Evaluation of Test Data Variability and Suitability of Predictive Equation Related to the Determination of Dynamic Modulus (E*) for Hot-Mix Asphalt

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ABSTRACT: The dynamic modulus ($|E^*|$) of hot-mix asphalt (HMA) is one of the fundamental inputs in the mechanistic-empirical (M-E) Design Guide developed in NCHRP Project 1-37A. The M-E Design Guide provides three levels for $|E^*|$ inputs, which depend on the importance of the pavement in service. Level 1 $|E^*|$ inputs require laboratory measured $|E^*|$ values while level 2 and 3 $|E^*|$ inputs are estimated using a predictive equation. To provide the laboratory measured $|E^*|$ inputs for implementation of the M-E Design Guide, a significant $|E^*|$ testing program was completed in Arkansas. The testing program included three replicate specimens from each of four aggregate types, three nominal maximum aggregate sizes, two PG binder grades, and two air-void levels. The $|E^*|$ tests were conducted using five test temperatures and six loading frequencies. The $|E^*|$ values obtained in this testing program exhibited much lower variability than those in other studies and complied with the required variability level specified in AASHTO TP 62-03. Therefore, the laboratory measured $|E^*|$ values can be used with confidence for level 1 material characterization inputs for HMA in the M-E Design Guide. Level 2 and 3 $|E^*|$ inputs, estimated using the predictive model provided sufficiently accurate predictions of pavement performance compared to performance predictions generated by the Level 1 inputs . In addition, the differences between level 2 and 3 predicted distresses were not significant. Thus, level 3 $|E^*|$ inputs could be used with confidence for initial implementation of the M-E Design Guide.

KEY WORDS: Dynamic modulus, test variability, predictive equation, mechanistic-empirical design, hot-mix asphalt.

1 INTRODUCTION

Recent published studies clearly emphasize the importance of dynamic modulus ($|E^*|$) testing of hot-mix asphalt concrete (HMA). The dynamic modulus is one of the fundamental inputs in the mechanistic-empirical (M-E) Design Guide developed through National Cooperative Highway Research Program (NCHRP) Project 1-37A. In addition, it is also a promising candidate for the Simple Performance Test recommended by NCHRP Project 9-19.

The M-E Design Guide incorporates a hierarchical method that includes three levels for specifying pavement design inputs. Level 1 provides the highest level of accuracy and would typically be used for designing heavily trafficked pavements. Level 2 provides an intermediate level of accuracy and could be used when level 1 inputs are not available. Level 3 provides the lowest level of accuracy and are intended for designing low volume roads. Level 1 material characterization inputs for HMA require the dynamic modulus tested in the laboratory, while level 2 and 3 HMA inputs are estimated using the Witczak predictive model (Andrei et al., 1999). However, level 2 dynamic modulus predictions require laboratory measured binder viscosity whereas level 3 $|E^*|$ predictions use the default binder properties established for all binder grades in the M-E Design Guide.

Recognizing the importance of obtaining the HMA dynamic modulus values for future implementation of the M-E Design Guide, the Arkansas State Highway and Transportation Department (AHTD) sponsored a project to determine the dynamic modulus values of all typical HMA mixtures used in Arkansas. The objectives of the project were: (1) developing the dynamic modulus database and determining the data variability for level 1 $|E^*|$ inputs; (2) evaluating the $|E^*|$ predictions for level 2 and 3 inputs using the Witczak predictive model; and (3) identifying the appropriate $|E^*|$ input level for the future applications in the Guide.

This paper presents the results of the abovementioned study by the University of Arkansas focusing on the evaluation of the $|E^*|$ test result variability and the suitability of the Witczak predictive equation related to the determination of the dynamic modulus for HMA in the Design Guide.

2 LABORATORY DYNAMIC MODULUS TESTING

Four aggregate sources were used in this study, including limestone from McClinton Anchor, Inc. (MCA), sandstone from Arkhola, Inc. (ARK) , syenite from Granite Mountain, Inc. (GMQ), and gravel from Jet Asphalt Company (JET). These sources reasonably bracket an expected range of mixes encountered in Arkansas. For each aggregate source, HMA mixtures were developed for nominal maximum aggregate sizes corresponding to surface mixes (12.5 mm), binder mixes (25.0 mm), and base mixes (37.5 mm). The mixes were designed using each of two binder grades, including PG 70-22 and PG 76-22.

2.1 Preparation of Test Specimens

The tests were performed at two air void levels, design (4 or 4.5 percent, depending on binder grade) and 7 percent to evaluate the effects of air voids on the dynamic modulus. It is noted that mixtures designed in Arkansas target different design void levels (e.g. 4.5 or 4.0 percent) for binder grades PG 70-22 and PG 76-22, respectively (AHTD, 2003). Each mixture sample was mixed and compacted at the temperature specified in the mix design and conditioned in the oven for four hours, which is specified for short-term mixture conditioning for mechanical property testing in AASHTO R30-02.

Three specimens of 150 mm diameter and 170 mm height were prepared for each testing combination. Dynamic modulus test specimens, 100 mm in diameter and 150 mm in height, were cored from the center of the gyratory compacted specimens and trimmed by sawing each end of the specimens. Finally, the air voids and geometric properties of each specimen were determined for the acceptance of the test specimen. The experimental plan required total 126 specimens to be tested.

2.2 Dynamic Modulus Test Procedure

Tests were conducted generally in accordance with AASHTO TP62-03. Test specimens were placed in an environmental chamber and allowed to equilibrate to the specified testing temperature $\pm 0.5^{o}$C. The specimen temperature was monitored using a dummy specimen with a thermocouple mounted at the center. Four linear variable differential transformers (LVDT) were mounted on the specimen using two aluminum rings, and they were adjusted to near the end of their linear range to allow the full range to be available for the accumulation of compressive permanent deformation. The LVDT setup was the only departure from the AASHTO testing specification. Friction reducing end treatments, consisting of two 0.5 mm thick latex membranes separated with silicone grease, were placed between the specimen ends and loading platens of the testing machine.

The test was run on each test specimen at five different temperatures, including -10, 4, 21, 38, and 54^{o}C, with the test starting at the lowest temperature and proceeding to the highest temperature. For each temperature level, the test was run at six different frequencies from the highest to the lowest, including 25, 10, 5, 1, 0.5, 0.1 Hz. All testing was conducted in an unconfined condition.

At a specified test temperature, a continuous uniaxial sinusoidal (haversine) compressive stress at a specified test frequency was applied to an unconfined cylindrical test specimen. The stress-to-strain relationship for a linear viscoelastic HMA specimen, as shown in Figure 1, is defined by a complex number called the complex modulus (E^*). The absolute value of the complex modulus, $|E^*|$, is defined as the dynamic modulus, and the dynamic modulus is a ratio between the maximum (peak) dynamic stress (σ_o) and the peak recoverable axial strain (ε_o), as presented in Equation (1). For each combination of testing temperature and frequency, one dynamic modulus value and one phase angle value were determined for each specimen.

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \tag{1}$$

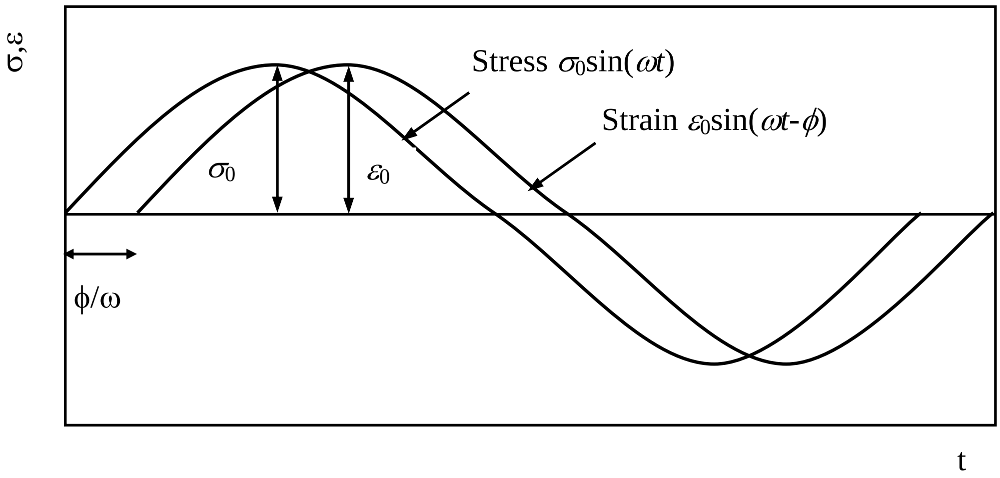

Figure 1: Stress-to-Strain Relationship for Dynamic Modulus Test.

3 VARIABILITY OF LABORATORY DYNAMIC MODULUS TEST RESULTS

The variability of the dynamic modulus test was evaluated using the variances related to the measurements within and between specimens. The “within” specimen variance measures the variability between the individual LVDT measurements in a specimen.

$$S_w^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \overline{X}_s\right)^2 \qquad (2)$$

where:

S_w^2 = "within" specimen variance
x_i = parameter from individual LVDT measurements
$\overline{X}_s$ = specimen average parameter
n = number of LVDTs per specimen

A pooled "within" variance for the replicates is the average of the associated "within" specimen variances. The "between" specimen variance measures the variability between the average parameters of the replicates.

$$S_b^2 = \frac{1}{m-1}\sum_{j=1}^{m}\left(\overline{X}_{sj} - \overline{X}\right)^2 \qquad (3)$$

where:

S_b^2 = "between" specimen variance
$\overline{X}_{sj}$ = specimen average parameter
$\overline{X}$ = grand average
m = number of specimens

Since the dynamic modulus of HMA mixtures changes dramatically across the test variables, such as temperature and frequency, the $|E^*|$ test variability should also be evaluated using the coefficient of variation (CV). The coefficient of variation has a normalizing effect allowing the test data to be compared across temperatures. The coefficient of variation, as a measure of test variability, is determined as follows:

$$CV = \frac{s}{\overline{X}} \times 100 \qquad (4)$$

where:

CV = "within" or "between" coefficient of variation
s = "within" or "between" standard deviation
$\overline{X}$ = grand average

The analyses of the "within" and "between" CVs were conducted using the SAS™ PROC GLM utility. The fixed effects for these two ANOVA tests were aggregate source (MCA, GMQ, ARK, and JET), aggregate size (12.5, 25, and 37.5 mm), binder grade (PG 70-22 and PG 76-22), air voids (design and 7 percent), temperature (-10, 4, 21, 38, and 54^{o}C), and frequency (0.1, 0.5, 1, 5, 10, 25 Hz).

With 95-percent confidence (e.g. $\alpha = 0.05$), all of the single fixed effects except the binder grade were significant. However, the interactions between the binder grade and temperature were significant. The observations based on the ANOVA tests were as follows:

- The larger the nominal maximum aggregate size, the higher the "between" and "within" coefficient of variation (the test variability).
- The higher the air voids of the test specimens, the higher the "within" coefficient of variation.

- The test variability was higher at higher temperatures or higher frequencies. The dynamic modulus of an asphalt mixture is primarily dependent on the aggregate structure at higher test temperatures. At lower test temperatures, the dynamic modulus is primarily dependent on the binder stiffness. In term of variability, the aggregate structure was more variable than the asphalt binder stiffness. Therefore, the test variability should be higher at higher test temperatures. The differences between the lowest and highest coefficients of variation for both temperature and frequency sweeps were about 1.5 percent for “within” values and about 0.6 percent for “between” values.

The overall test variability for this study is presented in Table 1. The variability of test results obtained in this study compared favorably to other studies – Witczak et al., 2000, Pellinen, 2001, and Bonaquist et al., 2003. However, it was noted that other studies used a different testing program that featured two replicate specimens instrumented with two LVDTs per specimen, compared to three replicates instrumented with four LVDTs used in this study.

Table 1: Analysis of Dynamic Modulus Test Variability

Study by	Coefficient of Variation for $|E^*|$ (%)		Coefficient of Variation for ϕ (%)	
	Within	Between	Within	Between
Witczak et al. (2000)	26.2	15.2	11.0	8.7
Pellinen (2001)	39.0	13.0	17.0	10.0
Bonaquist et al. (2003)		13.0		
University of Arkansas	18.7	7.5	8.5	7.4

The confidence interval of the dynamic modulus test results was then calculated based on the CVs. The average 95-percent confidence interval for the dynamic modulus test results obtained in this study was ±13.56 percent, which was less than the required value of ±15 percent, as specified in AASHTO TP 62-03.

In summary, the variability of the dynamic modulus values obtained in this study was much lower than those in other studies. This may be related to the fact that this study used more replicates and LVDTs on each specimen. In addition, the 95-percent confidence interval of the test results was less than the required value specified in AASHTO TP 62-03. It was recommended that the dynamic modulus values reported in this study be used for Level 1 material characterization inputs for HMA in the M-E Design Guide.

4 PREDICTION OF DYNAMIC MODULUS

Since the dynamic modulus test is relatively complex and expensive to perform, many state agencies and other roadway designers expect to use a predictive equation to estimate the dynamic modulus of their typical HMA mixtures. One of the most comprehensive predictive models available was developed by Witczak and colleagues over several years of research (Andrei et al., 1999). The Witczak predictive model was incorporated in the M-E Design Guide to estimate the dynamic modulus for Level 2 and Level 3. The Witczak model was developed using a variety of HMA modulus values, some of which were not generated using a compression-type test (such as used in this study); this certainly could influence direct comparisons of test values versus predicted values. However, it must be emphasized that the context of this study is to assess the suitability of the prediction model used in the new M-E

Design Guide versus measured $|E^*|$ values; a discussion of the suitability of the Witczak model for use in the M-E Design Guide is beyond the scope of this paper.

4.1 Witczak Predictive Model

The Witczak model is an empirical regression model developed based on 2750 laboratory measurements of the dynamic modulus tested over the last 30 years. The Witczak model for predicting the dynamic modulus of HMA, which was incorporated in the M-E Design Guide, is presented in Equation (5) (Andrei et al., 1999).

$$\begin{aligned}\log E = & -1.249937 + 0.02932\rho_{200} - 0.001767\rho_{200}^2 \\ & - 0.002841\rho_4 - 0.058097V_a - 0.802208\left(\frac{V_{b0eff}}{V_{beff} + V_a}\right) \\ & + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017\rho_{38}^2 + 0.005470\rho_{34}}{1 + e^{(-0.603313 - 0.313351\log(f) - 0.393532\log(\eta))}}\end{aligned} \tag{5}$$

where:

E	= dynamic modulus, 10^5 psi
η	= bitumen viscosity, 10^6 Poise
f	= loading frequency, Hz
V_a	= air void content, %
V_{beff}	= effective bitumen content, % by volume
ρ_{34}	= cumulative % retained on the 19-mm sieve
ρ_{38}	= cumulative % retained on the 9.5-mm sieve
ρ_4	= cumulative % retained on the 4.76-mm sieve
ρ_{200}	= % passing the 0.075-mm sieve

Equation (5) was calibrated in log space, and its goodness-of-fit statistics are as follows (Andrei et al., 1999):

- R^2 = 0.941 in log space (0.886 in arithmetic space)
- S_e/S_y = 0.244 in log space (0.338 in arithmetic space)

The binder viscosity required in Equation (5) at a given temperature was estimated using Equation (6). In this study, the *A* and *VTS* parameters in Equation (6) were estimated using the binder properties determined using a dynamic shear rheometer (DSR) on the rolling thin film oven (RTFO) aged binders for level 2 $|E^*|$ inputs. For level 3 $|E^*|$ inputs, the *A* and *VTS* parameters represent the default RTFO aged values based on the binder grades recommended in the M-E Design Guide.

$$\log\log\eta = A + VTS\log T_R \tag{6}$$

where:

η	= viscosity, cP
T_R	= temperature, Rankine
A	= regression intercept
VTS	= regression slope of Viscosity-Temperature Susceptibility

4.2 Evaluation of the Witczak Predictive Model

To recommend the Witczak predictive model for the future applications, precision and bias of the model was evaluated in this study. The accuracy of the predicted dynamic modulus values compared to the laboratory measured |*E**| values was assessed using goodness-of-fit statistics. The statistical parameters include a lack-of-fit statistic, S_e/S_y (the standard error of estimate/standard deviation), and correlation coefficient, R^2.

All laboratory measured dynamic modulus values in this study were used to compare to the corresponding level 2 and 3 predicted values. The goodness-of-fit statistics for level 2 and 3 |*E**| inputs, as shown in Table 3, were determined in arithmetic space. The rankings in Table 3 were based upon the evaluation criteria established in NCHRP project 9-19 Task C (Witczak et al., 2002). Overall, the predicted dynamic modulus values agreed quite well with the laboratory measured dynamic modulus values. The evaluation statistics for level 2 |*E**| inputs were even better than the calibrated statistics (R^2 = 0.886 and S_e/S_y = 0.338 in arithmetic space), and those for level 3 |*E**| inputs compared favorably to the calibrated statistics.

Table 3: Goodness-of-Fit Statistics for Level 2 and 3 Predicted |*E**| Inputs

Statistic	Level 2 RTFO-Aged Viscosity (DSR)	Level 3 RTFO-Aged Viscosity (Default)
S_e/S_y	0.318	0.334
R^2	0.900	0.889
Ranking	Excellent	Excellent

The laboratory measured and predicted dynamic modulus values were also compared by matching those values in a normal scale graph, as shown in Figure 2. It was observed that Level 2 predicted dynamic modulus values were more accurate than those of level 3, and the dynamic modulus for HMA mixtures was slightly over predicted using level 3 inputs.

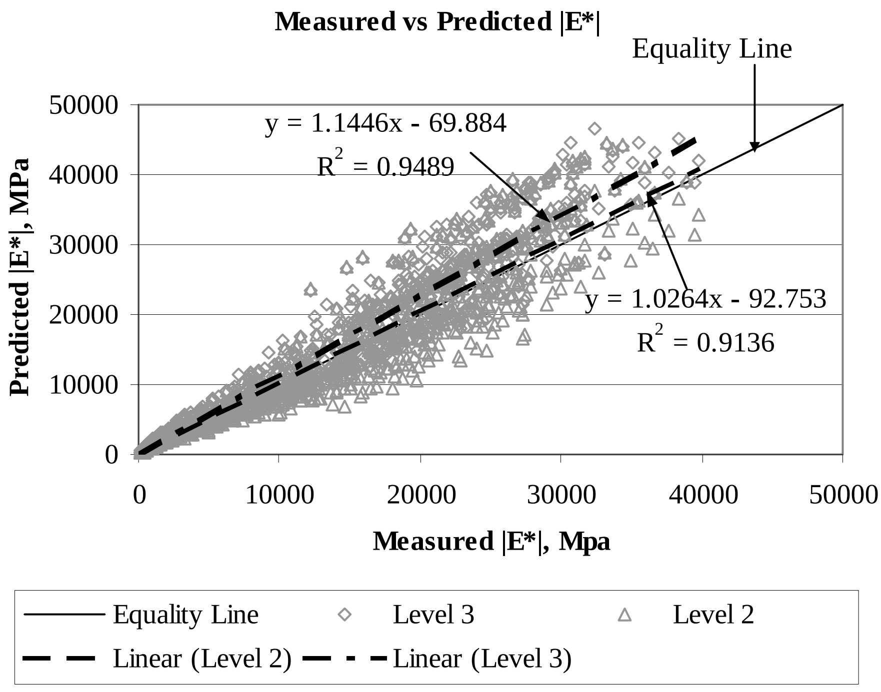

Figure 2: Measured (Level 1) vs Predicted (Level 2 and 3) |*E**| Inputs.

Even though Level 2 inputs seemed to predict the dynamic modulus values better than Level 3, further investigation showed that both input levels overpredicted the dynamic modulus of the mixtures at high test temperatures (compared to test results), as illustrated in Figure 3. It is noted that the relatively high strain values generated at high test temperatures produced extremely low modulus values which are outside the range of data used to develop the Witczak model – thus, high normalized errors at these modulus values are not surprising. However, these systematic errors (bias) may influence predicted pavement performance.

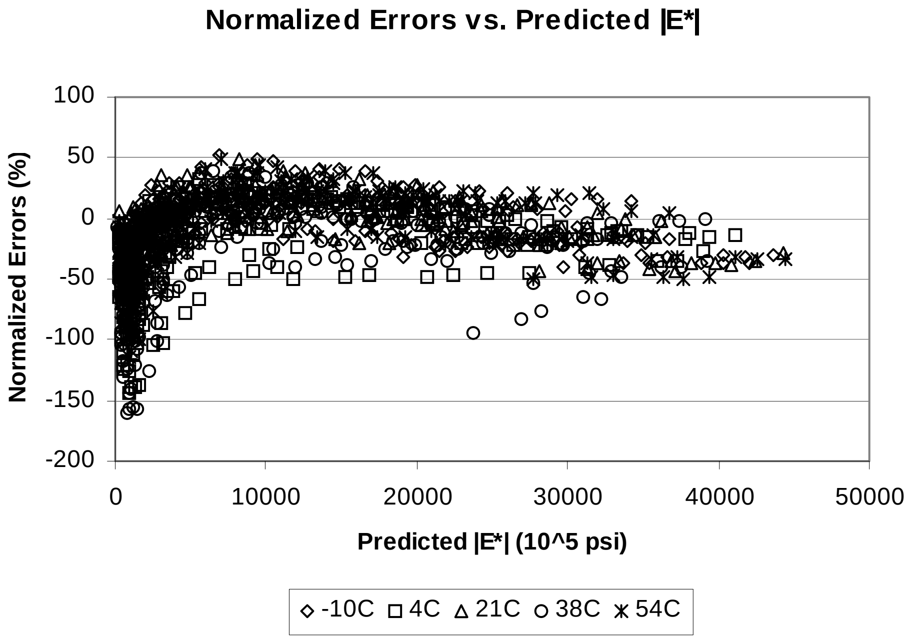

Figure 3: Normalized Errors vs Predicted |E*| for Level 2 Input.

At this point, it was questioned whether the estimated accuracy and bias was acceptable for future design applications; this question could be only answered by analyzing the effect of varying E* on pavement performance predictions provided by the M-E Design Guide.

4.3 Effect of Dynamic Modulus on Predicted Pavement Performance

The M-E Design Guide 2002 design software (version 0.700) was used to investigate the effects of level 2 and 3 |*E**| predictions on predicted pavement performance. The software was employed to design a new pavement consisting of 6 inches of asphalt concrete (AC) over 18 inches of crushed stone built on AASHTO A-7-5 subgrade. The pavement was subjected to an average annual daily truck traffic (AADTT) of 2500 vehicles-per-day for a 20-year service life. Level 1, 2 and 3 |*E**| inputs were varied to assess the impact of dynamic modulus on pavement performance. The context of the effort is emphasized: this project is based on providing inputs to the M-E Design Guide. The rutting and fatigue prediction models used in the M-E Design Guide may not be the best conceptual models for these phenomenon; however, this project was designed to provide answers for those wishing to use the Guide for flexible pavement analysis and design.

Figures 4 and 5 compare predicted alligator cracking and AC layer rutting using level 2 and 3 |*E**| inputs against values predicted using level 1 |*E**| inputs. It was observed that the predicted distresses using level 2 and 3 |*E**| inputs were not distinguishable in this study. All of the data points plotted in Figures 4 and 5 were relatively close to a line of equality; the maximum error for predicted alligator cracking using the measured and predicted |*E**| inputs was 25 percent, and that for predicted AC layer rutting was 26 percent. These errors in predicting distresses were considered reasonable.

Since the differences between level 2 and 3 predicted distresses were not significant; it is recommended that level 3 |*E**| inputs be used instead of level 2 for simplicity (binder testing would not be required). Currently, it is not clear which design level provides better performance predictions of in-service pavements, because the distress prediction models incorporated in the M-E software were calibrated using the default (Level 3) values. Therefore, it is recommended that level 3 |*E**| inputs be used in the early stages of implementation of the M-E Design Guide.

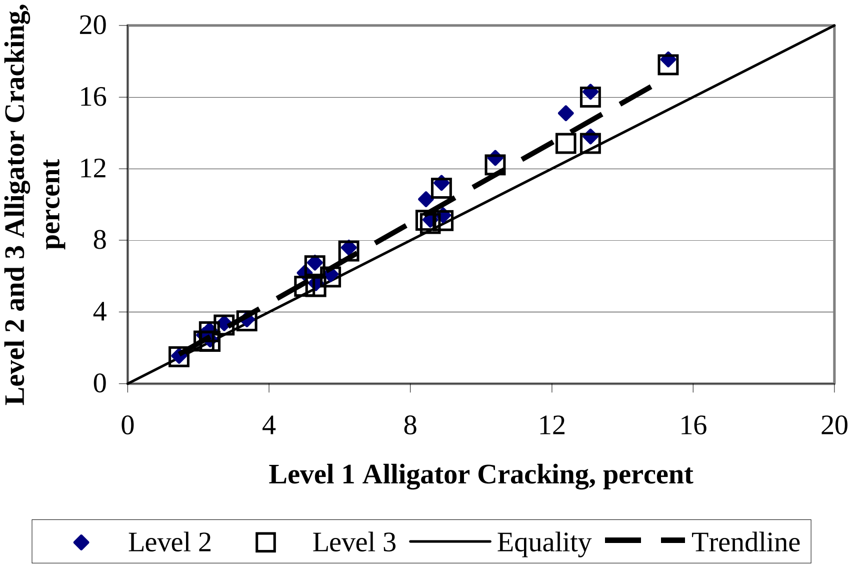

Figure 4: Predicted Alligator Cracking using Predicted and Measured |*E**|

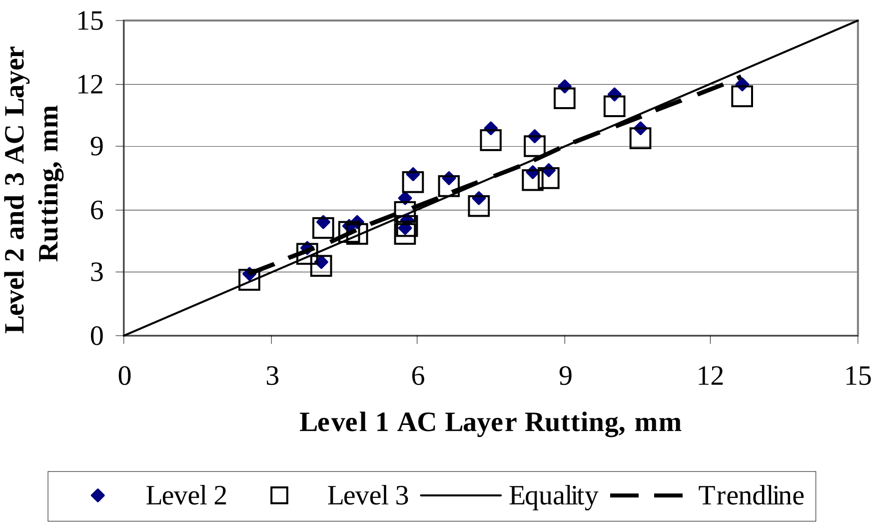

Figure 5: Predicted AC Layer Rutting using Predicted and Measured |*E**|

5 CONCLUSIONS AND RECOMMENDATIONS

This study provides laboratory measured dynamic modulus values for future implementation of the M-E Design Guide. The variability of |*E**| test results compared favorably to those reported by other studies and complied with AASHTO TP 62-03 requirements. Despite the |*E**| test complexity, state agencies and others should be able to determine the dynamic modulus of HMA in the laboratory following test protocols specified in AASHTO TP 62-03.

Overall, Level 3 dynamic modulus inputs using the Witczak predictive model yielded sufficiently accurate predictions of pavement performance compared to level 1 inputs even though prediction bias was still found at high testing temperatures. These findings agreed with those reported by others (Pellinen, 2001, Dongre et al., 2005, and Schwartz, 2005). In addition, the use of Level 1 dynamic modulus inputs may not be justified at present; the distress prediction models contained in the design software were calibrated using national default (Level 3) values. Therefore, Level 3 |*E**| inputs could be used in the early stages of implementation of the M-E Design Guide. However, it was recommended that the effect of dynamic modulus predictions on pavement performance predictions be re-evaluated when the performance data of in-service pavements become available. Furthermore, if dynamic modulus values representing high testing temperatures are required, the laboratory measured |*E**| values should be used.

It was also recommended that the design software add a new feature that allows the users to input state/regional calibration factors for the Witczak predictive model incorporated in Level 3 predicted dynamic modulus inputs. This feature would be useful for many states in which the Witczak predictive model requires some modifications to reasonably predict the dynamic modulus of local HMA mixtures.

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