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Nominal property based predictive models for asphalt mixture complex modulus (dynamic modulus and phase angle)

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HIGHLIGHTS

- Provides models that use only nominal inputs to make reliable property estimates during design phase.
- Presents generalized regression framework for developing asphalt property prediction models.
- Model is verified through statistical comparisons and comparisons with other predictive models.
- Application of proposed model for pavement performance prediction is demonstrated.

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ABSTRACT

Dynamic modulus (|E*|) and phase angle (δ) are necessary for determining the response of asphalt mixtures to in-service traffic and thermal loadings. While a number of |E*| and δ predictive models have been developed, many of them require lab measured properties (e.g. binder complex modulus). The majority of previous work has focused only on prediction of |E*|, limited models exist for prediction of δ. This research utilized generalized regression modelling of lab measurements (from 81 asphalt mixtures) to develop and verify prediction models for |E*| and δ using only nominal asphalt mix properties that are readily available during the initial mixture design and specification process.

2. Introduction and background

Complex modulus (E*) is one of the most commonly used property of asphalt mixtures for conducting pavement analysis and modelling. Two components of complex modulus are, dynamic modulus (|E*|), which describes materials stiffness at given temperature and frequency, and phase angle (δ), which describes the extent of viscous and elastic behavior of the material at a given temperature and loading frequency. Laboratory measurements of |E*| and δ are commonly done at different temperature and frequency combinations using AASHTO T342 procedure. An |E*| master curve is the primary asphalt mixture input in the current AASHTO PavementME design procedure.

Although |E*| and δ can be effectively used to predict the long term performance of asphalt mixtures using mechanistic analysis, there are limitations related to equipment requirements, specimen fabrication complexity, data analysis and other expenses in terms of man-power and time requirements. These limitations have severely restricted wide-spread usage of mechanistic empirical and mechanistic pavement analysis and design. In order to alleviate expensive and time-consuming laboratory testing requirements, a number of predictive equations for |E*| have evolved during the last three decades. Two of the most popular predictive equations for dynamic modulus are the Witczak model [1] and the Hirsh model [2]. Most of these predictive equations are based on regression analysis of large datasets and use the volumetric properties of mixtures along with the binder dynamic shear modulus (G*) as their primary input. While there are several models to predict |E*|, there have been far fewer attempts to predict δ.

A distinguishing factor the for research and the prediction model presented herein as compared to previous research is that here only nominal properties of asphalt mixtures, such as nominal maximum aggregate size, air void content, asphalt content, the percentage of recycled asphalt pavement (RAP) and recycled

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asphalt shingles (RAS) and asphalt binder performance grade (PG) are used in model development. These parameters are often readily available during the initial phases of asphalt specification and mix design process. The use of PG grades in lieu of other rheological properties of binder like viscosity and complex shear modulus (G^*) as a continuous factor in the model is logical, since binder PG grade (if not modified) has its own definite rheological characteristics that will impact mixture stiffness. For example, a PG 64-28 in the same temperature and loading condition for a given mix is expected to result in a stiffer (higher $|E^*|$ and lower δ) mixture compared to a PG 58-34. This simply means that actual rheological performance of a binder is expressed by the binder's PG grade. Therefore, the information based on PG can be utilized in a predictive model to capture the viscoelastic behavior of the mix. The use of NMAS instead of gradation of the aggregate relies on the fact that any dense graded aggregate with a given NMAS has to be in a specified gradation band to be adopted for construction purposes. Thus, the NMAS itself could be an indicator of the general gradation and can be used as a predictor in the model. Using these simple properties as effective factors in the model, the outcome not only eliminates the need for even simple lab tests, but also provides the pavement design engineers with a tool for specifying asphalt mixture that would yield the best performance and the lowest cost-benefit ratios. The development of phase angle prediction model used the same nominal mix properties as described, with the exception of $|E^*|$. This additional variable in prediction of δ was deemed necessary to be included during the initial model development trials. The existence of this variable is inevitable since δ is related to $|E^*|$ as discussed by Rowe et al. [3] and Oshone et al. [4]. In the initial development of the model, this research used lab measured $|E^*|$ values for the prediction of δ, however, the proposed model can effectively use predicted $|E^*|$ values.

As one of the most comprehensive equations for prediction of $|E^*|$, the Witczak 2006 model [1] shown below in Eq. (1) is applicable over a wide range of temperatures and frequencies. This model is a revised version of the Witczak 1999 model in which the viscosity-temperature susceptibility (VTS) method which assumes a linear relationship between temperature and log of viscosity is implemented to characterize the behavior of mixture. This assumption is generally valid for unmodified binders. However, for modified binders it may not be applicable. Thus, this approach could suffer from lack of accuracy when used for characterization of viscoelastic behavior of modified binders [5]. Several studies have been conducted to calibrate these predictive models based on local mixtures and binder types [6]. The Hirsch model alleviates some of these short-comings by using binder G^* which is applicable for both modified and conventional binders

$$Log|E^*| = -0.349 + 0.754(|G_b^*|^{-0.0052})6.65 - 0.032P_{200} + 0.0027P_{200}^2 + 0.011P_4 - 0.0001P_4^2\left(+0.006P_{38} - 0.00014P_{38}^2 - 0.08V_a - 1.06\left(\frac{V_{beff}}{V_{beff}+V_a}\right)\right) + \frac{2.558 + 0.032V_a + 0.713\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + 0.0124P_{38} - 0.0001P_{38}^2 - 0.0098P_{34}}{1 + e^{(-0.7814 - 0.5785log|G_b^*| + 0.8834log\delta_b)}} \quad (1)$$

where

$|E^*|$ = Asphalt mix dynamic modulus (psi),
V_a = Air voids in the mix (% by volume),
V_{beff} = Effective binder content (% by volume),
P_{200} = % Passing # 200 (0.075 mm) sieve,
P_4 = Cumulative% retained on # 4 (4.75 mm) sieve,
P_{38} = Cumulative% retained on 3/8 inch (9.5 mm) sieve,
P_{34} = Cumulative% retained on 3/4 inch (19 mm) sieve,
$|G_b^*|$ = Dynamic shear modulus of asphalt binder, (psi),
δ_b = Phase angle of binder associated with $|G_b^*|$, (degree).

The Hirsch model [2] is based on the Paul's law of mixtures which combines series and parallel elements of the material phases. According to this law, asphalt concrete tends to behave like a series composite at high temperatures and as a parallel composite at lower temperatures. Eq. (2) denotes the Hirsch model for predicting $|E^*|$.

$$|E^*| = PC\left[4200000\left(1-\frac{VMA}{100}\right) + 3|G^*|_{binder}\left(\frac{VFA.VMA}{10000}\right)\right] + (1-PC)\left[\frac{1-\frac{VMA}{100}}{4200000} + \frac{VMA}{VFA.3|G^*|_{binder}}\right]^{-1} \quad (2)$$

And,

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

where

$|E^*|$ = dynamic modulus, (psi)
$|G^*|_{binder}$ = binder dynamic modulus, (psi)
VMA = voids in the mineral aggregate, (%)
VFA = voids filled with asphalt, (%)
P_C = aggregate contact factor

Recently some new approaches have been developed to predict $|E^*|$ using artificial intelligence tools and one of them is the Artificial Neural Networks (ANN) method [7]. While this method has shown promising results with a high accuracy of prediction, there are some shortcomings such as, low convergence speed as well as lack of generalizing performance. In other words, even small changes in the input of the model could cause major effects in the model response. Furthermore, they might encounter an overfitting problem [8]. Dynamic modulus has also effectively been predicted using the rheological models like Burger's and Huet-Sayegh model [9]. Other models have been constructed based on viscoelastic and time–temperature superposition concepts [10]. Finite element based predictive models have been developed to predict dynamic modulus through modeling the effect of random aggregate arrangement during the compaction [11].

A well-known predictive equation for δ is based on non-linear regression analysis [12,13]. There are two major limitations to this model, the first being that it uses 16 variables to build up the model that could be decreased. Secondly, this model uses two different regression equations to construct the δ master curve resulting in a break point