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

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Abstract

The South African National Road Agency Limited (SANRAL) is developing a revised mechanistic-empirical pavement design guide for road pavements referred to as South African Pavement Design Method (SAPDM). Dynamic (complex) modulus is the resilient response property that will be used to characterise hot-mix asphalt (HMA) mixes in the SAPDM. The objective of this paper is to present resilient response models evaluated for implementation in the SAPDM. These models include sigmoidal master curves developed from dynamic modulus laboratory data of five South African asphalt mixes, 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 from this study, the Hirsch predictive model was found to be more promising in terms of predicting dynamic modulus than the Witczak model. However, it is noted that this conclusion is based on the test results of only five HMA mixes, and also, the fact that rolling thin film oven properties may not be valid for some of the five HMA mixes used for this study.

1. INTRODUCTION

The existing South African Mechanistic-empirical 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 mechanistic-empirical (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 five selected asphalt mixes in the SAPDM project;
- Present an evaluation of two resilient response equations commonly used for the prediction of dynamic modulus in ME pavement analysis.

A laboratory testing programme was conducted to establish dynamic modulus database using the asphalt samples studied. This data was used to construct master curves which would enable the prediction of resilient response of the selected mixes at any test temperature and loading frequency. The dynamic modulus predictive 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 in addition to other HMA characteristics (Witczak and Fonseca, 1996; Andrei and Witczak, 1999; Christensen et al, 2003).

2. RESILIENT RESPONSE AND HIERARCHICAL APPROACH TO DESIGN

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). The modulus properties of HMA materials are known to be a affected by temperature, 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). Regardless of the analysis level, dynamic modulus will be used in the SAPDM for resilient response characterisation of the HMAs.

It is assumed that the 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 binder viscosity values obtained from tabulated

historical data will be used as input for the predictive equations. 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 40/50 penetration-grade bitumen used as a binder.
- Coarse continuously graded mix with an SBS-modified binder (A-E2)
- Medium continuously graded mix with an SBS-modified binder of (A-E2).
- Medium continuously graded mix with a 60/70 penetration-grade bitumen, and
- Bitumen-Rubber Asphalt Semi-Open graded (BRASO) mix.

All the five mixes were designed by Much Asphalt plant in Eikenhof. The mixes were produced in accordance with the designs and tested in the CSIR pavement materials laboratory using Technical Methods for 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, based on 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 a 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), whereby the ageing temperature was defined as the compaction temperature. For instance, the BRASO mix was aged at 145°C (compaction temperature) for four 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 short-term aged samples only. Long-term ageing is achieved when compacted specimens made from the short-term aged samples are placed back in the oven and aged for five days at a temperature of 85°C.

An Industrial Process Controls Ltd (IPC) Servopac gyratory compactor was used to prepare cylindrical samples of 150 mm in diameter and 170 mm high for the dynamic modulus testing. A trial and error method was used to obtain the final design air voids content. Samples were initially compacted to higher voids content such that the final cored and cut specimens for dynamic modulus testing (100 mm diameter, 150 mm height) complied with the required design voids. In the dynamic modulus test protocol for SAPDM, samples whose voids content deviate by more than 0.5% from the design air voids are discarded (Anochie-Boateng et al., 2010).

3.2. 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. A strain controlled instead of stress controlled loading used in the AASHTO TP62 protocol was used in this protocol for SAPDM. Using this approach, the applied stress on the sample is automatically varied in the test software so that the magnitudes of the strains are always kept within the range of 75 to 125 microstrains in order to ensure linear behaviour of the sample. In addition, the AASHTO TP62 protocol recommends two replicate specimens when three LVDTs are used to record strains. However, five replicate specimens are proposed for the SAPDM dynamic modulus protocol to ensure a higher confidence in the test results. To achieve equilibrium temperature for samples before testing, dummy specimen with a thermocouple was placed next to the test specimen in the test chamber. This is used in the SAPDM protocol instead of the proposed equilibrium times of overnight for test temperatures of -10 and 4.4°C, three hours for 21.1°C, two hours for 37.8°C and one hour for 54.4°C as recommended by AASHTO TP 62.

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, 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.

$$\sigma^* = \sigma_0 e^{i\omega t} \tag{Eq.1a}$$

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

where σ is the applied stress, σ_0 is the stress amplitude; ε is the strain response, ε_0 is the strain amplitude; ω is angular frequency, which is related to loading 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.

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

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.

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

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. Recall that, master curves 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 loading 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 reference temperature is arbitrarily chosen even though in the standard AASHTO dynamic modulus test protocol temperature of 21°C (70°F) is used (AASHTO TP 62, 2009). Note that any of the testing temperatures could be chosen as the reference temperature. In the SAPDM test protocol, 20°C is chosen for convenience because it was one of the testing temperatures and, also close to 21°C, which is commonly used for dynamic modulus master curve construction (NCHRP 1-37A, 2004).

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

where

$|E^*|$ = dynamic modulus
δ = minimum value of $|E^*|$
$\delta+\alpha$ = maximum value of $|E^*|$
β, γ = shape parameters of the model

The fitting parameters (α, β, δ, γ, 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 = loading 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

η = 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.

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

where:

η = 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.

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

Where, c = fitting parameter

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 loading 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.

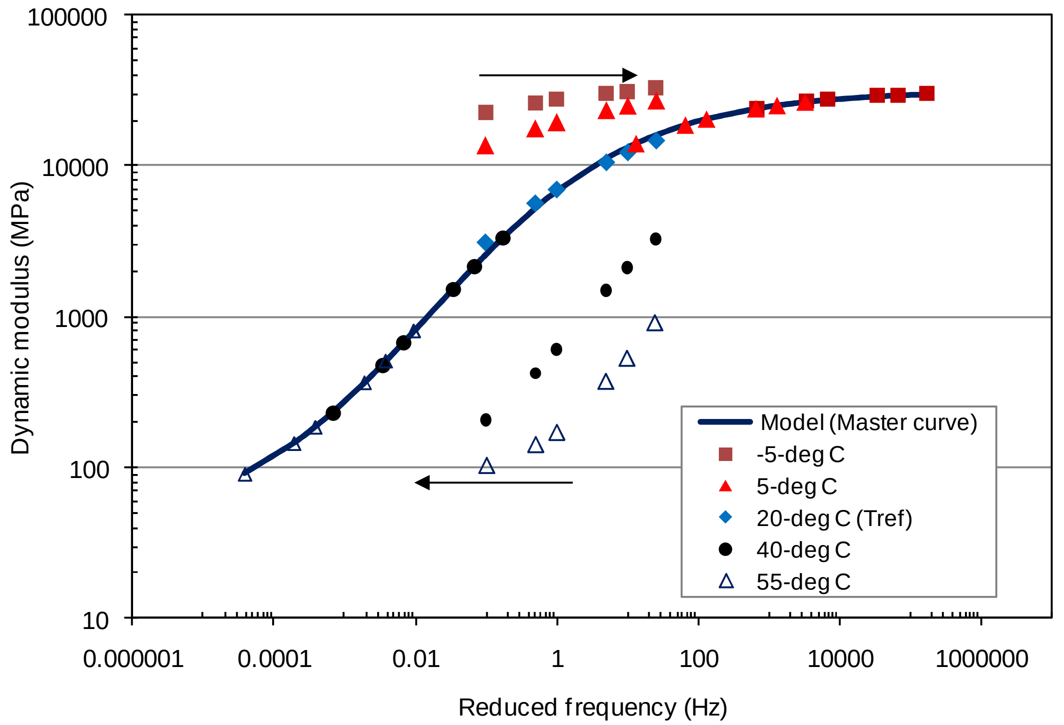


Figure 2. **Dynamic modulus master curve for medium 60/70 mix**

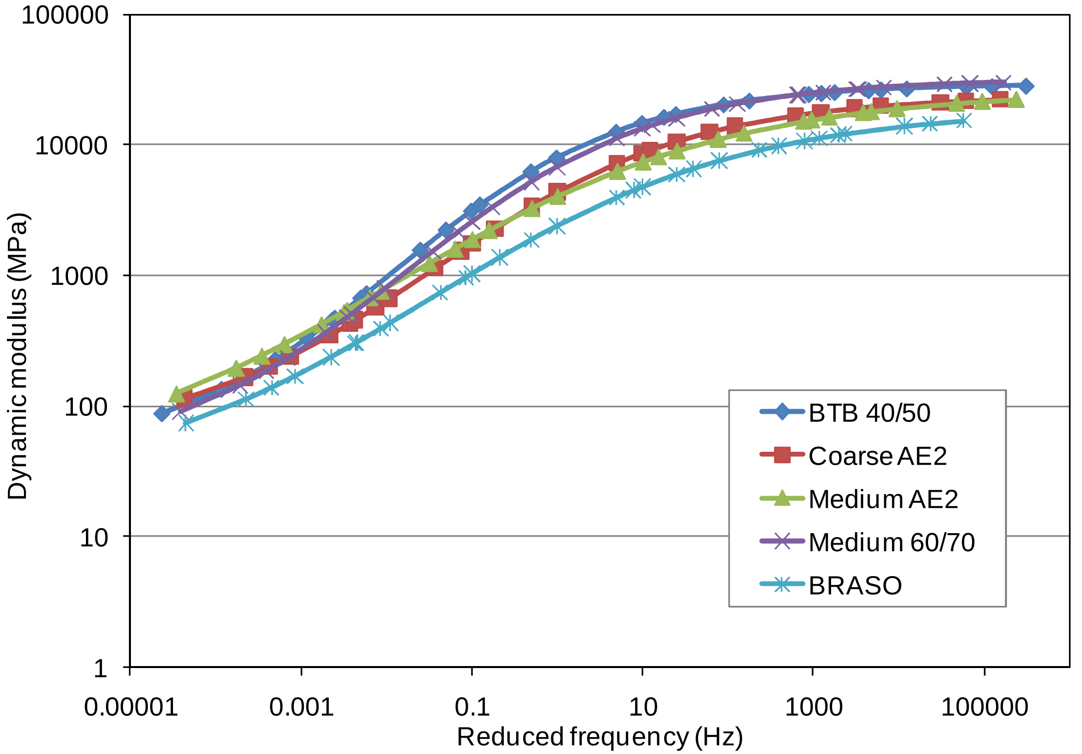


Figure 3. **Comparison of dynamic modulus of five South Africa HMA mixes**

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

4.2. Determining SAPDM Dynamic modulus inputs

Table 2 shows the sigmoidal model parameters developed for the five asphalt mixes. Each result represents an average dynamic modulus value of five replicate specimens. Equation 4 could be used to compute the dynamic modulus at the test temperatures -5, 5, 20, 40 and 55°C and loading frequencies 0.1, 0.5, 1, 5, 10 and 25Hz by substituting the A/VTS values determined from the binder consistency tests, and the sigmoidal fitting parameters (δ, α, β, γ, c) obtained through the numerical optimization. A total of 30 dynamic modulus values will be calculated.

Note that the sigmoidal model parameters presented in this paper will need to be calibrated/validated using additional laboratory or field tests for the selected mixes in order to introduce confidence in their usage.

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

Mix type	δ	α	β	γ	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

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 one or more 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.

$$\log \left|E^*\right| = 3.750063 + 0.029232\,P_{200} - 0.001767\,(P_{200})^2 - 0.002841\,P_4 - 0.058097\,V_a - 0.802208\,\frac{V_{beff}}{\left(V_{beff}+V_a\right)} + \frac{\left[3.871977 - 0.0021\,P_4 + 0.003958\,P_{38} - 0.000017\,(P_{38})^2 + 0.00547\,P_{34}\right]}{1+e^{\left(-0.603313-0.313351\,\log f-0.393532\,\log \eta\right)}} \quad \text{(Eq.9)}$$

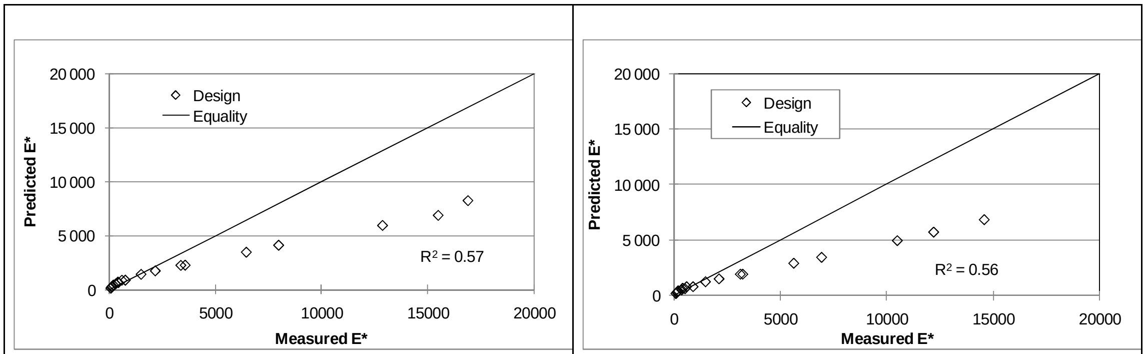
where:
$|E^*|$ = dynamic modulus, in psi (145 psi = 1 MPa);
η = binder viscosity, in 10^6 poise (10 Poise = 1 Pa.s);
f = loading frequency, in Hz;
V_a = % air voids in the mix, by volume;
V_{beff} = % effective bitumen content, by volume;
$P_{3/4}$ = % retained on ¾-in. [19.0-mm] sieve, by total aggregate 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 asphalt mixes tested. According to the MEPDG, viscosities from any of a number of types of consistency tests after rolling thin film oven treatment (RTFOT) are plotted on a graph of log-log viscosity (η) versus log temperature (T_R) yielding a straight line relationship. This relationship can then be used to derive a viscosity value at any temperature for input into the Witczak model. The binder viscosities after RTFOT for each HMA were derived for temperatures of 20, 40, and 55°C and a frequency of 1.59 Hz, and were used to predict dynamic modulus $|E^*|$ of the mix. The predicted $|E^*|$ values were compared with the dynamic modulus values obtained from laboratory.

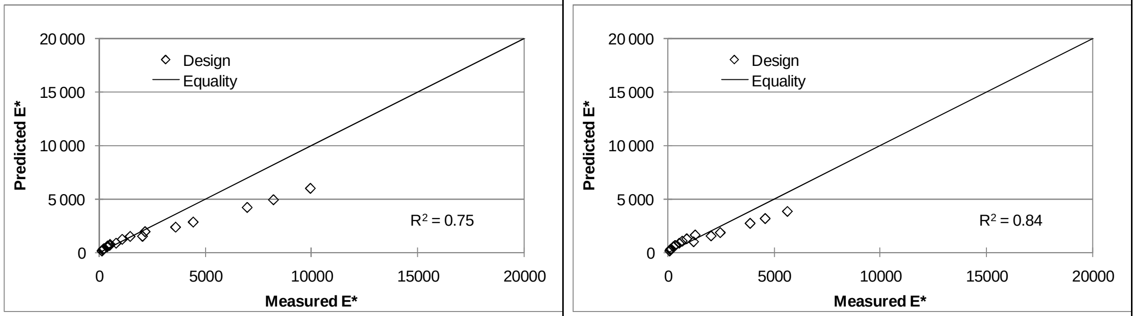
Figure 4 compares measured values from dynamic modulus test with predicted dynamic modulus values from Witczak's model for all the five asphalt mixes. A combined data for all the five mixes is also presented to indicate the overall predictability of the Witczak's model for South African mixes. Based 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. Furthermore, the predictions were based on the RTFOT viscosities, which were found to correlate poorly with the binder recovered from the short-term aged laboratory samples for most of the five mixes. This implies that the model was evaluated using mostly unrepresentative binder viscosities. 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.



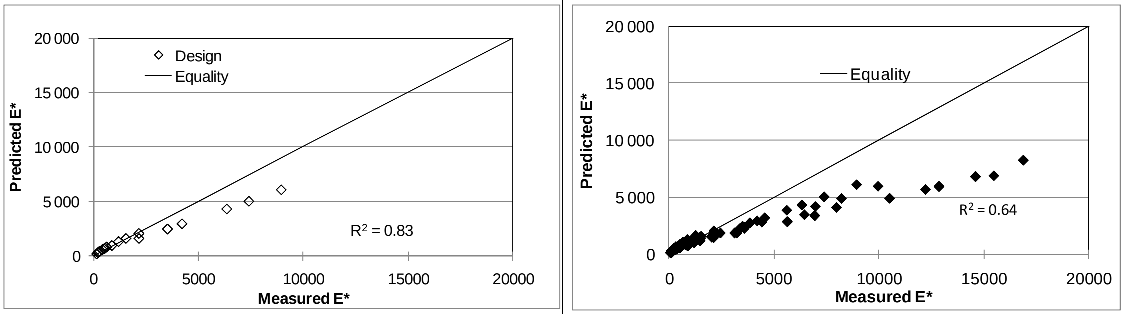
(a) BTB 40/50 mix

(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

The 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 the dynamic modulus of the mix. In the Hirsch model, the dynamic modulus IE^*I of asphalt mix is directly estimated from the complex shear modulus of binder IG^*I$_{binder}$ 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. Note that in Southern Africa context voids filled with binder (VFB) is the same as VFA.

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);

$|G^*|_{\text{binder}}$ = shear complex modulus of binder (psi);

VMA = percent voids in mineral aggregates

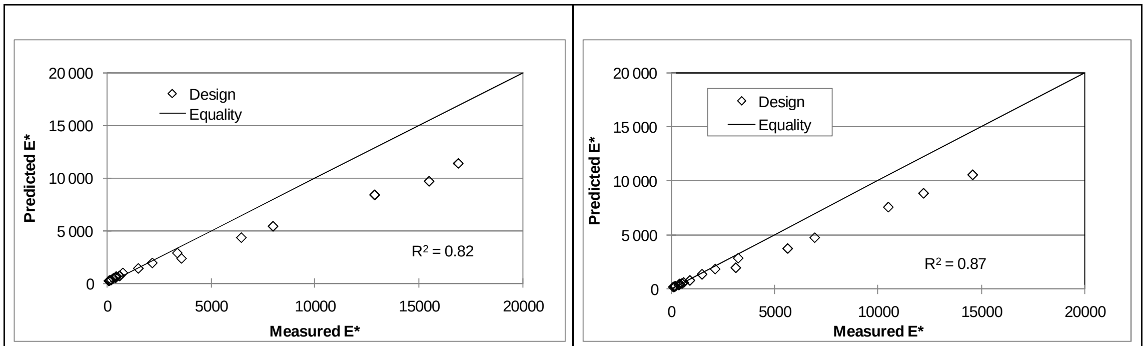
VFA = percent voids filled with binder

P_c = aggregate contact factor

5.2.1 Predicting dynamic modulus using Hirsch model

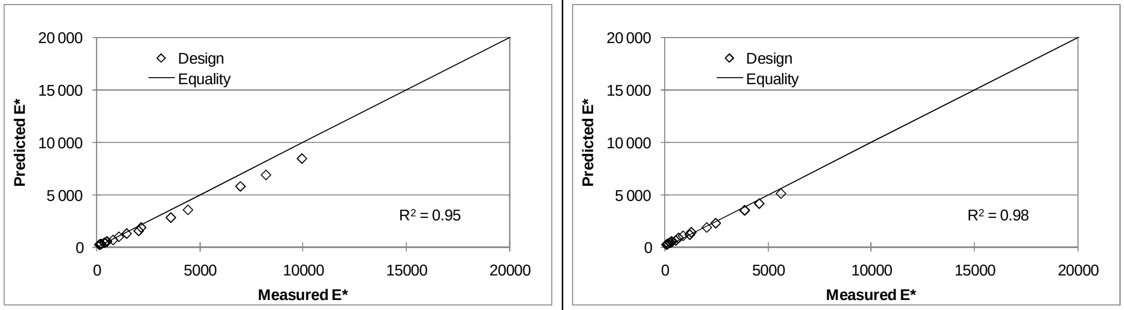
The Hirsch |*E**| model (see Equation 10) was used to predict dynamic modulus of the five mixes tested. The shear complex modulus values of the individual binders $|G^*|_{\text{binder}}$ at temperatures 20, 40, and 55°C and at frequencies 0.1, 0.5, 1, 5, 10 and 25 Hz were used to predict dynamic modulus |*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 the five asphalt mixes. A combined data for all the five mixes is also presented to indicate the overall predictability of South African HMA materials by 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. As was the case for the Witczak model, only five mixes were used in the Hirsch's model. Furthermore, as for the Witczak model, the predictions were based on the RTFOT viscosities, which were found to correlate poorly with the binder recovered from the short-term aged laboratory samples for most of the five mixes. Again, this implies that the model was evaluated using mostly unrepresentative binder viscosities. Additional data are required for detailed discussions on the Hirsch's predictive model in order to make valid conclusion for the SAPDM.



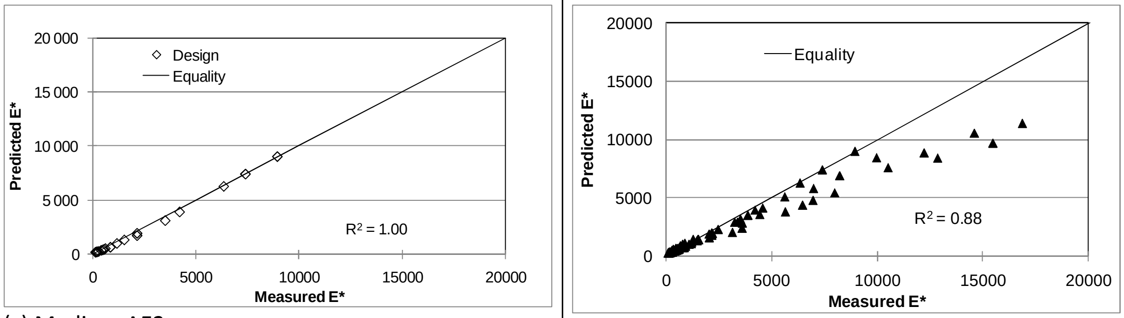
(a) BTB 40/50 mix

(d) Medium 60/70



(b)Coarse AE2

(e) BRASO



(c) Medium AE2

(f) Combined data for all mixes

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

6. CONCLUSIONS AND RECOMMENDATIONS

The objective of this paper was to present resilient response models evaluated 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 recommendations and 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.
- Two resilient response models recommended for the SAPDM require further analysis in

terms of their ability to predict dynamic modulus values of the HMA materials studied.

- Although the Hirsch resilient response predictive model agreed more closely to actual values obtained from laboratory results of the five asphalt mixes than the Witczak model, it must be taken into account that limited data were used to predict both models. Furthermore, the models were evaluated using mostly unrepresentative binder viscosities. Additional data are required to assess the final resilient response model in the future revision of SAPDM.
- A sensitivity analysis should be done for both predictive models in order to determine the effect of binder viscosity variation on the predicted dynamic modulus. Once such binder effects are established, a further sensitivity analysis of the current MEPDG to the variations in dynamic modulus (due to binder variation) and the resultant affect on pavement performance prediction would determine the importance of binder viscosity in the these predictive models.

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