

Dynamic Complex Modulus Prediction of Non-Conventional Asphalt Mixes

Myung Goo Jeong, Ph.D.
Georgia Southern University
Statesboro, Georgia

Younghan Jung, Ph.D., LEED AP BD+C
Old Dominion University
Norfolk, Virginia

The dynamic modulus of an asphalt pavement could serve as a more realistic pavement quality indicator in place of the individual asphalt mix properties currently used in the quality assurance of roadway construction. Because of the time and cost issue, it is thought that estimating the dynamic modulus using predictive equations is a more viable option rather than the measurement of the modulus in the laboratory. However, the database used for developing the predictive equations did not include some non-conventional mixes that are presently available such as Styrene-Butadiene-Styrene or Latex modified mix. This paper evaluates the accuracy of two dynamic modulus predictive equations incorporated in the Mechanistic-Empirical Pavement Design Guide, for the modernized asphalt mixes. Comparison between lab-measured and predicted modulus data indicate that the predictive equation developed in 1999 has a better ability to more accurately predict the dynamic modulus not only for the non-conventional mixes, but for the conventional mixes. The 2006 version predictive equation does not show effective prediction ability overall. It is also found that a more accurate prediction with the 1999 equation can be accomplished by adjusting the viscosity parameters of the originally designed binder grade.

Key Words: Dynamic Modulus, Predictive Equation, Asphalt Pavement, Asphalt Binder, Modified Binder.

Introduction

Current practice for evaluating the quality of asphalt pavement construction in most state highway agencies of the United States is mainly based on the quality of the individual mix properties such as asphalt content, air voids, density, aggregate gradation, etc. (Hughes, 2005). This practice assumes that these properties are closely related to the pavement performance during the pavement's designed service life. State highway agencies use a contractor payment system that is part of the pavement construction quality assurance process where individual mix properties are statistically evaluated (Hughes, 2005). If the properties do not conform to pavement construction specifications, then the penalty to the contractors is determined in accordance with the incentive/disincentive payment system. The underlying logic is that, if the pavement quality is poor, the pavement would deteriorate prior to the originally intended time (i.e., design life) and, accordingly, it would lead to an unexpected pavement repair cost (Jeong, 2010). The penalty would indemnify the contractors for poor pavement performance to some extent and would also be used for maintaining the pavement. While this logic sounds reasonable, questions have been raised, especially by contactors, claiming that a payment system based on the individual mix properties may not be rational and should, rather, be based on the pavement performance associated with the pavement distresses (National Cooperative Highway Research Program, 2011).

A research project sponsored by National Cooperative Highway Research Program (NCHRP) 9-19 recommended several performance-related mix parameters for the major asphalt pavement distresses (Witczak, 2005). The project identified dynamic complex modulus ($|E^*|$) as one of the parameters for evaluating the pavement performance with respect to permanent deformation, fatigue cracking, and low temperature cracking. Since the NCHRP 9-19 project, the $|E^*|$ has become prevalent in analyzing asphalt pavement performance as it is now incorporated in the Mechanistic Empirical Pavement Design Guide (MEPDG) - also known as "AASHTOWare Pavement ME Design." This computer program has the ability to predict the pavement performance using the $|E^*|$ as a major variable especially for fatigue cracking and permanent deformation. There are three hierarchical levels for the user inputs in the MEPDG (NCHRP, 2004). The level one option requires a user to input the lab-measured $|E^*|$ values. For the levels two and three, the MEPDG automatically calculates the $|E^*|$ values using an embedded $|E^*|$ predictive equation. The predictive equation is essentially a regressive model which is a function of some asphalt mix properties and environmental and traffic conditions. Although selecting the level one option for a MEPDG simulation provides the most accurate result, it requires a great deal of time and cost by the user because the |E*| values need to be measured through a comprehensive laboratory test. The |E*| laboratory test typically takes from three to five days, including the time to condition test specimens, since the test is conducted at three to five different temperatures and at four to six different loading frequencies per test temperature (Jeong, 2010). To save time and cost, selecting the lower levels for running the MEPDG is not unusual, although it is less accurate in evaluating the future pavement performance (Jeong, 2010).

Setting aside the benefits of the lower level options, concern often arises over the accuracy of the |E*| predictive equations (Bari and Witczak, 2006; Ceylan, Schwartz, Kim & Gopalakrishnan, 2009; Dongre, Myers, D'Angelo, Pauch, & Gudimettla, 2005; Yousefdoost, Vuong, Rickards, Armstrong, & Sullivan, 2013). The early version of the MEPDG had what is commonly called the 1999 version of the Witczak Predictive Equation (WPE) or the 1999 WPE. This 1999 WPE was developed using 2750 |E*| data points which combined 1980 conventional mix |E*| data with 770 modified mix |E*| data (NCHRP, 2004). Later, Bari et al. (2006) developed an enhanced version of the WPE, commonly called the 2006 WPE, using a total of 7400 |E*| data points using an extended |E*| database that contained the |E*| data from various mixes including modified binder mixes, open and gap graded mixes, and Lime modified mixes. However, the |E*| database used for the development of both predictive models did not include other non-conventional mixes that are currently gaining more popularity in the asphalt community, such as the Styrene-Butadiene-Styrene (SBS) modified mix and Latex modified mix with Reclaimed Asphalt Pavement (RAP).

Objective

The objective of this paper is to investigate the accuracy of the two WPE incorporated in the MEPDG for non-conventional asphalt mixes. Three non-conventional asphalt mixes listed below were used to evaluate the accuracy of both 1999 and 2006 versions of WPE and, as a comparison purpose, one conventional mix was also included.

- SBS Modified Asphalt Mix
- Dense-Grade Asphalt Mix w/ 15% RAP
- Latex Modified Asphalt Mix w/ 20% RAP
- Conventional Dense-Grade Asphalt Mix

Literature Review

Over the past several decades, |E*| predictive equations have evolved. As described above, the 1999 and 2006 |E*| predictive equations have been widely used in pavement research as they are incorporated in the MEPDG (Ceylan, Gopalakrishnan, & Kim, 2008; Ceylan et al., 2009). Equations shown below are the 1999 and 2006 WPEs, respectively. The equations look quite complicated at first, but they are simply a non-linear regressive model containing several variables believed to be significant in the pavement performance. The variables include some mix properties (air voids, binder viscosity, binder content, and gradation), traffic (loading frequency), and environmental factor (pavement temperature). It is noted that the 2006 WPE statistically improved the 1999 version by replacing the loading frequency and binder viscosity variables with dynamic shear modulus of asphalt binder and phase angle (Ceylan et al., 2009). Table 1 summarizes the goodness-of-fit statistics of these models where R^2 represents correlation coefficient, S_e standard error of estimate, S_y standard deviation of the measured |E*| values about the mean measured |E*|, and S_e/S_y the standard error ratio. It should be reminded that R^2 and S_e/S_y are measures of model accuracy. The higher R^2 value and the lower S_e/S_y value are, the more accurate the model.

$$\log_{10} E^* = -1.249937 + 0.02923\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a$$
$$- 0.82208\frac{V_{beff}}{V_{beff} + V_a} + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\rho_{34}}{1 + e^{(-0.603313 - 0.313351\log f - 0.393532\log\eta)}}$$

$$\log_{10} E^* = -0.349 + 0.754\left(|G_b^*|^{-0.0052}\right)\begin{pmatrix} 6.65 - 0.032\rho_{200} + 0.0027\rho_{200}^{2} + 0.011\rho_4 - 0.0001\rho_4^{2} \\ +0.006\rho_{38} - 0.00014\rho_{38}^{2} - 0.08V_a - 1.06\left(\frac{V_{beff}}{V_a + V_{beff}}\right) \end{pmatrix}$$

$$+\frac{2.558 + 0.032V_a + 0.713\left(\frac{V_{beff}}{V_a + V_{beff}}\right) + 0.0124\rho_{38} - 0.0001\rho_{38}^{2} - 0.0098\rho_{34}}{1 + e^{(-0.7814 - 0.5785\log|G_b^*| + 0.8834\log\delta_b)}}$$

Where:
E^* = dynamic modulus of mix, 10^5 psi and psi for the 1999 and 2006 WPE, respectively
ρ_{200} = percent passing #200 sieve
ρ_4 = cumulative percent retained on #4 sieve
V_a = air voids, percent by volume
V_{beff} = effective binder content, percent by volume
ρ_{38} = cumulative percent retained on 3/8 inch sieve
ρ_{34} = cumulative percent retained on 3/4 inch sieve
f = loading frequency, Hz
η = asphalt binder viscosity, 10^6 Poise
$|G_b^*|$ = dynamic shear modulus of asphalt binder, psi
δ_b = phase angle of binder associated with $|G_b^*|$, degree

Table 1

Goodness-of-fit Statistics of 1999 and 2006 Versions of Witczak Predictive Equation

	1999 WPE	**2006 WPE**
R^2, Arithmetic Scale	0.65	0.80
Se/Sy, Arithmetic Scale	0.60	0.45
R^2, Logarithmic Scale	0.88	0.90
Se/Sy, Logarithmic Scale	0.35	0.32

Christensen, Pellinen, & Bonaquist (2003) also developed a |E*| model based on 206 data points from 18 mixes. Along with the Witczak models, this model (also known as the Hirsch model) is widely used in the asphalt pavement analysis. Ceylan et al. (2008) developed a new |E*| prediction model using the Artificial Neural Networks (ANNs) technology. The ANN model dramatically improves the accuracy of predicting the |E*| values as compared to those predicted by the Hirsch model. Ceylan et al. (2009) extended their study on the |E*| predictive models by looking into the accuracy of two WPEs along with two ANN models. The comparison study concluded that the ANN model was better for the |E*| prediction and, accordingly, corresponding pavement performance predictions. However, it should be noted that all of these |E*| models did not include the modern asphalt mixes containing Latex with RAP or SBS modifier.

Yousefdoost et al. (2013) compared several |E*| predictive equations to evaluate them for Australian dense asphalt mixes. One of the findings in the study indicated that the 1999 WPE was most accurate in predicting the typical Australian mixes' |E*| although the 1999 WPE still underestimated the lab-measured |E*| by 31%. The study also showed that the Hirsch model underestimated the lab-measured |E*| values to a similar degree of the 1999 WPE, but the predicted |E*| values were more biased than those predicted by the 1999 WPE. It is interesting that the 2006 WPE, which is a statistically better model that the developer claimed (Bari and Witczak, 2006), showed significant overestimation of the lab-measured |E*| for the Australian mixes. It is to be noticed that the Australian mixes used in this study did include RAP mixes with varying content from zero up to 30%, but no Latex or SBS modified binders were used.

Dynamic Modulus Data

To evaluate the accuracy of the two WPEs, both lab-measured and predicted |E*| data sets were prepared for the aforementioned non-conventional and conventional mixes. The lab-measured |E*| database was obtained from one of the national research projects (NCHRP, 2012). The NCHRP 9-22A project obtained asphalt materials (i.e., aggregate, asphalt binder, and additives) from several actual job sites to manufacture |E*| test specimens based on design job mix. The specimen manufacturing process was in compliance of AASHTO Standard PP 60. Two replicate specimens were manufactured for each of the following mixes: 1) SBS Modified Asphalt Mix, 2) Unmodified Asphalt Mix w/ 15% RAP, 3) Latex Modified Asphalt Mix w/ 20% RAP, and 4) Conventional Dense Asphalt Mix. These specimens were then tested following AASHTO Standard TP 62; a full |E*| test at five temperatures (14, 40, 70, 100, and 130°F) and six loading frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz) at each temperature was conducted to observe the |E*| values at various combinations of temperature and frequency.

The mix variables and the traffic and environmental variables listed under the above referenced equations were retrieved from the job mix formula of each of the four mixes. These variables were plugged in both 1999 and 2006 WPEs for the |E*| prediction. Since there were 30 combinations of the time-temperature condition (5 temperatures times 6 frequencies), a total of 30 |E*| values for each mix type was obtained. The individual |E*| value predicted at a single temperature-frequency combination was compared to those measured in the laboratory.

Dynamic Modulus Comparison

The predicted |E*| data for the four mixes using the 1999 and 2006 WPEs and lab-measured |E*| data were plotted in reference to the line of equality, in order to evaluate the accuracy of each predictive equation. The left plot of Figure 1 shows the lab-measured |E*| data versus |E*| data predicted by 1999 WPE. The goodness-of-fit statistics are presented in Table 2. The plot and statistics indicate that the regular dense-grade mix with 15% RAP shows the most accurate prediction by the 1999 WPE followed by the conventional mix. The R^2 values for the 15% RAP mix and 0.97 and 0.95, respectively. The Latex modified mix with 20% RAP also shows a good prediction by the 1999 WPE although it shows some scatter in the low and middle range of the |E*| values. The R^2 is found to be 0.94 for this mix. The SBS modified mix shows the least accurate prediction result by the 1999 WPE where the |E*| values are over-predicted by the model over the entire ranges. The R^2 is found to be only 0.58 for this mix. Despite of the poor prediction for the SBS mix, the overall |E*| prediction ability of the 1999 WPE appears excellent. Note that the data is presented in a logarithmic scale to clearly visualize the scatter plot, but the goodness-of-fit statistics parameters (R^2 and S_e/S_y) were calculated based on the arithmetic scale.

The right plot of Figure 1 visualizes the measured versus predicted |E*| values by the 2006 WPE. The goodness-of-fit parameters for all mixes indicate the very poor prediction ability of the model for the four mixes overall as well as the individual mixes. In particular, the high |E*| values of the Latex modified mix with 20% RAP are very poorly predicted by this model. The high range of the |E*| values are typically obtained in the laboratory testing at the lower temperature (i.e., 14°F). The prediction for the conventional mix is also very poor over the entire range of the plot. Overall, significant over-prediction is observed.

Discussion

The comparison results shown in Figure 1 clearly indicate that the 1999 WPE has a relatively better ability to predict the |E*| over the 2006 WPE for both conventional and non-conventional mixes. It is interesting to come to this conclusion because the 2006 WPE was developed to enhance the 1999 WPE. As mentioned earlier, the 2006 WPE expanded the 1999 WPE |E*| database by adding more conventional and modified mixes. However, the 2006 model does not seem to work well for the mixes used for this study. Interestingly, a similar result was also observed in the literature (Yousefdoost, et al., 2013) where the 1999 WPE showed a superior |E*| prediction ability for the typical Australian mixes.

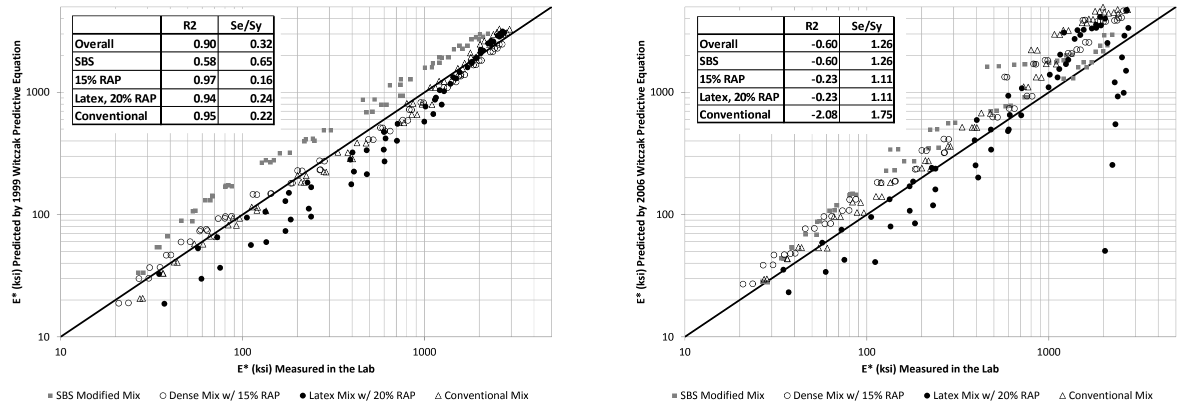

Figure 1: Comparison of Dynamic Modulus between Predicted and Lab-Measured by 1999 WPE (left) and 2006 WPE (right)

Table 2

Goodness-of-fit Statistics of the 1999 and 2006 Witczak Predictive Equations

	1999 WPE		**2006 WPE**	
	R^2	**S_e/S_y**	**R^2**	**S_e/S_y**
Overall	0.90	0.32	-0.60	1.26
SBS Mix	0.58	0.65	-0.60	1.26
15% RAP Mix	0.97	0.16	-0.23	1.11
Latex, 20% RAP Mix	0.94	0.24	-0.23	1.11
Conventional Mix	0.95	0.22	-2.08	1.75

Although the 1999 WPE has a better ability to predict the |E*|, the predicted |E*| for the SBS mix and the Latex with 20% RAP mix is less accurate than the conventional mix or the 15% RAP mix. This may be because the characteristic of the asphalt binder originally used in the mix design has been changed by the SBS and Latex modifiers. The 1999 WPE uses the distinct binder parameters, known as A and VTS, to calculate the asphalt viscosity value at a certain temperature and frequency condition. For each binder grade designated by the performance grade or PG, the recommended A and VTS values was typically provided and used for the binder characterization (NCHRP, 2004). If a binder was modified by additives such as SBS or Latex and accordingly the characteristic of the binder might have been changed, then the A and VTS values for the original binder may not be suitable for the use of the predictive equations. Thus, by plugging the realistic viscosity parameters in the predictive equations instead of using the original binder viscosity parameters, the prediction ability of the 1999 WPE would be enhanced. The left of Figure 2 proves this theory where most of the scattered data disappears and the goodness-of-fit statistics is significantly improved after adjusting the viscosity parameters; the overall R^2 value after this transformation is 0.96 from 0.90 in the previous comparison plot. Table 3 summarizes the binder grade (PG) with its corresponding A and VTS values for the original binder used in the mix design and for the adjusted binder used in the predictive equation. A similar approach was also used for the 2006 WPE for possible improvement of the |E*| prediction. However, it was not as effective as the 1999 WPE as shown in the right plot of Figure 2. Little improvement was observed in the data points in terms of the goodness-of-fit statistics although some scattered data points are shifted to the line of equality. Table 4 summarizes the recalculated statistics of the WPEs for the mixes.

The effect of RAP on the prediction doesn't seem significant as the mix with 15% RAP shows a good prediction without adjusting the binder grade (Left of Figure 1) and the Latex mix with 20% RAP also shows a good prediction after adjusting the binder grade (Left of Figure 2). That is, the RAP effect seems independent of the prediction ability of the WPEs. This conclusion is valid because the database used in developing the predictive equations included mixes with RAP.

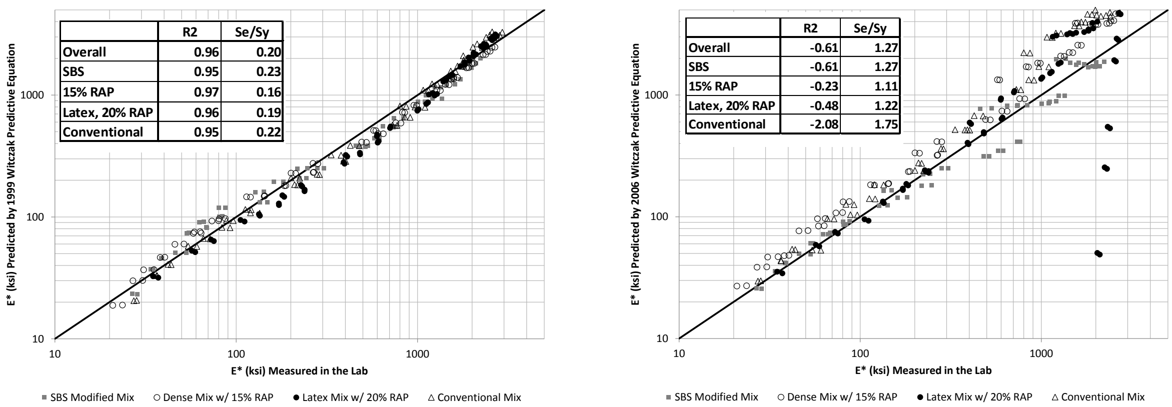

Figure 2: Comparison of Dynamic Modulus Predicted by 1999 WPE (left) and 2006 WPE (right) with Suggested Binder Properties

Table 3

Asphalt Binder Grade and Viscosity Parameters (A and VTS) for the SBS and Latex Mixes

	Original Binder Grade (PG)	**Suggested Binder Grade (PG) for Modified Mixes**
SBS Mix	PG 76-28 (A: 9.200, VTS: -3.024)	PG 70-40 (A: 8.129, VTS: -2.648)
Latex, 20% RAP Mix	PG 64-22 (A: 10.980, VTS: -3.680)	PG 76-22 (A: 9.715, VTS: -3.208)

Table 4

Goodness-of-fit Statistics of the 1999 and 2006 Witczak Predictive Equations with Adjusted Binder Grade (Only for SBS and Latex Mixes)

	1999 WPE		**2006 WPE**	
	R^2	**S_e/S_y**	**R^2**	**S_e/S_y**
Overall	0.96	0.20	-0.61	1.27
SBS Mix	*0.95*	*0.23*	*-0.61*	*1.27*
15% RAP Mix	0.97	0.16	-0.23	1.11
Latex, 20% RAP Mix	*0.96*	*0.19*	*-0.48*	*1.11*
Conventional Mix	0.95	0.22	-2.08	1.75

Concluding Remarks

This paper evaluates the two dynamic complex modulus (|E*|) predictive equations currently used in the Mechanistic-Empirical Pavement Design Guide with respect to the accuracy of the equations for non-conventional asphalt mixes. The following summarizes findings from this study:

- The 1999 version of the WPE has a better ability to predict the |E*| values for all asphalt mixes used in this study including the SBS and Latex modified asphalt mixes and conventional mixes with and without RAP.
- The overall accuracy of the 2006 version of the WPE is very poor regardless of mix type.
- To accurately predict the dynamic modulus for modified asphalt mixes, it is recommended that the original binder grade (PG) and its viscosity parameters (A and VTS) be adjusted. However, this approach is only effective for the 1999 WPE. The approach barely improves the accuracy of the |E*| predicted by the 2006 WPE.
- There is no significant effect of RAP on the accuracy of both versions of the WPE.

For future research, it is recommended that more lab-measured |E*| test data be collected and compared with predicted |E*| based on the predictive equations. Accurate |E*| prediction will lead to significant reduction on laboratory test efforts and furthermore makes it possible to enhance current quality assurance practice.

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