Measured Versus Predicted Dynamic Modulus of Asphalt Concrete Used in Colorado

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ABSTRACT

The dynamic modulus (E*) of Asphalt Concrete (AC) is the primary material property used in asphalt pavement design. However, the testing of dynamic modulus of AC is very expensive considering time, equipment and skills. This is why, instead of conducting the testing, the available regression equations in the literature are very often used to determine the dynamic modulus of AC. This research evaluated the mostly used regression equation (known as the viscosity based Witczak model) for 105 asphalt mixtures used in Colorado. The dynamic modulus of AC is predicted using the viscosity based Witczak model and is compared with the measured dynamic modulus. Results show that the predicted dynamic modulus correlated well with the measured dynamic modulus. Hence, the viscosity based Witczak model can be used reasonably in case of no test data is available.

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Introduction

Asphalt Concrete (AC) is a viscoelastic material. Viscoelasticity of a material is the property that exhibit both viscous and elastic characteristics when subjected to deformation. In purely elastic materials, stress and strain are in phase. In viscous materials, there is a phase difference between stress and strain. A 90° phase lag is observed for the strain in purely viscous material (Figure 1). In viscoelastic materials, the behavior is somewhere in between that of purely elastic and purely viscous materials, exhibiting some phase lag less than that for purely viscous materials. Upon applying (σ), the resulting cyclic strain (ε) can be expressed as:

$$\varepsilon = \varepsilon_o \sin(\omega t + \phi) \quad (1)$$

where ε_o is the strain amplitude, ω is the frequency of strain oscillation, t is time, and ϕ is phase lag between stress and strain. The applied stress (σ) can be expressed as:

$$\sigma = \sigma_o \sin \omega t \quad (2)$$

where σ_o is the stress amplitude.

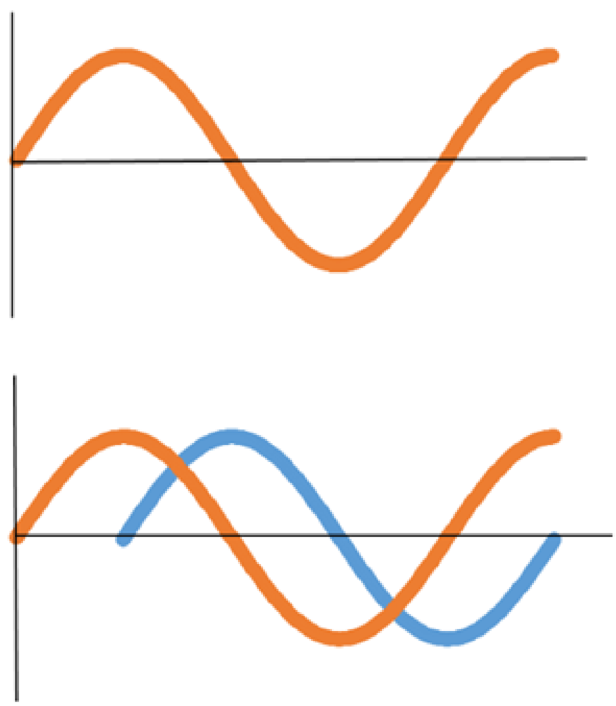

Figure 1 Stress-strain behaviours of elastic and viscoelastic materials.

The storage modulus measures the stored energy representing the elastic portion of the response. The loss modulus represents the viscous response measuring the energy dissipated as heat. The storage modulus (E') and the loss modulus (E'') can be mathematically expressed by Eq. (3) and Eq. (4) respectively.

$$E' = \frac{\sigma_o}{\varepsilon_o} \cos \phi \quad (3)$$

$$E'' = \frac{\sigma_o}{\varepsilon_o} \sin \phi \quad (4)$$

The ϕ-value can be defined as shown in Eq. (5).

$$\phi = \tan^{-1}\left(\frac{E''}{E'}\right) \tag{5}$$

The dynamic modulus (E*) is then expressed as:

$$E^* = E' + iE'' \tag{6}$$

The absolute value of this complex modulus is thus:

$$|E^*| = \sqrt{(E')^2 + (E'')^2} = \sqrt{\left(\frac{\sigma_0}{\varepsilon_0}\right)^2 \left(\sin^2\delta + \cos^2\delta\right)} = \frac{\sigma_0}{\varepsilon_0} \tag{7}$$

where $|E^*|$ is the dynamic modulus, σo is the peak dynamic stress and εo is the peak recoverable axial strain. Thus, the |E*| is defined mathematically as the ratio of σo and εo.The ϕ-value can also be determined as:

$$\varphi = 2\pi\omega\Delta t \tag{8}$$

where, ϕ is the phase angle in radian, ω is the frequency in Hz, and Δt is the time lag between stress and strain in seconds.

The $|E^*|$ of AC depends on many mix factors: aggregate, binder, air void, etc. Few empirical based $|E^*|$ models are available in the literature addressing these factors to determine the stiffness of AC such as viscosity (η) based Witczak model (also called Witczak's I-37A Prediction Model), shear modulus based Witczak model, and Hirsch model (Islam et al. 2019 and Rahman et al. 2019). The viscosity based Witczak model is the primary $|E^*|$ prediction model in the recently developed AASHTOWare pavement Mechanistic-Empirical (ME) design software (AASHTO 2015). The viscosity based Witczak model, presented in Eq. (9), uses η of binder as the main input parameter to capture the effect of binders, aggregate gradation, temperature and air void (AASHTO 2015).

$$\begin{aligned}\log|E^*| = {} & 3.750063 + 0.02932\,\rho_{200} - 0.001767\,(\rho_{200})^2 - 0.002841\,\rho_4 \\ & - 0.058097\,V_a - 0.802208\left(\frac{V_{beff}}{V_{beff} + V_a}\right) \\ & + \frac{3.871977 - 0.0021\,\rho_4 + 0.003958\,\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\,\rho_{34}}{1 + e^{(-0.603313 - 0.313351\log(f_r) - 0.393532\log(\eta))}}\end{aligned} \tag{9}$$

Eq. (9) can be presented similar to the sigmoid function mentioned below:

$$\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma\log(f_r)}} \tag{10}$$

where

$$\delta = 3.750063 + 0.02932\,\rho_{200} - 0.001767\,(\rho_{200})^2 - 0.002841\,\rho_4 - 0.058097\,V_a - 0.802208\left(\frac{V_{beff}}{V_{beff} + V_a}\right)$$

$$\alpha = 3.871977 - 0.0021\,\rho_4 + 0.003958\,\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\,\rho_{34}$$

$$\beta = -0.603313 - 0.393532\log(\eta)$$

$$\gamma = -0.313351$$

$$f_r = a(T) * f$$

$$\log f_r = \log f + \log[a(T)]$$

$$\log f_r = \log f + c(\log\eta - \log\eta_{T_r})$$

$$c = 1.255882$$

|E*| = dynamic modulus, psi
ρ34 = cumulative % retained on the ¾ in sieve
ρ38 = cumulative % retained on the 3/8 in sieve
ρ4 = cumulative % retained on the No. 4 sieve
ρ200 = % passing through the No. 200 sieve
η = viscosity of binder at the temperature of interest, 106 Poise
ηTr = viscosity at the reference temperature, 106 Poise
Vbeff = effective binder content, % by volume
Va = air void content, %
fr = reduced frequency at the reference temperature, Hz
f = frequency at a given temperature of interest, Hz
a(T) = shift factor as a function of temperature
T = temperature of interest, °F

Literature Review

The performance of η-based Witczak model for predicting |E*| of AC was evaluated by several researchers. Clyne et al. (2003), Christensen et al. (2003), Tran and Hall (2005), and Mohammad et al. (2005) reported the η-based Witczak model produces slightly less value. On the other hand, Birgisson et al. (2005) found an over prediction of |E*| value by the η-based Witczak model. Kim et al. (2005) reported that the η-based Witczak equation predicts better at low temperature. Dongré et al. (2005) implemented the η-based Witczak model for original, Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) aged binder. It was reported that the η-based Witczak model produces unreasonable estimates for modulus below 700 MPa (100,000 psi) and underpredicts measured |E*| for air void and binder content higher than the mix design. They also recommended to improve the η-based Witczak model by revising the coefficients of volumetric variables, such as the percentage of voids in mineral aggregate (VMA), the percentage of voids filled with asphalt (VFA), AC percentage, and Va. Robins (2009) studied four different mix types were incorporated in the investigation including Superpave mixes (super), stone matrix asphalt mixes (SMA), and a rich bottom layer (RBL). Research finding from different studies are summarized in Table 1. It shows that the η-based Witczak model sometimes predicts lower, sometimes larger and very few times reasonable dynamic modulus compared to the measured values. Therefore, research is needed to find out a solid answer or find an appropriate answer for Colorado's mixes. This is why, this study is motivated to evaluate the η-based Witczak model for Colorado's mixes.

Table 1. Summary of the Performances of the Predictive Models

References	Brief Description	Performance
Rahman et al. (2016)	Tested 21 SP mixtures in New Mexico	Under-predicts
Weldegiorgis (2014)	Tested 5 SP mixtures in New Mexico	Under-predicts
Robbins (2009)	Studied Alabama's SP, SMA, RBL mixtures	Scattered
Clyne et al. (2003)	Four different asphalt mixtures from the Mn/ROAD site were studied	Under-predicts
Mohammad et al. (2005)	Studied asphalt mixtures used in Louisiana	Under-predicts
Tran and Hall (2005)	Studied asphalt mixtures used in Arkansas	Under-predicts
Birgisson et al. (2005)	28 common mixtures in Florida were tested	Reasonable
Dongre et al. (2005)	Five pavement construction sites across the US were studied	Reasonable
Yousefdoost et al. (2013)	28 different Australian mixtures were tested	Under-predicts
Mateosa and Soaresb (2015)	Eight Spanish mixtures were tested	Reasonable
Biligiri and Way (2014)	A total of 2834 test sections from Arizona were used	Under-predicts
Ceylan et al. (2009)	205 unaged mixtures were used from NCHRP 9–19 project.	Under-predicts
Gedafa et al. (2010)	Nine SP mixtures were tested from Kansas	Scattered
Georgouli et al. (2016)	15 mixtures from Greece were tested	Reasonable
Hou et al. (2016)	Asphalt mixtures used in China were studied.	Scattered
Khattab et al. (2014)	25 different HMA mixtures in Saudi Arabia were studied.	More Reasonable
Li et al. (2013)	3 different mixtures of China were studied.	Under-predicts

Results and Analysis

The measured dynamic modulus data is also plotted with the Witczak's I-37A Prediction Model (viscosity-based model) which is widely used in the PMED software for level 2 or Level 3 analysis. The comparison is plotted in Figure 4. It shows that the predicted -dynamic modulus values are well correlated with the measured data.

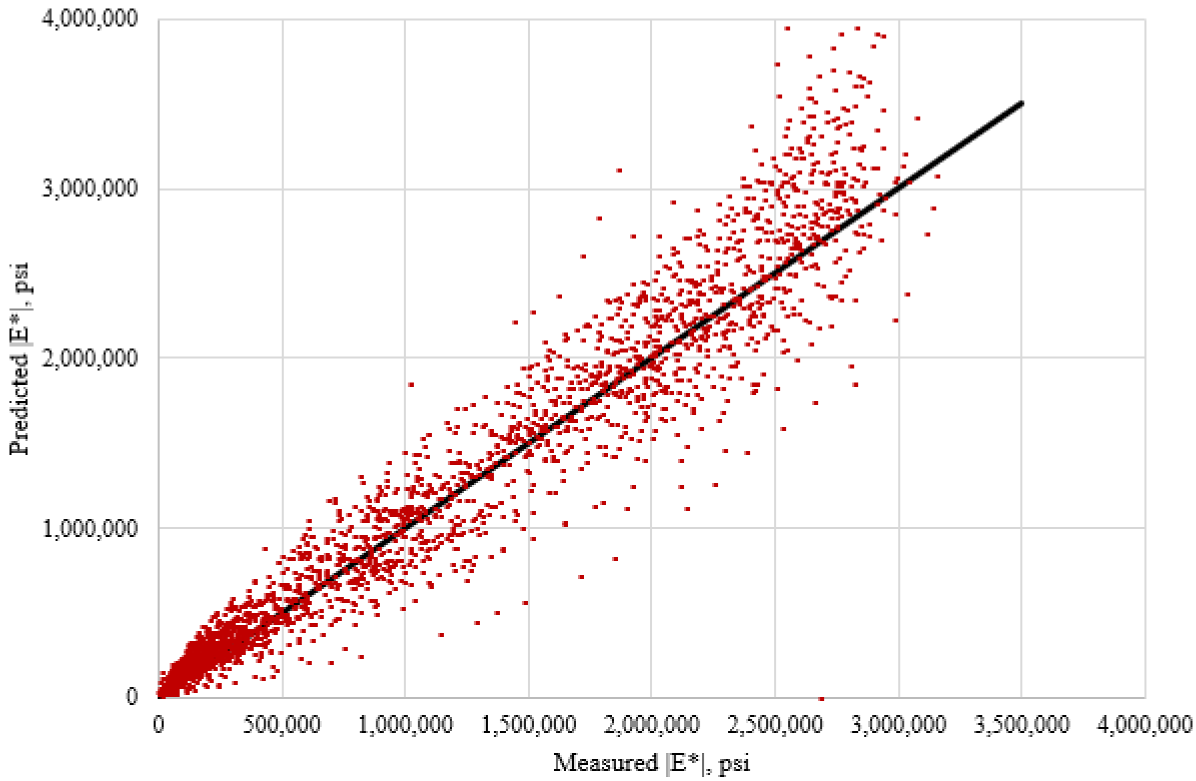

Figure 4. I-37A Model-Predicted dynamic modulus with the measured values

Conclusions

This study found that the predicted dynamic modulus using the viscosity based Witczak model is well correlated with the measured dynamic modulus of mixes used in Colorado.

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