0.954 | -0.659 | 0.994 |
| Medium AE2 | 1.461 | 2.954 | -0.969 | -0.507 | 0.898 |
| Medium 60/70 | 1.550 | 2.947 | -1.225 | -0.692 | 1.186 |
| BRASO | 1.365 | 2.910 | -0.808 | -0.544 | 1.611 |

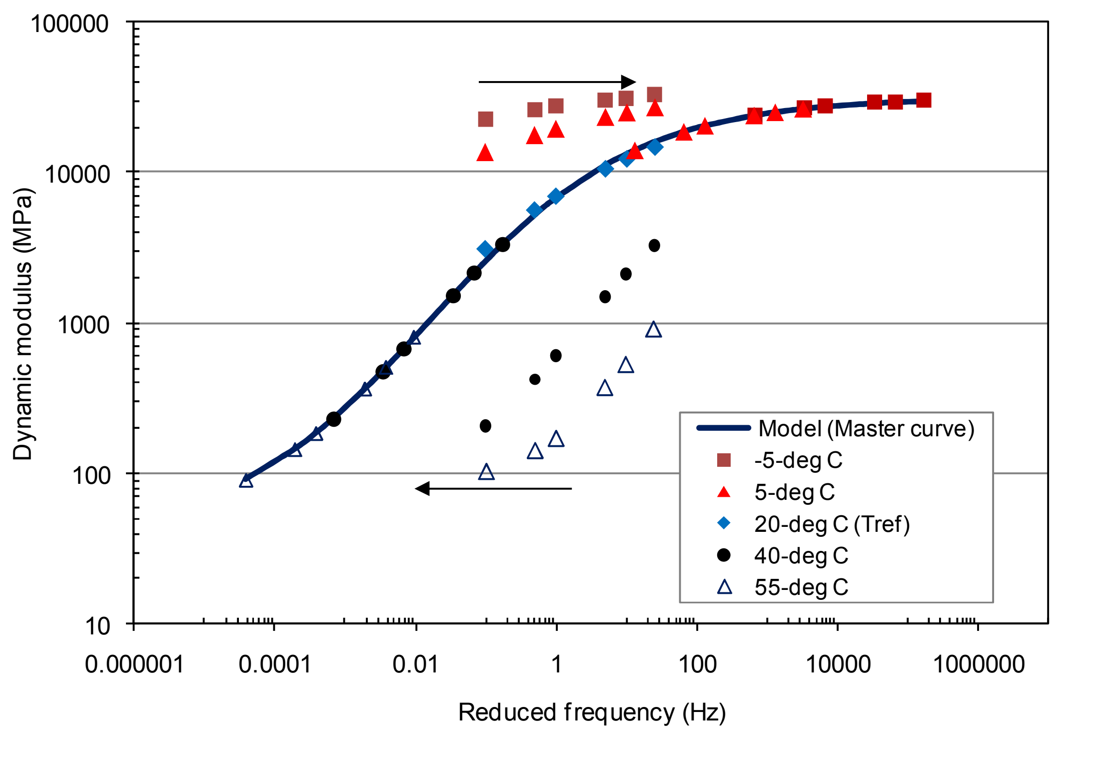



**Figure 2. Dynamic modulus master curve for medium 60/70 mix**

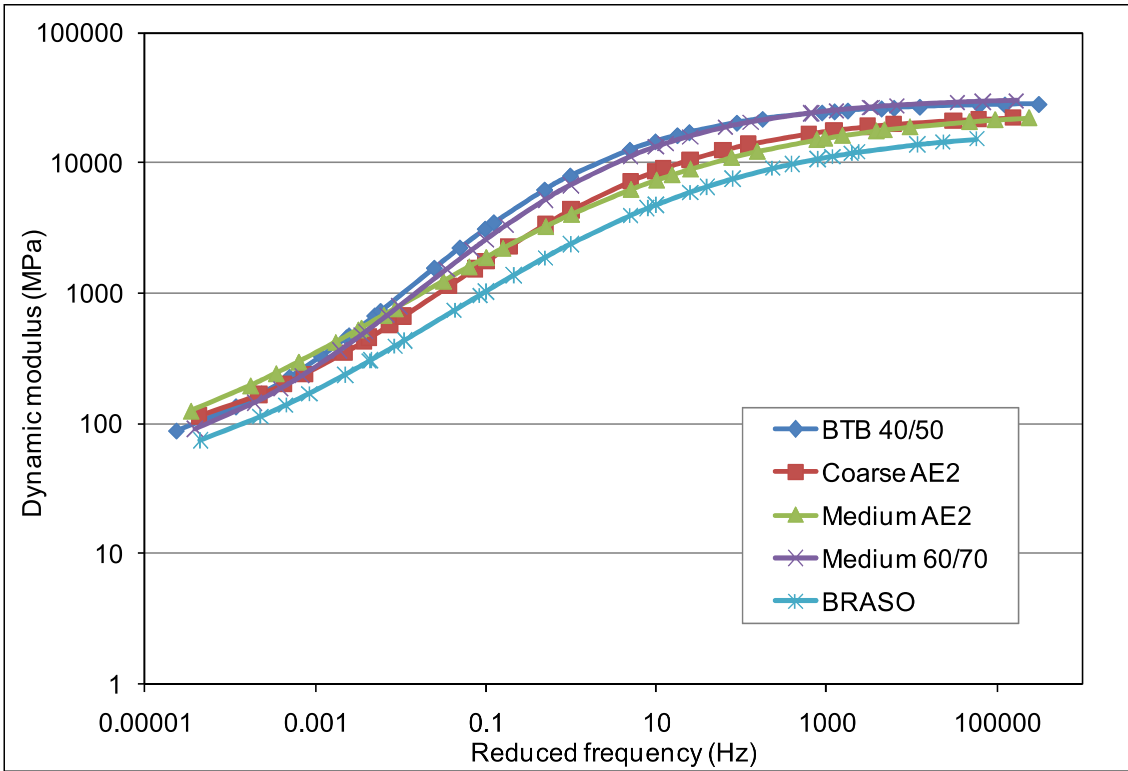



**Figure 3. Comparison of dynamic modulus of five South Africa HMA mixes**

## 5. DYNAMIC MODULUS PREDICTIVE EQUATIONS

The two commonly used predictive equations for HMA dynamic modulus values are the Witczak and Hirsch models. These models are recommended for Levels 2 and 3 analyses of the MEPDG and SAPDM design guides as alternative to dynamic modulus values obtained from laboratory testing (SANRAL PB/2007/HPS, 2008; NCHRP 1-37A, 2004). Improvement of these models will be further refined by the CSIR. In this paper, the predicted results of the five mixes tested at design voids were compared with the dynamic modulus values obtained from the laboratory testing programme.

### 5.1. Witczak predictive model

The MEPDG recommends the use of the Witczak predictive model to predict dynamic modulus of HMA materials. The Witczak equation uses properties of the bituminous binder, aggregates, and some volumetric properties of the mix as input parameters. The equation used in the MEPDG was developed based on 171 types of conventional asphalt mixes and 34 modified asphalt mixes (Andrei and Witczak, 1999). Equation 9 represents the Witczak predictive model that was investigated for SAPDM.

$$\log\left|E^*\right| = 3.750063 + 0.029232\,P_{200} - 0.001767\,(P_{200})^2 + 0.002841\,P_4 - 0.058097\,V_a$$
$$- 0.82208\,\frac{V_{beff}}{\left(V_{beff} + V_a\right)} + \frac{\left[3.871977 + 0.0021\,P_4 + 0.003958\,P_{38} - 0.000017\,(P_{38})^2 + 0.00547\,P_{34}\right]}{1 + e^{(-0.603313 - 0.313351\,\log f - 0.393532\,\log \eta)}} \quad \text{(Eq.9)}$$

where:

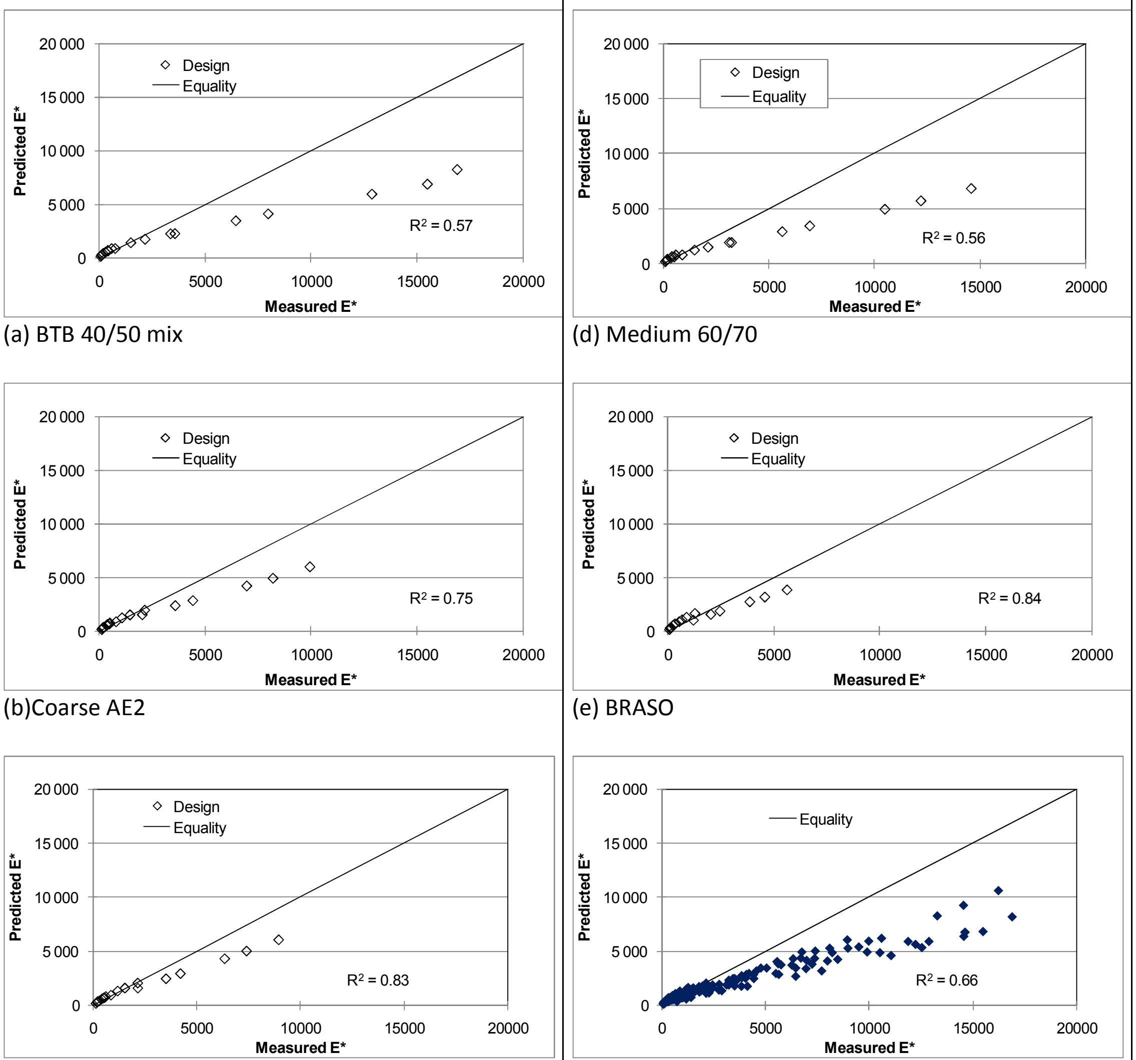
| | |
|---|---|
| $\|E^*\|$ | = dynamic modulus, in psi (145 psi = 1 MPa); |
| $\eta$ | = binder viscosity, in $10^6$ poise (10 Poise = 1 Pa.s); |
| $f$ | = load frequency, in Hz; |
| $V_a$ | = % air voids in the mix, by volume; |
| $V_{beff}$ | = % effective bitumen content, by volume; |
| $P_{3/4}$ | = % retained on ¾-in. [19.0-mm] sieve, by total aggregate weight (cumulative); |
| $P_{3/8}$ | = % retained on 3/8-in. [9.5-mm] sieve, by total aggregate weight (cumulative); |
| $P_4$ | = % retained on No. 4 [4.75-mm] sieve, by total aggregate weight (cumulative); |
| $P_{200}$ | = % passing No. 200 [0.075-mm] sieve, by total aggregate weight. |

#### 5.1.1 Predicting dynamic modulus with Witczak model

The Witzack $|E^*|$ model (see Equation 9) was used to predict dynamic modulus of the five mixes tested. The binder viscosity of individual asphalt mixes at temperatures 20, 40, and 55°C and frequencies 0.1, 0.5, 1, 5, 10 and 25 Hz were used to predict dynamic modulus $|E^*|$ of the mix (minimum test temperature of the binder in this case was 20°C). The predicted $|E^*|$ values were compared with the dynamic modulus values obtained from laboratory.

Figure 4 compares measured values from dynamic modulus test with predicted dynamic modulus values from the Witczak's model for all the five asphalt mixes. A combined data for all the five mixes is also presented to indicate the overall predictability of the Witczak's model for South African mixes. Based on the test results presented in this paper, the dynamic modulus of all the mixes were not well predicted by the Witczak equation. However it should be mentioned that the test data are very limited, and represent only five mixes. Additional data are needed for detailed discussions on the Witczak's predictive model in order to make valid conclusion for the SAPDM.

Note that each data point on the graphs represents the average dynamic modulus value of five specimens tested at five temperatures and six loading frequencies.




(a) BTB 40/50 mix
(d) Medium 60/70
(b)Coarse AE2
(e) BRASO
(c) Medium AE2
(f) Combined data for all mixes

**Figure 4. Witczak Predicted |E*| vs. Lab measured |E*|**

### 5.2. Hirsch dynamic modulus predictive model

Hirsch dynamic modulus predictive equation is a much used alternative to the Witczak dynamic modulus predictive model of HMA mixes (Christensen et al. 2003). In comparison, the Hirsch model uses a reduced number of material parameters to determine dynamic modulus of the mix. In the Hirsch's model, the dynamic modulus $|E^*|$ of asphalt mix is directly estimated from the complex shear modulus of binder $|G^*|_{binder}$ determined in the laboratory from a dynamic shear rheometer (DSR) test. The voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) are the two mix properties used in the Hirsch's model.

In this study, the Hirsch model was used to predict dynamic modulus of the five asphalt mixes and compare with dynamic modulus values obtained from laboratory. Equation 10 presents the Hirsch model for dynamic modulus $|E^*|$.

$$|E^*|_{mix} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3|G^*|_{binder}\left(\frac{VFA\times VMA}{10{,}000}\right)\right]+\frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000}+\frac{VMA}{3VFA|G^*|_{binder}}\right]} \quad \text{(Eq.10)}$$

$$P_c=\frac{\left(20+\frac{VFA\times 3|G^*|_{binder}}{VMA}\right)^{0.58}}{650+\left(\frac{VFA\times 3|G^*|_{binder}}{VMA}\right)^{0.58}}$$

where:

| | |
|---|---|
| $\|E^*\|$ | = dynamic modulus, psi (145 psi = 1 MPa); |
| $\|G^*\|_{binder}$ | = shear complex modulus of binder (psi); |
| *VMA* | = percent voids in mineral aggregates |
| *VFA* | = percent voids filled with binder |
| $P_c$ | = aggregate contact factor |

### 5.2.1 Predicting dynamic modulus using Hirsch model

The Hirsch $|E^*|$ model (see Equation 10) was used to predict dynamic modulus of the five mixes tested. The shear complex modulus values of the individual binders $|G^*|_{binder}$ at temperatures 20, 40, and 55°C and at frequencies 0.1, 0.5, 1, 5, 10 and 25 Hz were used to predict dynamic modulus $|E^*|$ of the mix (minimum test temperature of the binder in this case was 20°C). The predicted $|E^*|$ values were compared with the dynamic modulus values obtained from laboratory (Table 1).

Figure 5 compares measured values from dynamic modulus test with predicted dynamic modulus values from the Hirsch's model for all five asphalt mixes. A combined data for all five mixes is also presented to indicate the overall predictability of the Hirsch's model. The results presented in this paper indicate that the dynamic modulus of all the mixes could be well predicted by the Hirsch equation. Similar to the Witczak model only five mixes were used in the Hirsch's model. Additional data are required for detailed discussions on the Hirsch's predictive model in order to make valid conclusion for the SAPDM.

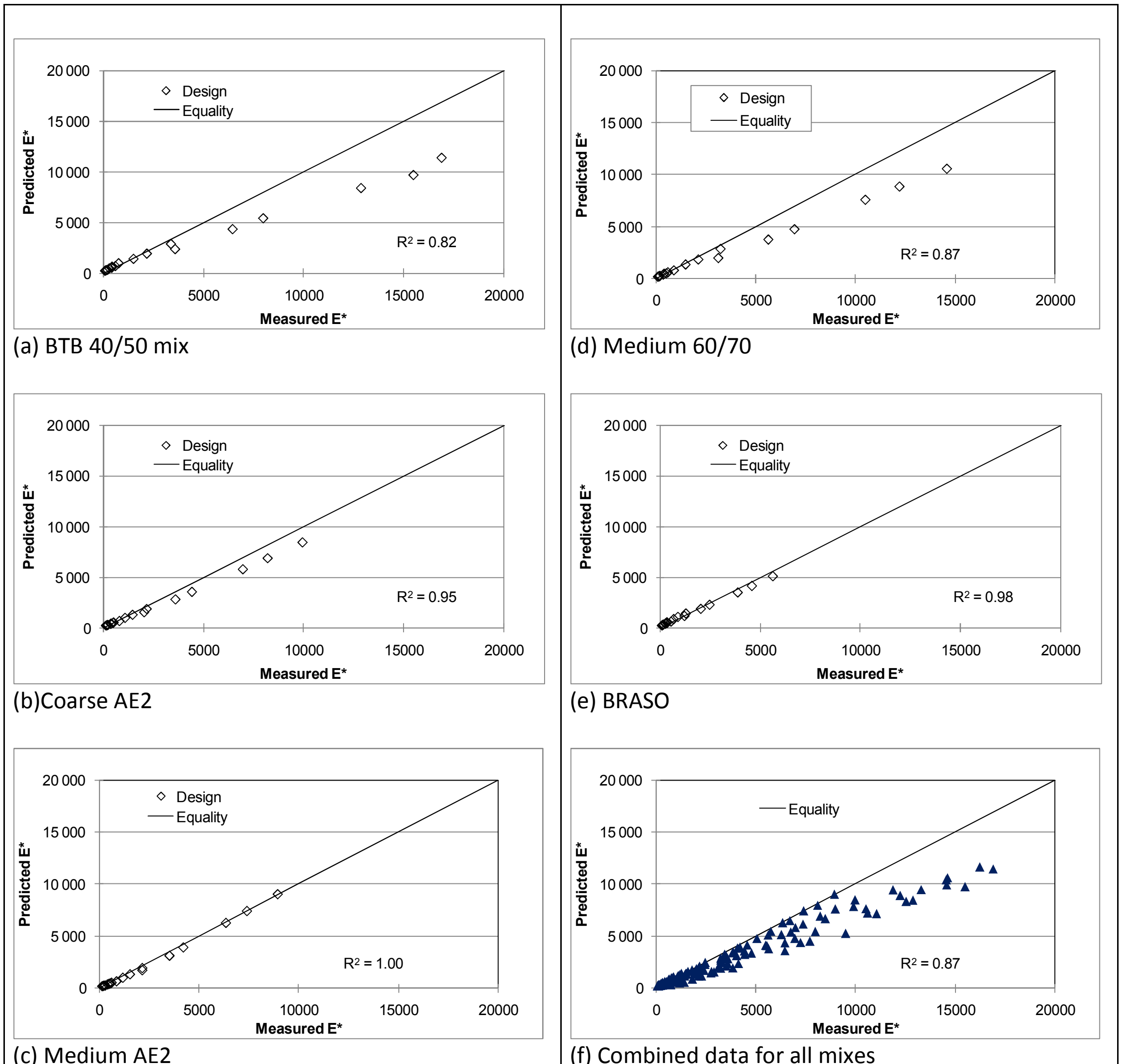



**Figure 5. Hirsch Predicted |E*| vs. Lab measured |E*|**

## 6. CONCLUSIONS

The objective of this paper was to present resilient response models investigated for implementation in the South African Pavement Design Method (SAPDM) using five HMA materials. These models will be used in static and dynamic pavement analysis to predict the structural response of the pavement system and particularly HMA surface and base course. The models should accurately simulate temperature and rate of loading effects of the HMA material during the life of the pavements. Additional factors to consider in the final implementation of the models in the SAPDM include the effects of change in density of the asphalt mixes, the visco-elastic response of the HMA materials at different temperatures and loading speeds, and ageing of the binder.

Based on the study presented in this paper, the following conclusions can be made:

- Dynamic modulus testing and the development of dynamic modulus master curves were successfully done for the five South African mixes studied for SAPDM. The testing procedure and step-by-step approach to construct the master curves were done based the CSIR HMA test protocol developed as part of the SAPDM project.

- Two resilient response models evaluated for the SAPDM appears very promising in terms of their ability to predict dynamic modulus values of the HMA materials studied.
- A reasonable prediction was obtained when using Hirsch's models to predict dynamic modulus values compared to the Witczak predictive model for the five mixes studied.
- A wide range of results are therefore, desired to effectively compare dynamic modulus predicted by the Witczak and Hirsch predictive equations in order to provide reasonable comparison with the values obtained from laboratory testing.
- Also, additional data are required to further optimise the final resilient response model in future revisions of SAPDM.
- It can be concluded at this stage that, Hirsch's resilient response model appear to predict dynamic modulus better than the Witczak model, and could be recommended for implementation in the SAPDM.

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