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New predictive models for the dynamic modulus of hot mix asphalt

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HIGHLIGHTS

- Developing two models for predicting the $|E^*|$ of hot mix asphalt mixtures.
- Modeling is based on viscoelastic and time–temperature superposition concepts.
- The models use different mixture and binder properties to predict $|E^*|$ values.
- Witczak and Hirsch models were evaluated using an exhaustive database.
- New models can be used in performance analyses of asphalt concrete pavements.

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ABSTRACT

This paper presents a fundamental modeling framework for prediction of dynamic modulus of hot mix asphalt mixtures based on viscoelastic principles. The outcomes are two closed-form models that can be used to predict the mixture dynamic modulus for a wide range of temperatures (−10°, 4.4°, 37.8°, and 54.4 °C) recommended in the American Association of State Highway and Transportation Officials (AASHTO) TP62-03 test protocol. To develop and verify the models a large database that covers the complete range of potential input conditions was assembled. In general, the proposed models predict the dynamic modulus with a very good level of accuracy.

1. Introduction

The dynamic modulus, $|E^*|$, is a fundamental property that defines the stiffness characteristics of hot mix asphalt (HMA) mixtures as a function of loading rate and temperature. The significance of this material property is threefold. First, it is one of the primary material property inputs in the Mechanistic-Empirical Pavement Design (MEPDG) and software developed by NCHRP Project 1-37A [1]. The MEPDG uses a mastercurve and time–temperature shift factors in its internal computations. In the MEPDG, the mastercurve is constructed using a hierarchical structure of inputs ranging from laboratory tests on HMA mixtures and binders to estimates based on properties of the HMA mixtures. Second, the $|E^*|$ is one of the primary HMA properties measured in the Superpave simple performance test protocol that complements the volumetric mix design. Third, the $|E^*|$ is one of the fundamental linear viscoelastic (LVE) material properties that can be used in advanced HMA and pavement models that are based on viscoelasticity.

Researchers developing the MEPDG implemented a hierarchical input structure in recognition of the fact that the $|E^*|$ values for materials used in a particular design might not be available when the analysis is performed. In the lowest level of this structure, users may choose to utilize a predictive equation based on mixture volumetric and binder properties to predict the mixture modulus [1]. For this purpose two different versions of Witczak predictive models have been used which use viscosity and shear modulus of binder as their primary inputs. In addition to these predictive models, Witczak models, others have developed predictive models, and

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those that have gained some national interest are the Hirsch model [2], a modified or latest form of Witczak's original model [3] referred to as the *modified Witczak model*, and a modified form of the Hirsch model referred to as the Al-Khateeb model [4]. These regression models also tend to have some limitations when applied for a wide range of mixture properties and at high and low temperatures. Various researchers have reviewed these models using independent data sets and have concluded that, while both have advantages and disadvantages in terms of necessary inputs and ease of use, the predictive capabilities of each could be improved [5–8]. To capture the behavior of a HMA mixture fully, very low and high temperature zones are critical and need to be taken into account appropriately.

The use of Artificial Neural Network (ANN) techniques for predicting the mixture $|E^*|$ has also been undertaken by few research efforts [9–11]. Ceylan et al. developed a series of ANN-based models and compared the predictions with the ones estimated from few existing dynamic modulus predictive models [9]. The results showed that ANN-based $|E^*|$ model showed a better performance than Witczak model both in terms of fitness and bias [9]. Also, the model demonstrated an improved sensitivity to mixture variables at different temperatures and frequencies of testing.

Singh et al. developed a model that utilizes aggregate shape parameters (i.e., angularity, texture and form) in estimating the dynamic modulus of asphalt mixes. The performance of this model was compared with the widely accepted Witczak model that does not use shape parameters of the aggregates. The results indicated that the mean average relative error for the Witczak model was estimated significantly higher than the developed model [12]. Dai developed a micromechanical finite-element (FE) model for predicting the dynamic modulus and phase angle of asphalt mixtures. The simulation results of the asphalt mixture samples showed good correlations with the numerical calibration of asphalt mastic specimen. The results of this study also indicated that the developed micromechanical FE model can provide a computational tool for predicting the global viscoelastic properties of asphalt mixtures with captured microstructure and ingredient properties [13]. You et al. utilized a clustered distinct element method for modeling asphalt concrete microstructure to predict compressive dynamic modulus of asphalt mixtures. This modeling approach showed promising results in terms of estimating the dynamic modulus and was implemented to portray bulk material behavior in conjunction with fracture models to study crack behavior in hot mix asphalt as well [14].

In this study, two close-form models are developed based on a procedure that employs viscoelastic and time–temperature superposition (t–TS) concepts, appropriate treatment of data censoring, identification of dominant parameters, and efficient use of modeling techniques to thoroughly characterize the material behavior under different testing conditions. These models use HMA mixture gradation, volumetric and binder rheological properties, such as the binder shear modulus ($|G^*|$), and test conditions of $|E^*|$ measurements. The laboratory test data used are a combination of multiple comprehensive databases based on the American Association of State Highway and Transportation Officials (AASHTO) TP62-03 and asphalt mixture performance tester (AMPT) test protocols. Also, the databases include test measurements from different aging conditions and various types of modified and unmodified binders.

2. Objective

The objective of this research is to develop regression predictive models for the dynamic modulus of HMA mixtures based on viscoelastic concepts and using different physical and mechanical properties of mixture and binder.

3. Database

One of the most comprehensive database existing, for both binder and mixture moduli, is the one used to develop the modified Witczak model [3]. This database is extensive and covers a wide range of material characteristics. At the outset of this study, it was felt that such a database was sufficient to meet the research goals. However, a careful, in-depth evaluation of the database has identified three major issues that affect its usability:

- Different definitions of *frequency* for the binder $|G^*|$ and mixture $|E^*|$ data are used;
- Estimated, rather than measured, $|G^*|$ and phase angle data are used to populate the database; and
- The estimated $|G^*|$ data at temperatures lower than or equal to 4.4 °C are estimated in a manner that is inconsistent with other temperatures; in conjunction with this inconsistency is that the method of estimation is not satisfactorily explained.

When the modified Witczak model was developed and thus when the Witczak database was populated with binder $|G^*|$ data, the developers used what is referred to in this paper as an *inconsistent definition* of frequency. In short, this means that if one wants to predict the mixture $|E^*|$ using the modified Witczak model at, for example, 25 Hz at 20 °C then that person would have to input into the model the binder $|G^*|$ measured at 25 rad/s at 20 °C. The reason for these differences appears rooted in the conventions of the time definition typically applied in binder rheology research and in asphalt mixture research, given in Eqs. (1) and (2) respectively. The developers of the database required that the frequency used for binder should be such that the time by the binder definition was equal to the time defined for the mixture. The argument regarding the appropriateness of these definitions is well beyond the scope of this paper; however, it is important to understand that this is state of data in the Witczak database.

$$t_{\text{binder}} = \frac{1}{\omega} \tag{1}$$

$$t_{\text{mixture}} = \frac{1}{f} \tag{2}$$

where ω is the angular velocity in radians per second, t is time and f is the frequency in hertz.

A more logical approach, which incidentally is used in all of the other $|G^*|$-based models, is to use a *consistent definition* for the frequencies. That is to say if one wants to predict the mixture $|E^*|$ using a model at, for example, 25 Hz at 20 °C then that person would input in the model the binder $|G^*|$ measured at 25 Hz at 20 °C. For this effort, the complete Witczak database was repopulated which consumed substantial effort. It is critical that the reader understands that all possible efforts have been taken to ensure that the proper definitions of frequency (inconsistent or consistent) are used for the respective models. This means that all databases have been populated twice, once using the inconsistent model for predictions with the modified Witczak model and once using the consistent definition for new model development and evaluation of Hirsch model.

Most of the database used to develop the new models contains a comprehensive set of test data that was assembled and used as part of the long-term pavement performance (LTPP) project [15], which itself is based on 14,341 test data points from 801 HMA mixtures. This database later was expanded by assembling the expanded North Carolina State University (NCSU) database. Now, the database includes 20,209 data points from 1008 mixes tested under different aging conditions and includes both modified and unmodified binders measured based on two test protocols, i.e.,