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EVALUATION OF THE HIRSCH MODEL FOR DYNAMIC MODULUS ESTIMATION OF ASPHALT MIXTURES

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The dynamic modulus of the asphalt mixtures is an important factor in designing or analyzing an asphalt concrete pavement, but it is expensive and time consuming to measure. Therefore, it is important to develop a model to predict this value. In this regard, the Hirsch model is a popular model, however, it is developed based on a range of U.S. asphalt mixtures and standards. Therefore, it is not certain that it can be used for asphalt mixtures based on materials and codes other than U.S. This article investigated whether this model performs satisfactorily with two typical asphalt mixtures in Western Australia (WA) containing 0, 10, 20, and 30% of recycled asphalt pavement. To do so, cylindrical samples were made with materials and locally established standards in Western Australia and then tested in Asphalt Mixture Performance Tester (AMPT) machine to acquire their dynamic modulus and phase angle values in different loading frequencies (0.01 to 10 Hz) and temperatures (4 to 40^{o}C). Meanwhile, the results are estimated by the Hirsch model using some properties of the mixture and binder. The properties of the binder in different test conditions are obtained using a dynamic shear rheometer. The comparison of the results showed that the dynamic modulus underestimation or overestimation error can reach to 50 and 280% respectively. Generally, this model did not perform well in this study.

Keywords: E*, Phase angle, Prediction model, Dynamic shear rheometer (DSR), Asphalt mixture performance tester (AMPT), Recycled asphalt pavement (RAP).

1 INTRODUCTION

The dynamic modulus (E*) of the asphalt mixtures plays an important role in a variety of pavement design guidelines (AASHTO 2008, Li *et al.* 2011). This feature is under the influence of both elastic and viscous properties of the asphalt specimen under harmonic loading. This feature can be obtained through testing the sample in different loading frequencies and temperatures to understand the behavior of the sample in different conditions. The loading can be done in compression, tension and the combination of both modes, while the results expected to be similar because asphalt concrete can be assumed to be an isotropic material (Sondag *et al.* 2002). The dynamic modulus can be obtained by different tests. For instance, Lee (2011) recommended using indirect tensile test for acquiring this parameter. However, it is more popular to obtain this parameter by monitoring the response of a cylindrical asphalt sample under a sinusoidal load as advised in as (AASHTO 2007) and (Bonaquist 2008). No matter which method is being used to determine the dynamic modulus, this test is a time-consuming and expensive procedure. Therefore, having a reliable predictive model to estimate the dynamic modulus is very beneficial to reduce the cost of unnecessary trials and experiments when analyzing or designing a pavement structure.

In this regard, the Hirsch model is a popular model to estimate the dynamic modulus of the asphalt samples. This model is developed based on the US mixtures and standards and it is not clear whether it performs well for the asphalt mixtures from other regions other than the US. In this paper, its performance is studied for the recycled asphalt pavement (RAP) incorporated asphalt mixtures made by Western Australian material and design codes.

2 LITERATURE REVIEW

Due to the importance of developing a model to predict the dynamic modulus accurately, many studies have been done in this field and different models have been developed. A group of these models is Hirsch, Al-khateeb, Witczak 1-37A, Witczak 1-40D model and artificial intelligence based methods including the artificial neural network. (Al-Khateeb *et al*. 2006, Kim *et al.* 2011, Timm and Robbins 2011, Yousefdoost *et al*. 2013).

However, to the best knowledge of the author, there is no model which are developed based on the asphalt mixtures designed by Western Australian (WA) materials and standards. Moreover, the RAP incorporated mixtures have not being used in developing of some of these models. Therefore, the applicability of these models for the mixtures in the WA which might contain recycled asphalt pavement is not assured. Among these models, the Hirsch model has an extra advantage. This model not only predicts the dynamic modulus of the mixture but also estimates its phase angle. This model also has been widely used by researchers and engineers. For example Bonaquist (2008) used this model to estimate the maximum dynamic modulus of an asphalt mixture using maximum binder’s complex modulus for constructing the dynamic modulus master curve. Also Zofka (2004) used this model to back calculate the binder’s stiffness. Because of the abilities of the Hirsch model and its popularity, the Hirsch model is chosen in this study to check its performance for the asphalt mixtures in this study.

3 METHODOLOGY

To evaluate the usability of the Hirsch model for asphalt mixtures designed and made in the Western Australia, a series of the sample with two different nominal size and four levels of RAP content were prepared. These samples then tested to obtain their dynamic modulus and phase angle in different loading frequencies and temperatures. In total, 150 different records were obtained for this study. Later, the Hirsch model was used to estimate the dynamic modulus of the tested samples in similar testing conditions and then the results compared with the actual results. The details of these procedures are described in the following sections.

3.1 Hirsch model For Dynamic Modulus Prediction of Asphalt Mixtures

This model is developed based on a simple composite material system which is consisted of three phases; aggregates, asphalt binder and air voids. These phases are placed in a combination of series elements and a parallel component as described in (Christensen and Bonaquist 2015). Based on such a system, a dynamic modulus and phase angle of the mixture can be find using Eq. (1) and Eq. (2) (Timm and Robbins 2011).

$$|E^*|_m = P_c\left[4200000\left(1-\frac{VMA}{100}\right)+3|G^*|_b\left(\frac{VFA\times VMA}{10000}\right)\right]+\frac{(1-P_c)}{\frac{\left(1-\frac{VMA}{100}\right)}{4200000}+\frac{VMA}{3|G^*|_b(VF}} \quad (1)$$

$$\varphi = -21(logP_c)^2 - 55logP_c \tag{2}$$

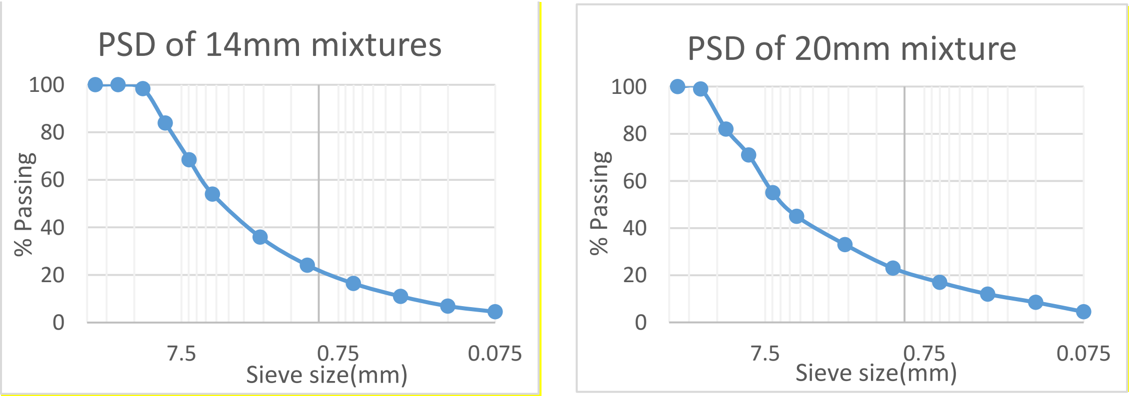
$$P_c = \frac{\left(20 + 3|G^*|_b(VFA)/(VMA)\right)^{0.58}}{650 + \left(3|G^*|_b(VFA)/(VMA)\right)^{0.58}} \tag{3}$$

where $|E^*|_m$ is dynamic modulus of HMA (psi), $|G^*|_b$ is dynamic shear modulus of binder (psi), VMA is percentage of voids in mineral aggregates, VFA is percentage of void filled with asphalt, Φ is phase angle of HMA (Degrees) and P_c is aggregate contact volume calculated by Eq. (3).

3.2 Experimental Program

3.2.1 *Materials and mixtures*

Two typical mixtures in WA with C320 binder and nominal size of 14 and 20 mm were designed. The 14mm mixture was redesigned to have 0, 10, 20 and 30% of RAP by the total of its weight in a way that final product has the similar PSD and binder content as the original mixture. These mixtures were designed and made based on local specifications and material. The particle size distributions of the mixtures are shown in Figure 1. Moreover, the mixtures' binder contents are 4.7 and 4.3% by the total weight for 14 and 20 mm mixtures respectively.



(a) (b)

Figure 1. Particle size distribution of (a) 14mm mixtures and (b) 20 mm mixtures.

3.2.2 *Sample preparation and dynamic modulus testing*

Minimum three samples were made per mixture by pouring a mixture in a cylindrical mould and take a 100mm in diameter core from it after compaction. Later the samples were cut to have 150mm height using IPC global Auto-saw machine. After checking the air void of the samples according to WA Main roads specification (Main Roads Western Australia 2012), the samples were tested in AMPT machine from IPC Global Company by applying sinusoidal compression load at different temperatures while monitoring the response of the sample. The frequencies used in 20°C and 4°C were 10, 1, and 0.1 Hz. At 40°C a load with 0.01 Hz frequency was also applied in addition to other frequencies. Having monitored the load and the response of the sample over time, the dynamic modulus of the sample can be calculated by dividing the amplitude of applied stress by the amplitude of measured strain. The phase angle can also be calculated based on the delay between the measured strain and applied stress on the sample. Totally, 150 data points were collected.

3.2.3 *Binder properties*

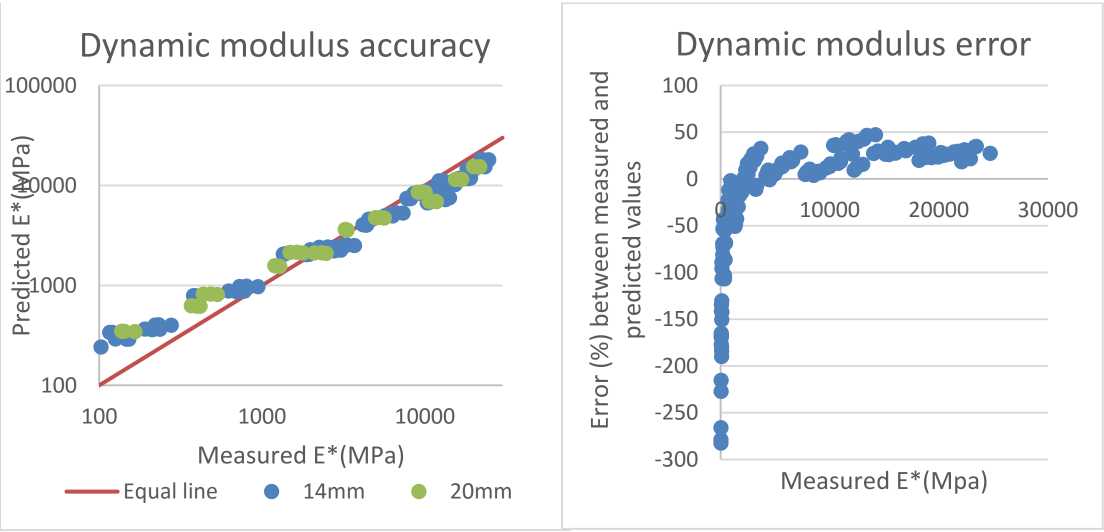
As explained before, the Hirsch model requires the dynamic shear modulus of the binder. Therefore, the binder of each mixture was extracted and recovered using a rotary evaporator according to (Main Roads Western Australia 2011) and (NSAI 2013). Later, the recovered binders were tested in a dynamic shear rheometer (DSR) machine at frequencies between 0.1 to 10 Hz and 5, 20, 30 and 40°C. However, no binder data was available at 4°C. Also, at 40°C, no binder tested at the 0.01Hz frequency. For these situations, the time-temperature superposition principle was used to determine the response of the binder in conditions other than what they were tested in a similar procedure recommended in (Bonaquist 2008).

4 RESULTS AND DISCUSSIONS

This section, the results of the experimental tests are compared with the estimated results from the Hirsch model for all the 150 available data records. For making the comparison more convenient, an error between the actual value and estimated value is defined as Eq. (4) shows.

$$Error\ (\%) = \frac{Measured\ Value - Predicted\ Value}{Measured\ Value} \times 100 \qquad (4)$$

Figure 2(a) shows the accuracy of the Hirsch model to predict the dynamic modulus of the asphalt samples in this study. Also, the equal line was drawn which shows the complete correlation of the model and experiment. If the points are below or above the line it can be interpreted as underestimation or overestimation of the parameter in interest. Also, the Figure 2(b) shows the amount of the error against the experimentally measured dynamic modulus.

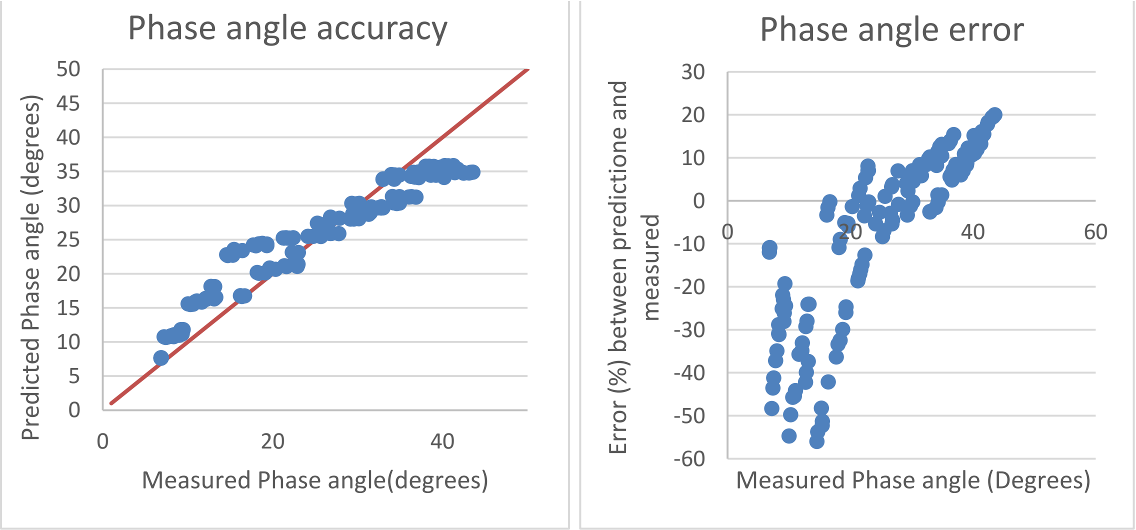


(a)

(b)

Figure 2. Dynamic modulus prediction accuracy of Hirsch model against measured E*.

As Figure 2(a) shows, the Hirsch model has a tendency to overestimate the dynamic modulus of the samples with dynamic modulus lower than approximately 2000 MPa; while underestimating the same parameter for the samples with higher actual dynamic modulus. It also shows that this trend is similar for both 14mm and 20mm nominal aggregate size samples. According to the Figure 2(b), the error of Hirsch model in overestimation and underestimation of the E* can reach up to 280 and 50% respectively. Similarly, Figure 3 compares the estimated phase angle by the Hirsch model with the actual result obtained from the experiment.



(a) (b)

Figure 3. Phase angle accuracy of Hirsch model against measured phase angle.

With regards to the phase angle, Figure 3(a) illustrates that the phase angle of the samples, in general, were overestimated for the samples with phase angle lower than 30 degrees while it underestimated the rest of the samples. Also, Figure 3(b) shows that the maximum error in overestimation and underestimation of the phase angle was 56 and 20%, respectively.

Generally, the Hirsch model tends to overestimate the dynamic modulus or phase angle when their actual values are relatively low. However, for samples with relatively high dynamic modulus or phase angle, the Hirsch model underestimated these parameters.

5 CONCLUSION

This study investigated the efficiency of the Hirsch model to predict the dynamic modulus and phase angle of the two typical asphalt mixtures in the Western Australia with different level of RAP incorporation. These samples were tested in the AMPT machine in different testing conditions.

In total, 150 data record were produced. The data was then compared to the outcome of the Hirsch model for similar situations. It was found that the model has a tendency to overestimate the dynamic modulus and phase angle of the samples when these parameters are relatively low (less than 2000 Mpa for E* and 30° for phase angle). These overestimation errors can reach to 280 and 56 % for dynamic modulus and phase angle respectively. It also underestimates these parameters (with errors up to 50% for E* and 20% for phase angle) when the actual measured parameter is relatively high (greater than 2000 Mpa for E* and 30° for phase angle). Overall, the results are not suggesting using the Hirsch model for estimation the properties of the asphalt mixtures in this study due to a high level of errors and further research is recommended for developing a more reliable model for dynamic modulus prediction of the asphalt mixtures in the Western Australia.

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