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Investigation on the pavement performance of asphalt mixture based on predicted dynamic modulus

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HIGHLIGHTS

- NCHRP 1-40D model yielded better E^* values compared to NCHRP1-37A for base asphalt.
- Master curve of predicted E^* can characterize the asphalt mixtures by CAM model.
- Witczak models were useful in estimating pavement performance.

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ABSTRACT

The objective of this study is to evaluate the pavement performance through model analysis using predicted dynamic modulus (E^*). E^* is predicted based upon the two global prediction models (NCHRP 1-37A and NCHRP 1-40D models). Christensen–Anderson–Marasteanu (CAM) model is utilized to fit master curve to the predicted E^*. Results indicate that the models are applicable to predict E^* of asphalt mixture. Mastercurve of predicted E^* can characterize the pavement performance by nonlinear fitting based on CAM model. Comparison of predicted results of pavement performance (rutting, cracking and fatigue) with measured results is made to verify the applicability of this approach. It is believed that the Witczak models are useful in estimating pavement performance associated with the CAM model, when actual E^* tests or other performance tests are not possible or practicable in practice.

1. Introduction

The dynamic modulus of hot asphalt mixture (HMA), denoted as E^*, is one of the most important parameters to determine the strains and displacements (deflection) of layered pavement structures. E^* defines the stiffness characteristics of HMA as a function of loading rate and temperature, and it is widely used in pavement design and analysis process. It is also a key parameter for prediction of field performance in pavement design process [1–3]. Dynamic modulus of asphalt mixture is highly correlated to deterioration of pavements due to rutting, low temperature cracking, fatigue cracking, and other types of distresses. For example, a relatively low dynamic modulus at low frequencies is related to a low resistance to rutting deterioration. In addition, a high stiffness at high frequencies is related to low resistance towards fatigue cracking deterioration and low temperature cracking. Therefore, it is necessary to accurately determine the dynamic modulus of asphalt mixes over a wide range of temperatures and frequencies in order to evaluate the resistance to rutting, fatigue cracking and low temperature cracking of flexible pavements.

The Mechanistic Empirical Pavement Design Guide (MEPDG) provides three hierarchical levels of inputs (i.e. Level 1, Level 2, and Level 3). Dynamic modulus values for Level 1 are measured in the laboratory at selected combinations of temperatures and loading frequencies. However, dynamic modulus (Level 1) is not always feasible to measure due to the availability of the required equipments, high cost and time constraints for many institutions [4]. Dynamic modulus for Level 2 and Level 3 are estimated based on the asphalt binder and volumetric properties of the compacted samples. By comparing predicted E^* values to actual E^* values, a preliminary judgment would be available to reasonably realize to what degree a given model could be used to estimate E^* at Levels 2 and 3, and for those situations where a Level 1 suite testing is

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not practicable. The MEPDG emphasizes the use of dynamic modulus of asphalt mixes at all three different levels of design to predict the performance of flexible pavements. Therefore, the use of Level 2 and Level 3 seems to be a reasonable approach for the design and the analysis of pavements.

Attempt has been made by many researchers to predict dynamic modulus of mixture at Levels 2 and 3. Witczak model was firstly proposed to predict dynamic modulus by Kallas and Shook. Witczak and his colleagues further corrected and improved the model considering many other factors [5–10]. Dai developed a micromechanical finite-element (FE) model to predict dynamic modulus $(E)^*$ and phase angle (δ) of asphalt mixtures [11]. You et al. adopted a clustered distinct element method for modeling asphalt mixture microstructure to predict E^* of asphalt mixtures [12]. The results showed that these models had a good prediction of pavement performance.

To achieve better correlations between the measured and the predicted E^*, advanced models were developed to correlate the predations to actual field performance characteristics. The most recently and commonly well-utilized two equations (NCHRP 1-37A and NCHRP 1-40D) are described in this paper. It is noteworthy that the two models illustrated are used in the MEPDG to predict E^* of the mixes at various temperatures and frequencies under Levels 2 and 3. In comparison to other models, the prediction of E^* by means of Witczak Models are more consistent at all temperatures since it is reasonable that both two NCHRP Models employ a sigmoidal function to fit the data and a larger database as a basis of formulating those two equations and in the meanwhile they were calibrated with actual measured E^*. Many studies [13,14] show that Witczak prediction models provide sufficiently accurate and reasonable dynamic modulus comparing with other models. Schwartz also stated that the temperature is the main influence factor in Witczak predictive models. And the models reduce the influence of other parameters (such as aggregate shape parameters, i.e. angularity, texture and form), which makes the models have more application scope [15].

Dynamic modulus is highly dependent on the time and the temperature. The relationship between the loading frequency and modulus measured at a specified test temperature can be represented in a graphical form using the master curve, which is a critical input parameter in the flexible pavement design. The master curve is constructed based on the principle of time–temperature superposition. In practice, engineers are interested in pavement properties in the worst scenarios. The master curve provides the information of E^* over a wide range of temperature and frequency which also can be used to estimate the dynamic modulus out of the lab testing range [16].

Moreover, the master curve can be used to calculate mechanical parameters of asphalt mixtures and forecast the long-term mechanical and pavement properties using nonlinear regression approach on basis of some models. Among these models, CAM model [17,18] is developed to improve the descriptions of unmodified and polymer-modified bitumens, especially at low and high frequencies. And the model with definite physical meaning parameters is able to satisfactorily describe the rheological properties of asphalt mixture [19]. So master curve of prediction E^* of mixtures should be accurate to evaluate mechanical property and pavement performance of asphalt mixtures utilizing CAM model.

In this paper, the suitability of those two close-form models (NCHRP 1-37A and NCHRP 1-40D Models) was discussed. CAM model was selected to fit master curve to the predicted E^*. The predicted E^* of asphalt mixtures by NCHRP 1-40D model can be utilized to estimate the pavement performance associated with CAM model. In the last part of this paper, the measured pavement performance characteristics were compared with predicted results to identify the feasibility of the method.

2. Experiment

2.1. Raw materials

Investigation was conducted with two base bitumens and the basic properties of bitumen were exhibited in Table 1. The bitumen were all 70# base asphalt, but were produced from different oil field.

The gradation curves of the asphalt mixtures were shown in the Fig. 1, and optimum asphalt content was 4.7%; various volumetric properties of mixtures were provided in the Table 2.

2.2. Methods

2.2.1. Frequency sweep test

Frequency sweep tests were carried out to evaluate rheological property of asphalt using MCR101 Dynamic Shear Rheometer (DSR) produced by Anton Paar Company (Austria). Sweep frequency used in this study is in a range from 400 to 0.1 rad/s. The testing temperatures were set as 0, 10, 20, 30, 40, 50, and 60 °C, respectively. A 25 mm loading plate in diameter were used in the test on a layer of 1 mm bitumen at high temperature (higher than 30 °C); 8 mm diameter plates with 2 mm gap were used at low temperature (lower than 30 °C).

2.2.2. Dynamic modulus test

Dynamic modulus tests were conducted using the Universal Testing Machine-25 (UTM-25, produced by IPC, Australia) with an environmental chamber. The specimens with a diameter of 100 mm and 150 mm in height were prepared. Six frequencies (25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, 0.1 Hz) and five testing temperatures (−10 °C, 5 °C, 20 °C, 35 °C, 50 °C) were selected to obtain the dynamic modulus in different combinations.

2.2.3. Wheel tracking test

The wheel tracking tests were adopted to evaluate high-temperature permanent deformation performance of asphalt mixtures. A contact pressure of 0.7 MPa and total wheel load of 1.37kN was applied on the 300 mm × 300 mm × 50 mm square asphalt slab at 60 °C for 5 h under a dry condition. The wheel moves in a speed of 42 ± 1 times per minute along the center line of the slab.

2.2.4. Three-point bending test

Three-point bending tests were conducted to estimate low-temperature cracking resistance performance of asphalt mixtures by using UTM-25. The specimens (250 mm in length × 30 mm in width × 35 mm in thickness) were conditioned at −10 °C for 4 h before the test start. The tests were performed at −10 °C and the deformation rate of 50 mm/min was applied.

2.2.5. Four-point bending test

Four-point bending tests were performed to evaluate fatigue resistance performance of asphalt mixture. All Tests were carried out at 20 °C, 10 Hz, and in a controlled strain mode (500 με microstrain) by using UTM-25. Fatigue life could be defined as the number of cycles, at which the stiffness of mixture was reduced to 50% of initial stiffness.

In this paper, two replicative samples were tested to obtain the basic properties and rheological properties of asphalt binders to ensure the accuracy of the experiment for statistical purposes. For each mixture, four replicative specimens were prepared and tested for volumetric properties, dynamic modulus and pavement performance (high temperature rutting, three-point bending, and fatigue property). The mean value of effective specimens was chosen as measured data.

3. Results and discussion

3.1. Analysis based on Witczak's prediction models

3.1.1. NCHRP 1-37A η-based E prediction model

This model predicts mixture stiffness over a wide range of temperatures and loading frequencies from data that is readily available from the volumetric properties of mixture. It was developed based on a large database containing 2750 measurements of com-

Table 1
Basic properties of bitumen.

Properties	*A*	*B*
Penetration (25 °C, 100 g, 5 s) (0.1 mm)	68.1	63.1
Ductility (5 cm/min, 15 °C) (cm)	150	160
Softening point (ring and ball method) (°C)	47	50.3