DEVELOPMENT OF A MASTER CURVE (E*) DATABASE FOR LIME MODIFIED ASPHALTIC MIXTURES

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EXECUTIVE SUMMARY

This study demonstrates that the standard test and design methodologies in the new NCHRP mechanistic-empirical (M-E) pavement design guide entitled “2002 Design Guide: Design of New and Rehabilitated Pavement Structures” can be used effectively for lime-modified asphalts. Using the new M-E pavement design guide methodologies, lime was found to increase the dynamic modulus (E*) stiffness by an overall average of 25%. The specific E* appeared to be random relative to the mixture type, test temperature and frequency. Across the range of mixtures, lime percentage and temperature; the average E* increase ranged from 0% to 100% improvement. The average E* across all lime contents tested varied from 17% to 65% increase.

Hydrated lime is often used as a mineral filler or antistripping additive in Hot Mix Asphalt (HMA). In fact, many agencies across North America require the use of hydrated lime in all HMA mixtures being placed on high-volume roadways. Many studies have shown that HMA mixtures with lime have longer service lives and lower amounts of rutting and cracking in comparison to unmodified HMA mixtures.

Lime’s benefits have been demonstrated by standard laboratory tests, such as the indirect tensile test and repeated load permanent deformation test in uniaxial compression. The Asphalt Pavement Analyzer (APA) and Hamburg Loaded Wheel Tester have also been used by various agencies to show the enhanced performance characteristics of lime-modified mixtures in resisting rutting in the laboratory.

The M-E Pavement Design Guide (developed under National Cooperative Highway Research Program (NCHRP) Project 1-37A), however, uses the Dynamic Modulus (E*) as the primary material property of HMA mixtures. In the Level 1 analysis of the design guide, E* is calculated from a master curve that is constructed from laboratory E* and binder testing data. In Levels 2 and 3 analyses of the design guide, E* is calculated by a regression equation that uses mixture volumetric and asphalt properties to predict E* at the design temperature and loading frequency. Thousands of test data

from hundreds of HMA mixtures were historically used to develop the current E* predictive equation. However, very few of those mixtures contained hydrated lime. Thus, to determine the effect of lime on E* and to confirm the accuracy of the dynamic modulus regression equation for lime-modified HMA mixtures, this extensive laboratory test program was conducted to develop a database which agencies may use in structural design based upon the M-E principles of the NCHRP 1-37A Project.

A wide range of aggregate types and gradations were used to prepare seventeen different mixtures. These aggregates and gradations were sampled from six different project sites across the United States. Six mixtures contained no lime and eleven had hydrated lime contents up to 3% (by aggregate weight). NCHRP Provisional Test Method DM-1 entitled "Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures" was used to measure E* of these mixtures over a range of temperatures and loading frequencies. Four different asphalt cement (AC) binders used in these seventeen mixtures were also tested and characterized. These binders had lime content ranging from 0% to about 23% (by binder weight). Conventional and Superpave binder tests were conducted to characterize the binders.

In conclusion, lime was found to increase E* (dynamic modulus) by an average of 25%. The magnitude of the average E* increases varied across mixtures and lime contents. This research also demonstrated that these testing procedures and the E* predictive equation can be used for lime-modified HMA. This report outlines a protocol for evaluating lime modified HMA mixtures using any of the three levels of analysis in the M-E Pavement Design Guide.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER-1 : INTRODUCTION

Introduction

Hydrated lime is widely recognized as an excellent antistripping agent for use in hot mix asphalt (HMA). Other widely-accepted reasons to add hydrated lime to HMA include reducing optimum asphalt content, specification compliance for aggregate gradation, and increasing mixture stability (*1*). The pavement industry has been using lime in hot mix asphalt (HMA) to reduce moisture sensitivity and stripping since 1910 in the United States (*2*). For many years, the Federal Highway Administration (FHWA) has been promoting the use of lime as an antistripping agent, as well. Although lime has long been an acknowledged anti-stripping additive for HMA pavements, it possesses other benefits (*3*, *4*, *5*, *6*, *and 7*):

1. Lime stiffens the mix and binder to resist rutting.
2. It improves toughness and resistance to fracture growth at low temperatures.
3. It changes oxidation chemistry in the binder to reduce age hardening.
4. It alters clay fines to improve moisture stability and durability.
5. Lime is also useful to upgrade marginal aggregates.

The related mechanisms and reactions involved in the change of performance of lime-modified HMA mixtures are not fully understood. Nevertheless, when hydrated lime is added to HMA, it strengthens the bond between the bitumen and the stone. Some of the added lime reacts with the highly polar molecules of the asphalt binder, which could otherwise react in the mix to form water-soluble soaps that promote stripping (*2*). When those molecules react with hydrated lime, they form insoluble salts that no longer attract water. In addition, the dispersion of the tiny hydrated lime particles throughout the mix makes it stiffer and tougher, reducing the likelihood that the bond between the asphalt cement and the aggregate will be broken mechanically, even if water is not present. It is also reported that a portion of the lime can reduce the viscosity-building polar components in the asphalt binder, which in turn improves the long-term oxidative aging characteristics of HMA (*3*, *5*). The structure of hydrated lime consists of differently sized proportions. The smaller fraction of lime increases binder film thickness, enhances binder viscosity and improves binder cohesion leading to increased adhesion between the aggregates and binder, which reduces mixture segregation (*3*). The larger fraction performs as a filler to increase the indirect tensile strength and resilient modulus, and improvement (i.e. decrease) in both the indirect tensile creep slope and fatigue slope (with higher number of cycles to failure of HMA (*3*, *6*). It is also reported that addition of lime to HMA improves its stiffening properties, which in turn can improve the HMA's resistance to rutting (*7*, *8*, *and 9*).

Stiffness (dynamic modulus) is a key material property that determines strains and displacements in pavement structures. The *2002 Design Guide: Design of New and Rehabilitated Pavement Structures,* developed under NCHRP Project 1-37A, uses the HMA dynamic modulus (E*) as the design stiffness parameter and the E* test for all three levels of hierarchical input for the HMA characterization (*10*). The 2002 Design Guide is referred to herein as the new Mechanistic-Empirical Pavement Design Guide (M-E PDG).

The E* test is also a leading candidate for the SPT (Simple Performance Test), developed under NCHRP Project 9-19, for use in the Superpave Mix Design procedure. Thus, the E* test will be playing a very dominant role in the material characterization behavior of all dense-graded HMA mixtures in the future technological methodologies.

The new M-E PDG uses laboratory E* data for the Level 1 input (the most comprehensive design input level). For input Levels 2 (with some laboratory test data) and 3 (with no laboratory data), E* values are calculated using the Witczak E* predictive equation. Prior to this study, applicability of the E* predictive equation had not been verified for lime-modified HMA mixtures.

Research Objectives

The primary objective of this research study is to establish an initial database of E* results for lime modified asphalt mixtures. This database includes all of the sigmoidal model coefficients necessary to characterize the E* master curve and a summary of statistically determined time-temperature shift parameters for each lime modified asphalt mix evaluated.

This report also presents a series of provisional protocols for lime modified HMA mixtures, to use in conjunction with the new M-E PDG.

Other secondary objectives are to:

1. Assess any changes in HMA stiffness (E*) that are observed with the addition of hydrated lime into the HMA, and assess how sensitive the change is to the amount of lime added.

2. Compare the test results of the E* testing of the lime modified HMA mixtures to predicted results from the Witczak E* equation. Both the predicted and laboratory stiffness data are used to assess what portion of the lime added to HMA goes into the asphalt binder or reacts with the binder to change the stiffness properties of the HMA mixture.

CHAPTER-2 : BACKGROUND ON MASTER CURVES

Dynamic Modulus (E*)

For linear viscoelastic materials such as HMA mixes, the stress-to-strain relationship under a continuous sinusoidal loading is defined by its complex dynamic modulus (E*). This is a complex number that relates stress to strain for linear viscoelastic materials subjected to continuously applied sinusoidal loading in the frequency domain. The complex modulus is defined as the ratio of the amplitude of the sinusoidal stress (at any given time, t, and angular load frequency, ω), $\sigma = \sigma_0 \sin(\omega t)$ and the amplitude of the sinusoidal strain $\varepsilon = \varepsilon_0 \sin(\omega t - \phi)$, at the same time and frequency, that results in a steady state response as shown in Figure 1.

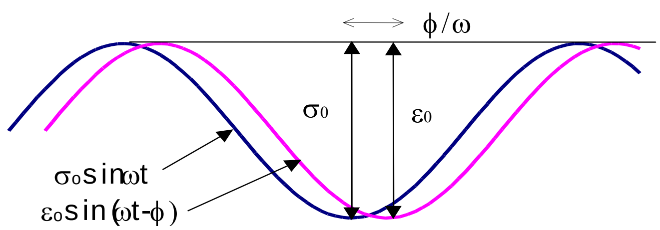


Figure 1. Dynamic (Complex) Modulus

The complex dynamic modulus (E*) can be mathematically expressed as follows:

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0 e^{i\omega t}}{\varepsilon_0 e^{i(\omega t - \phi)}} = \frac{\sigma_0 \sin \omega t}{\varepsilon_0 \sin(\omega t - \phi)} \qquad (1)$$

Where,

σ_0 = peak (maximum) stress

ε_0 = peak (maximum) strain

ϕ = phase angle, degrees

ω = angular velocity

t = time, seconds

Mathematically, the "dynamic modulus" is defined as the absolute value of the complex modulus, i.e. $|E^*| = \sigma_0/\varepsilon_0$. As a conventional practice, however, the dynamic modulus is denoted as E* (not |E*|) in this report. Stiffness data of an HMA mix as obtained from the E* test provide very important information about the linear viscoelastic behavior of that particular mix over a wide range of temperature and loading frequency.

Time-Temperature Superposition of E*

In the new M-E PDG the stiffness of HMA, at all levels of temperature and time rate of load, is determined from a master curve constructed at a reference temperature (generally taken as 70°F). Master curves are constructed using the principle of time-temperature superposition. The data at various temperatures are shifted with respect to time until the curves merge into single smooth function. The master curve of the modulus, as a function of time, formed in this manner describes the time dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. In general, the master modulus curve can be mathematically modeled by a sigmoidal function described as:

$$\text{Log}\,|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log t_r)}} \tag{2}$$

Where,

- t_r = reduced time of loading at reference temperature
- δ = minimum value of E*
- $\delta + \alpha$ = maximum value of E*
- β, γ = parameters describing the shape of the sigmoidal function

The shift factor can be shown in the following form:

$$a(T) = \frac{t}{t_r} \tag{3}$$

Where,

- a(T) = shift factor as a function of temperature
- t = time of loading at desired temperature

t_r = reduced time of loading at reference temperature

T = temperature of interest

For precision, a second order polynomial relationship between the logarithm of the shift factor i.e. log $a(T_i)$ and the temperature in degrees Fahrenheit is used. The relationship can be expressed as follows:

$$\text{Log } a(T_i) = aT_i^2 + bT_i + c \quad (4)$$

Where,

$a(T_i)$ = shift factor as a function of temperature T_i

T_i = temperature of interest, °F

a, b and c = coefficients of the second order polynomial

Input Levels for the M-E PDG

In the new M-E PDG, the stiffness of the HMA is determined from a master curve using one of three alternate input levels, depending on the availability and type of related data. The master curve for input Level 1 is developed using numerical optimization to shift the laboratory mixture test data into a smooth master curve. Prior to shifting the mixing data, the relationship between binder viscosity and temperature must be established. This is done by first converting the asphalt stiffness data at each temperature to viscosity using equation 5. The parameters of the ASTM A_i-VTS_i equation are then found by linear regression of equation 6 after log-log transformation of the viscosity (in centi-poise) data and log transformation of the temperature (in °Rankine) data.

$$\eta = \frac{G^*}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628} \quad (5)$$

$$\log \log \eta = A + VTS \log T_R \quad (6)$$

Where,

η = asphalt viscosity, cP

G* = asphalt complex shear modulus, Pa

δ = asphalt phase angle, degree

A, VTS = regression parameters

T_R = temperature, ºRankine

The master curve for the Level 2 input is developed using the Witczak E* Predictive Model (discussed in the following paragraph shown in equation 7) from specific laboratory test data. The Level 3 input requires no laboratory test data for the asphalt binder but requires certain volumetric properties of the mix.

E* Predictive Equation

As noted, the new M-E PDG uses the laboratory E* data for input Level 1, while it uses E* values from the Witczak E* predictive equation for input Levels 2 and 3. The Witczak E* predictive model was based upon 2750 test points and 205 different HMA mixtures (34 of which are modified). Most of the 205 HMA mixtures were dense-graded and unmodified. The current version of the E* predictive equation, updated in 1999, is:

$$\log E^* = -1.249937 + 0.02923\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a$$
$$-0.82208\frac{V_{beff}}{V_{beff}+V_a} + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\rho_{34}}{1+e^{(-0.603313-0.313351\log(f)-0.393532\log(\eta))}} \quad (7)$$

Where,

- E^* = dynamic modulus, 10^5 psi
- η = asphalt viscosity at the age and temperature of interest, 10^6 Poise (use of RTFO aged viscosity is recommended for short-term oven aged lab blend mix)
- f = loading frequency, Hz
- V_a = air void content, %
- V_{beff} = effective asphalt content, % by volume
- ρ_{34} = cumulative % retained on 3/4 in (19 mm) sieve
- ρ_{38} = cumulative % retained on 3/8 in 9.5 mm sieve
- ρ_4 = cumulative % retained on #4 (4.76 mm) sieve
- ρ_{200} = % passing #200 (0.075 mm) sieve

Witczak's E* predictive equation (equation 7) can be presented in the same form as equation 2 for a mixture-specific master curve as follows:

$$\text{Log}\,|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log t_r)}} \qquad (8)$$

Where,

$|E^*|$ = dynamic modulus, 10^5 psi

$\delta = -1.249937+0.02923\rho_{200}-0.001767(\rho_{200})^2-0.002841\rho_4-0.058097V_a-0.82208\left(\frac{V_{beff}}{V_{beff}+V_a}\right)$

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

β = $-0.603313-0.313532\log(\eta_{Tr})$

γ = 0.313351

t_r = reduced time of loading at reference temperature

η_{Tr} = asphalt RTFOT viscosity at the reference temperature, 10^6 Poise

As of July 2004, another 5,700 E* test points have been collected and will be integrated into future enhancements of the E* predictive model.

CHAPTER-3 : EXPERIMENTAL PLAN

This chapter of the report presents the experimental plan used to expand the E* database of lime-modified HMA mixtures, and the materials that were used in that test program.

Materials and Mixtures

Six different aggregates and four different binders were used to produce six different sets of HMA mixtures. Seventeen different HMA mixtures were tested, containing up to 3% lime (by weight of the total aggregates). Within any set of mixes, one fixed optimum asphalt content and one fixed job mix formula was used. To maintain consistent gradations in all of the mixes, the amount of filler was adjusted in the mixes containing lime (see the materials and mixture data in Table A1 of Appendix A).

Asphalt Testing Program

Four different asphalts were used in this study, which are listed below:

- PG 64-22 binder was used in the Two Guns, Maryland DOT, and WesTrack mixtures.
- PG 58-28 was used in the Bidahouchi Base mixtures.
- PG 76-16 was used in the Salt River Base mixtures.
- AC-5 was used in the FHWA-ALF mixtures.

For the asphalt test program, 0.50, 0.75, and 1% hydrated lime (by weight of respective mix aggregates) were thoroughly hot-mixed with the above asphalts at about 135°C (275°F). Each virgin and lime modified asphalt was tested in two aging conditions: (1) Tank or Original, and (2) plant aging simulated by RTFOT (Rolling Thin Film Aging Oven Test). RTFOT was conducted according to the AASHTO T 240 protocol. For characterization purpose, the Penetration, Ring and Ball softening point, and Brookfield™ rotational viscosity tests were conducted on each asphalt binder.

The Penetration tests were conducted with 100 gm load for 5 seconds at 15, 25, and 35°C (59, 77, and 95°F) according to AASHTO T49-93 protocol. The Ring and Ball softening point tests were conducted using the AASHTO T53-92 protocol. Finally, the rotational viscosity tests were conducted at 60, 80, 100, 121, 135, and 177°C (140, 176, 212, 250, 275, and 350°F) using the Brookfield™ Viscometer and the AASHTO TP48 protocol.

Test Specimen Preparation

NCHRP 1-37A Test Method DM-1 entitled "Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures" was followed for the laboratory E* test specimen preparation and testing (*11*). Specifically, each E* test specimen was fabricated according to the Test Protocol UMD 9808, "Method for Preparation of Triaxial Specimens" – prepared by the Superpave Models Team Inter-Laboratory Testing Manual, Internal Team Report, University of Maryland, October 1998.

The mixing and compaction temperature was determined using consistency test results and the viscosity-temperature relationship determined for the chosen asphalt. The aggregates (with or without lime) and asphalt were hot mixed according to the job mix formula. The HMA mixture was then short-term oven aged 4 hours at 275ºF, according to the AASHTO Test Method AASHTO PP2 – "Standard Practice for Short and Long Term Aging of Hot Mix Asphalt," before compaction.

The test sample was then compacted with a "Servopac Gyratory Compactor" into a 6-in (≈ 150-mm) diameter mold to approximately 6.7-in (≈ 160-mm) height. The test specimen was cored from the center of the Gyratory compacted sample. Approximately 0.2″ (≈ 5-mm) were sawn from each sample end to have the final 4-in diameter x 6-in high E* test specimen. Before the E* testing, AASHTO T166-93 was followed to measure the bulk specific gravity and water absorption of the specimens. All the test specimens were compacted to about 7% air voids that were measured according to AASHTO T269.

Dynamic Modulus Testing

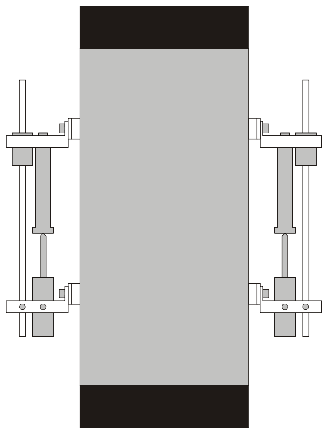
NCHRP 1-37A Test Method DM-1 was followed for E* testing (11). For each mix, three replicates were prepared for testing. For each test specimen, E* tests were conducted at 14, 40, 70, 100 and 130°F at loading frequencies of 25, 10, 5, 1, 0.5 and 0.1Hz. A 60 second rest period was used between each frequency to allow some specimen recovery before applying the new loading at a lower frequency. Table 1 presents the E* test conditions.

Table 1. Test Conditions of the Dynamic Modulus (E*) Test

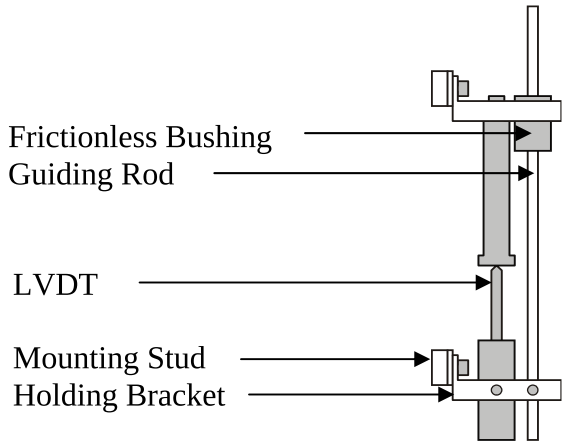
Test Temp. (°F)	Freq. (Hz)	Cycles	Rest Period (Sec)	Cycles to Compute E*
14, 40, 70, 100, 130	25	200	-	196 to 200
	10	100	60	196 to 200
	5	50	60	96 to 100
	1	20	60	16 to 20
	0.5	15	60	11 to 15
	0.1	15	60	11 to 15

The E* tests were done using a controlled stress mode, which produced strains smaller than 200 micro-strain. This ensured, to the degree possible, that the response of the material was linear across the temperature used in the study. The dynamic stress levels were 10 to 100 psi for colder temperatures (14 to 70°F) and 2 to 10 psi for higher temperatures (100 to 130°F). All E* tests were conducted in a temperature-controlled chamber capable of holding temperatures from 3.2 to 140°F (–16 to 60°C).

The axial deformations of the specimens were measured through two spring-loaded Linear Variable Differential Transducers (LVDTs) placed vertically on diametrically opposite sides of the specimen. Parallel brass studs were used to secure the LVDTs in place. Two pairs of studs were glued on the two opposite cylindrical surfaces of a specimen; each stud in a pair, was 100-mm (4 inch) apart and located at approximately the same distance from the top and bottom of the specimen. Top and bottom surface friction is a problem for compressive type testing. In order to eliminate the possibility of having shear stresses on the specimen ends during testing, pairs of rubber membranes, with vacuum grease within the pairs, were placed on the top and bottom of each specimen during testing. Figure 2 shows the instrumentation of the test samples used in the dynamic modulus testing.



a. Sample Assembly



b. Lateral View

Figure 2. Specimen Instrumentation of E* Testing

CHAPTER-4 : TEST RESULTS

Asphalt Test Results

All asphalt test data were converted to viscosity in units of centi-poise. Research by Shell Oil, which was later confirmed by Mirza and Witczak, indicates that for most unmodified asphalts, the ring and ball softening point corresponds to a viscosity of 1,300,000 centi-poise (cP) (*12*). The Penetration test data were converted to viscosity using the following equation (*12*):

$$\log \eta = 10.5012 - 2.2601 \log(Pen) + 0.00389(\log(Pen))^2 \qquad (9)$$

Where,

η = viscosity, Poise (P)

Pen = measured penetration for 100g, 5 sec loading in 0.10 mm

As previously noted, each percent lime-asphalt-aging combination was also subjected to the Brookfield viscosity tests at a range of temperatures. Viscosity temperature data points were developed using the Softening Point, Penetration, and Brookfield test results. Finally, the Log Log viscosity (in cP) data were plotted against temperature (in °Rankine) for each percent lime-asphalt-aging combination. The viscosity-temperature susceptibility parameters ("A" and "VTS") of the ASTM A_i-VTS_i equation were estimated by linear regression of equation 6. The asphalt test data and the regression plots with "A" and "VTS" values are presented in Appendix B.

E* Test Results

Laboratory E* Data

The quality of the E* test data for the 17 mixtures evaluated in the study was thoroughly checked by Black Space diagrams, Cole-Cole Plane plots, E* vs. loading frequency plots, and a statistical variation study. The laboratory E* test data (dynamic modulus and phase angle) for a matrix of five test temperatures and six test loading frequencies for each replicate and their overall average are summarized in Appendix C.

E* Measurements from Master Curves

Similar to the new M-E PDG's input Level-1 approach, E* master curves of all mixtures were constructed for a reference temperature of 70°F using the principle of time-temperature superposition (*10*, *11*). The data at various temperatures were shifted with respect to time until the curves merge into a single sigmoidal function representing the master curve using a second order polynomial relationship between the logarithm of the shift factors, log $a(T_i)$ and the temperature. The time-temperature superposition was done by simultaneously solving for the four coefficients of the sigmoidal function (δ, α, β, and γ) as described in equation 2 and the three coefficients of the second order polynomial (a, b, and c) as described in equation 4. The "Solver" function of the Microsoft™ Excel was used to conduct the nonlinear optimization for simultaneously solving these seven parameters. For each of the seventeen mixtures, the set of master curve parameters were obtained for: (i) average E* of all replicates, (ii) E* of all replicates, and (iii) each replicate. The results are presented in Appendix D. Plots of master curves for individual mixtures are presented in Appendix E.

The E* of each mix at five test temperatures and six test loading frequencies were also computed using the master curve and shift coefficients (based on the average E* of all replicates). These "master curve obtained E* (MC E*)" and the laboratory measured E* data are presented in Appendix C.

As an example, construction of master curve for the Two-Guns mixture with 1% lime is shown in Figures 3, 4 and 5. Figure 3 is a plot of E* (in psi) versus loading time (in seconds). In Figures 4 and 5, the E* data are shifted using a non-linear optimization by simultaneously solving seven master curve and shift parameters (δ, α, β, γ, a, b and c). These seven parameters are then used in the equations 2, 3 and 4 to calculate the E* of the particular mix at any temperature and loading frequency within the range used in the E* testing.

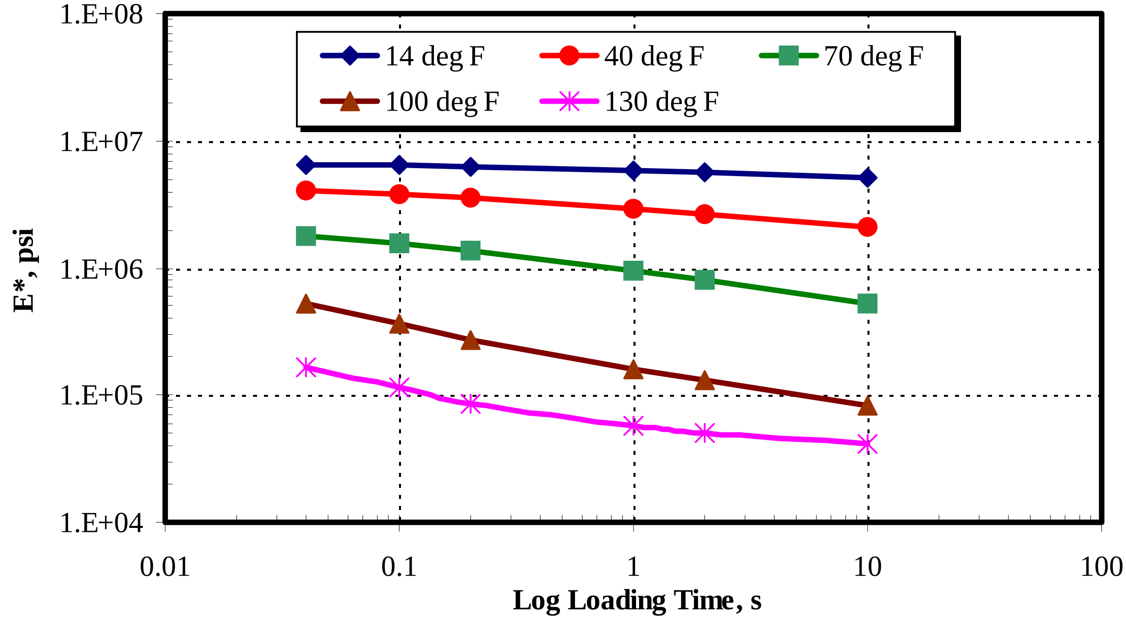


Figure 3. Laboratory E* versus Loading Time for Two-Guns Mix with 1% Lime

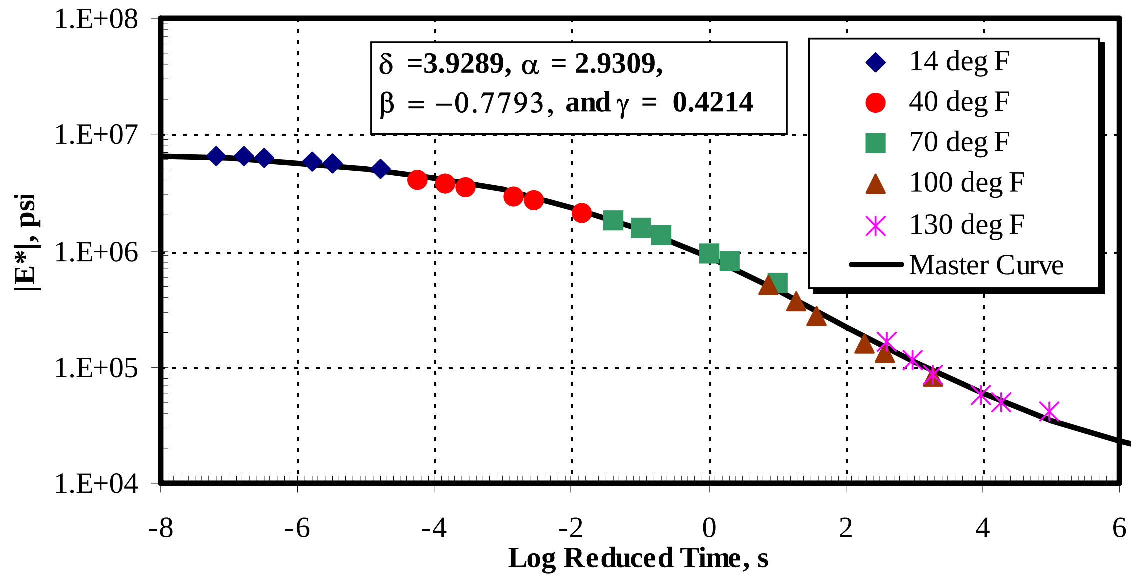


Figure 4. Master Curve with Shifted E* Data for Two-Guns Mix with 1% Lime

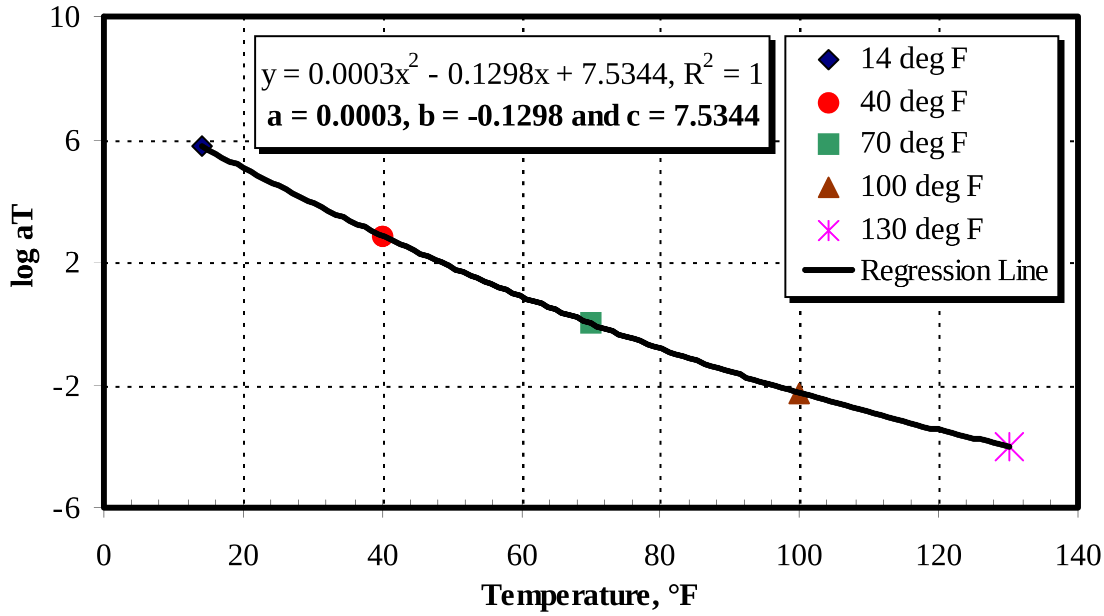


Figure 5. Shift Factor versus Temperature for Two-Guns Mix with 1% Lime

CHAPTER-5 : ANALYSIS

Effect of Lime on E*

Comparison of E* of Mixtures with Different Lime Contents

Lime addition resulted in a general increase in the mix stiffness (E*) for all mixtures evaluated, within the range of temperature and loading frequency used in the E* testing. As an example, Figure 6 shows a comparison of master curves of the Two-Guns mixtures with different lime contents. In this case, the E* stiffness of the Two-Guns mixtures increased due to lime addition.

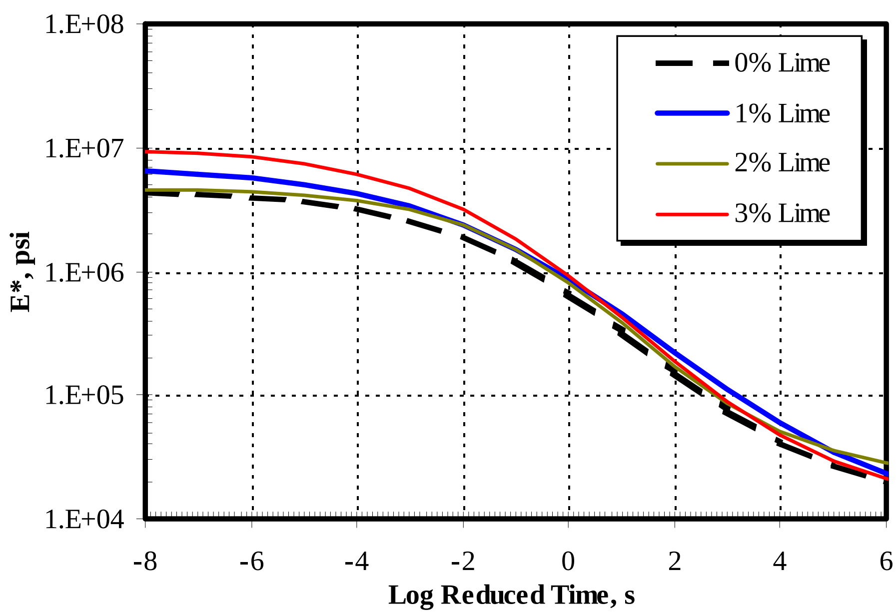
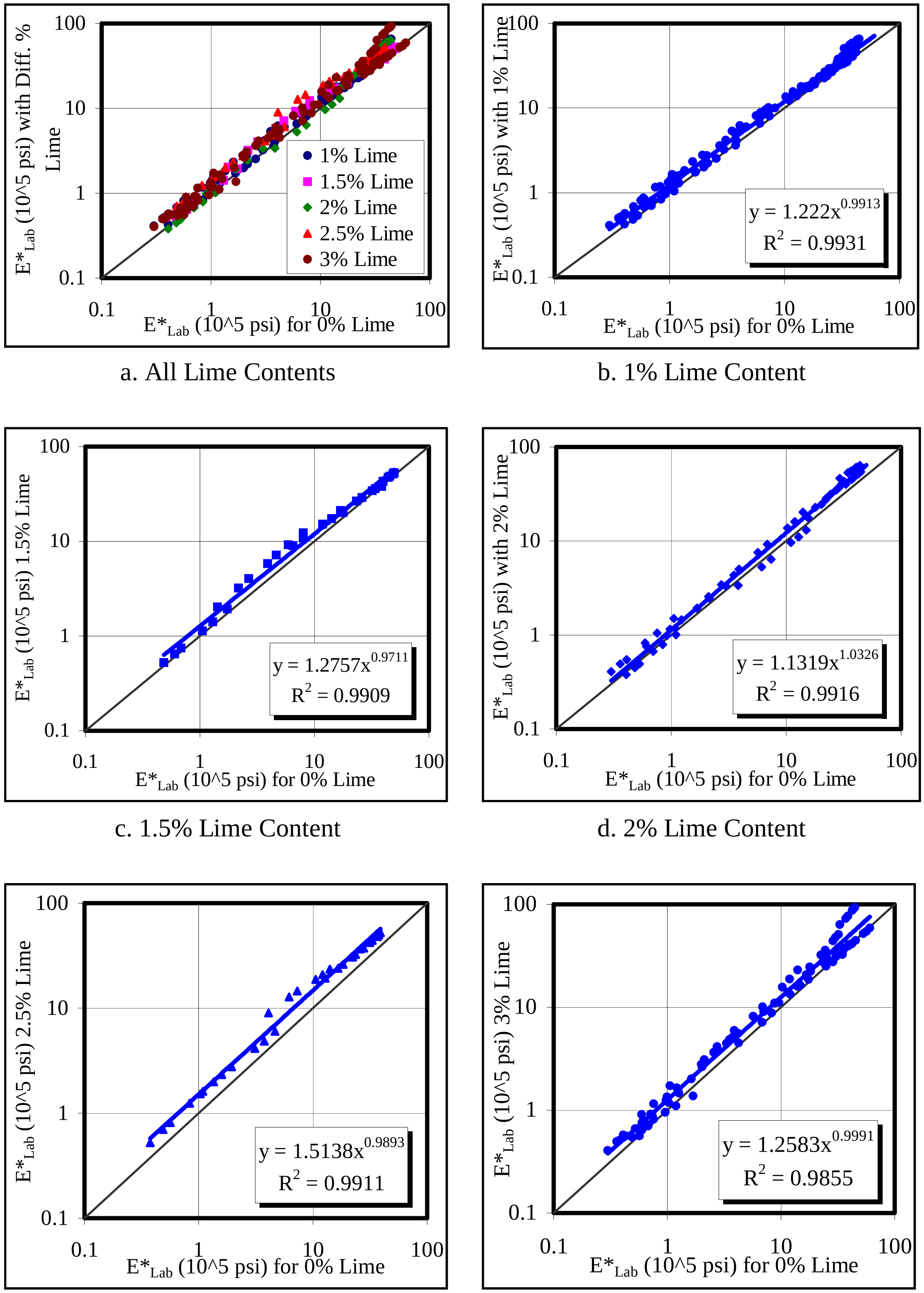


Figure 6. Master Curves of Two-Guns Mixtures with Different Lime Contents

Figures 7 and 8 present an alternative means of showing the increase in E*, by comparing E* data of all eleven lime modified HMA mixtures to the E* data of the same six mixtures without any lime. Figure 7 presents the E* values obtained from the laboratory data for each mixture. Figure 8 presents the E* values obtained from the master curve for each mixture. Each plot is in log-log space with a line of equality. Points above the line of equality represent an increased E* due to the lime addition.



a. All Lime Contents

b. 1% Lime Content

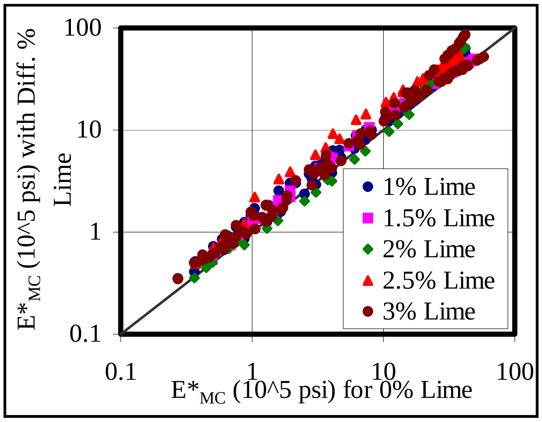
c. 1.5% Lime Content

d. 2% Lime Content

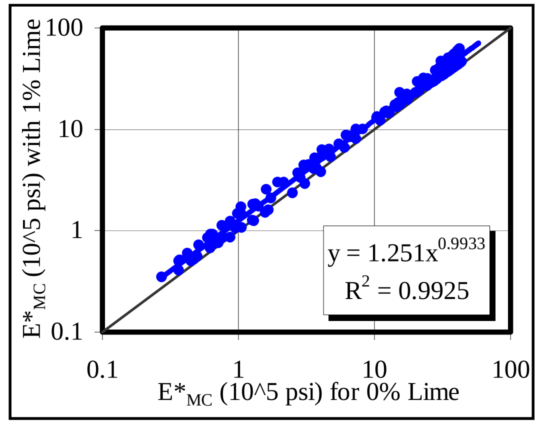
e. 2.5% Lime Content

f. 3% Lime Content

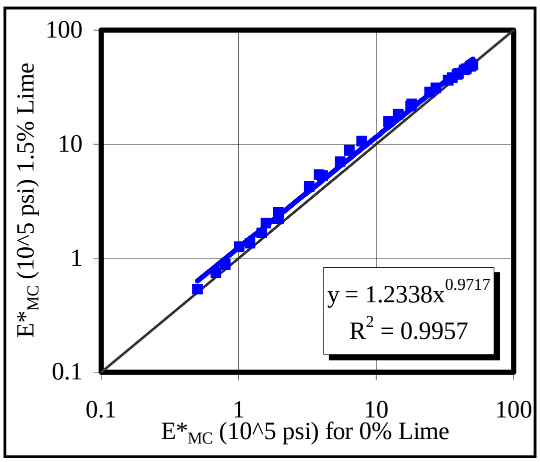
Figure 7. Lab E* of Mix With Lime Versus Without Lime



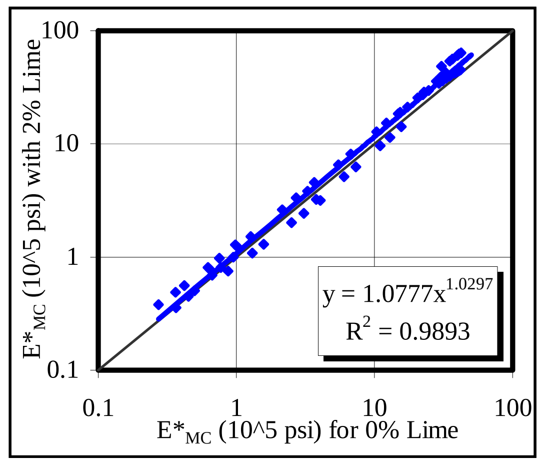
a. All Lime Contents



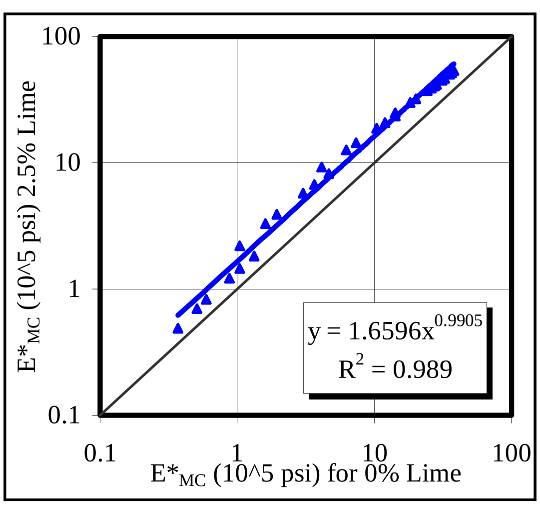
b. 1% Lime Content



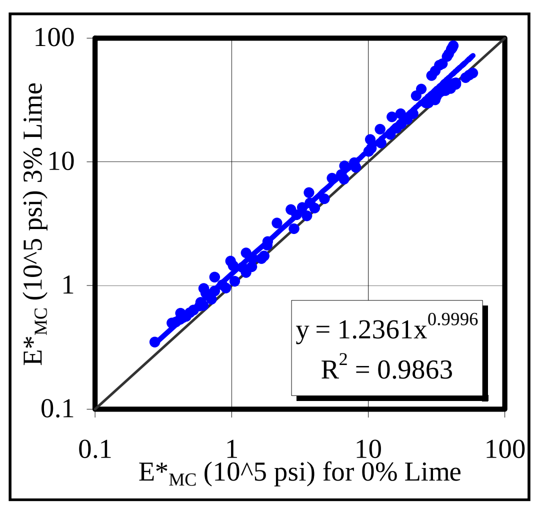
c. 1.5% Lime Content



d. 2% Lime Content



e. 2.5% Lime Content



f. 3% Lime Content

Figure 8. Master Curve Obtained E* of Mix With Lime Versus Without Lime

The equations within each figure show that all of the power values (exponents) are close to one. Thus the intercept coefficient (e.g. 1.222 for 1% lime content) denotes that the average lab E* of lime modified mixtures (1% lime) is approximately 22% greater than the lab E* of a non-lime modified mix. Figures 7a and 8a illustrate the general increase in dynamic modulus due to lime addition for all mixtures. Figures 7b through 7g and 8b through 8g separately show the effect on each mixture. For each case, lime increases both the laboratory and master curve obtained E* values and the plots obtained from the laboratory data and master curve are very consistent.

<u>Changes in Mix Stiffness (E*)</u>

The ratio of the E* of lime modified mixtures, to that of the same mix without lime, were calculated at each of the five test temperatures and six test frequencies evaluated. The ratio for both the laboratory E* data and E* values obtained from the master curves are summarized in Tables F-1 through F-6 in the Appendix F. For mixtures without lime, the logarithm of the corresponding reduced times of loading (t_r) at reference temperature of 70°F (as described in equations 2 and 3) are also summarized in these tables. For all mixtures, master curve E* corresponded closely to the laboratory data. The analysis of data presented in Tables F-1 through F-6 of Appendix F provides the followings:

- E* data of the Two Guns mixtures with 1, 2, and 3% lime (by weight of aggregate) yielded E* increases on the average of: 1.38, 1.21 and 1.58 times, respectively, compared to the corresponding mixtures without lime. E* ratio values (E* with lime to E* without lime) ranged from 1.09 to 2.11.
- Laboratory E* of the Maryland DOT mixtures with 1 and 3% lime (by weight of aggregate) increased 1.11 and 1.13 times, respectively, due to the lime addition. The E* ratio ranged from 0.82 to 1.43.
- The Bidahouchi Base lab E* for 1 and 2% lime increased to 1.12 and 1.14 times, respectively, with increases ranging from 0.86 to 1.59.
- The lab E* of the Salt River Base mixtures with 1 and 2.5% lime, increased 1.24 and 1.50 times, respectively, due to the lime addition. The individual E* ratio values ranged from 1.02 to 2.21.

- The lab E* ratio of the WesTrack mixtures with 1.5% lime addition ranged from 0.98 to 1.56 with an average of 1.21.
- The lab E* of the ALF (FHWA) mixture for 3% lime addition increased 1.14 times, with individual values ranging from 0.94 to 1.35.

Table 2 presents average E* ratio all of the tested mixtures. For 1, 1.5, 2, 2.5, and 3% lime addition (by aggregate weight), the laboratory E* increased 1.21, 1.21, 1.17, 1.50, and 1.28 times, respectively. For the lab data, the overall average increase was 1.25 times for 1% to 3% lime addition (based on 330 data points from all tested mixtures). The master curve obtained E* values provided almost identical results: E* value increase of 1.23, 1.17, 1.17, 1.65, and 1.26 times, respectively. The overall average increase for the master curve data was 1.26.

Effect of Other Variables on Mix Stiffness (E*)

The ancillary studies regarding the effect of loading time, temperature and reaction of lime with asphalt on the stiffness of lime-modified mixtures are discussed in Appendices G through L.

Table 2. All Test Mixtures: Average Ratio of E* With Lime to E* Without Lime

Temp	Freq	E* Ratio from Lab Data					E* Ratio from Master Curve				
°F	Hz	1%	1.5%	2%	2.5%	3%	1%	1.5%	2%	2.5%	3%
14	25	1.22	1.06	1.27	1.34	1.36	1.23	0.99	1.42	1.41	1.32
14	10	1.24	1.05	1.28	1.32	1.36	1.22	0.99	1.39	1.42	1.31
14	5	1.24	1.06	1.30	1.31	1.35	1.22	1.00	1.37	1.42	1.31
14	1	1.25	1.07	1.31	1.33	1.34	1.21	1.01	1.32	1.43	1.30
14	0.5	1.25	1.08	1.33	1.34	1.32	1.20	1.02	1.30	1.44	1.29
14	0.1	1.26	1.08	1.35	1.35	1.33	1.19	1.05	1.23	1.47	1.28
40	25	1.11	0.98	1.27	1.41	1.20	1.19	1.06	1.26	1.48	1.30
40	10	1.11	1.05	1.24	1.38	1.21	1.18	1.07	1.22	1.51	1.29
40	5	1.11	1.06	1.22	1.38	1.22	1.18	1.09	1.20	1.53	1.29
40	1	1.11	1.11	1.21	1.43	1.23	1.18	1.14	1.14	1.60	1.28
40	0.5	1.12	1.14	1.19	1.44	1.23	1.18	1.17	1.12	1.64	1.27
40	0.1	1.14	1.26	1.15	1.51	1.25	1.19	1.23	1.07	1.76	1.25
70	25	1.18	1.12	1.08	1.68	1.37	1.18	1.22	1.12	1.67	1.30
70	10	1.22	1.22	1.05	1.72	1.33	1.19	1.25	1.10	1.74	1.29
70	5	1.23	1.28	1.05	1.78	1.31	1.20	1.28	1.09	1.80	1.28
70	1	1.27	1.36	1.05	1.99	1.29	1.25	1.35	1.07	1.96	1.24
70	0.5	1.30	1.40	1.06	2.07	1.28	1.27	1.38	1.06	2.04	1.23
70	0.1	1.36	1.48	1.05	2.21	1.25	1.33	1.42	1.05	2.24	1.19
100	25	1.17	1.54	1.17	1.30	1.38	1.22	1.29	1.12	1.77	1.25
100	10	1.16	1.56	1.17	1.30	1.37	1.25	1.30	1.11	1.84	1.23
100	5	1.17	1.54	1.16	1.34	1.35	1.27	1.31	1.11	1.90	1.22
100	1	1.21	1.51	1.12	1.42	1.25	1.32	1.30	1.12	2.01	1.21
100	0.5	1.25	1.47	1.11	1.47	1.23	1.33	1.29	1.12	2.05	1.20
100	0.1	1.28	1.42	1.15	1.48	1.19	1.36	1.25	1.13	2.11	1.21
130	25	1.23	1.11	1.12	1.47	1.22	1.20	1.13	1.14	1.38	1.25
130	10	1.25	1.09	1.13	1.48	1.24	1.21	1.13	1.14	1.39	1.25
130	5	1.25	1.07	1.15	1.49	1.27	1.22	1.12	1.15	1.40	1.25
130	1	1.24	1.09	1.12	1.45	1.25	1.23	1.10	1.15	1.39	1.25
130	0.5	1.23	1.08	1.14	1.44	1.26	1.23	1.09	1.16	1.38	1.25
130	0.1	1.25	1.08	1.15	1.39	1.27	1.22	1.07	1.17	1.33	1.26
Minimum Value		**0.95**	**0.98**	**0.86**	**1.30**	**0.82**	**0.94**	**0.99**	**0.92**	**1.33**	**0.90**
Maximum Value		**1.55**	**1.56**	**1.59**	**2.21**	**2.11**	**1.64**	**1.42**	**1.75**	**2.24**	**2.06**
Average Value		**1.21**	**1.21**	**1.17**	**1.50**	**1.28**	**1.23**	**1.17**	**1.17**	**1.65**	**1.26**
Standard Deviation		**0.16**	**0.19**	**0.18**	**0.23**	**0.28**	**0.16**	**0.13**	**0.19**	**0.27**	**0.27**
Coeff. of Variation, %		**13**	**15**	**15**	**16**	**22**	**13**	**11**	**16**	**16**	**22**
Number of Points, N		**120**	**30**	**60**	**30**	**90**	**120**	**30**	**60**	**30**	**90**
Gross Average of the E* $Ratio_{Lab}$ for all lime contents of all mixtures = 1.25											
Gross Average of the E* $Ratio_{Master\ Curve}$ for all lime contents of all mixtures = 1.26											
Total Number of Points = 330											

Comparison of Master Curve E* Data with Lab E* Data

As noted, similar to the new M-E PDG's Level-1 input approach, E* master curves for all mixtures (10, 11). Dynamic modulus of each mixes at five test temperatures (14, 40, 70, 100 and 130°F) and six test loading frequencies (25, 10, 5, 1, 0.5 and 0.1Hz) were computed using the respective master curve and shift coefficients. Findings in the previous sections clearly showed that master curve obtained E* produced nearly identical results when compared to laboratory E* test data.

To further evaluate their relationship, the E* ratios obtained from laboratory E* test data were plotted against the E* ratios obtained from the mix master curves. The results are shown in Figure 9. The E* ratios obtained from the laboratory and master curves were generally very close. Hence, for practical purpose, E* values obtained from a master curve may be substituted for the laboratory E* test data.

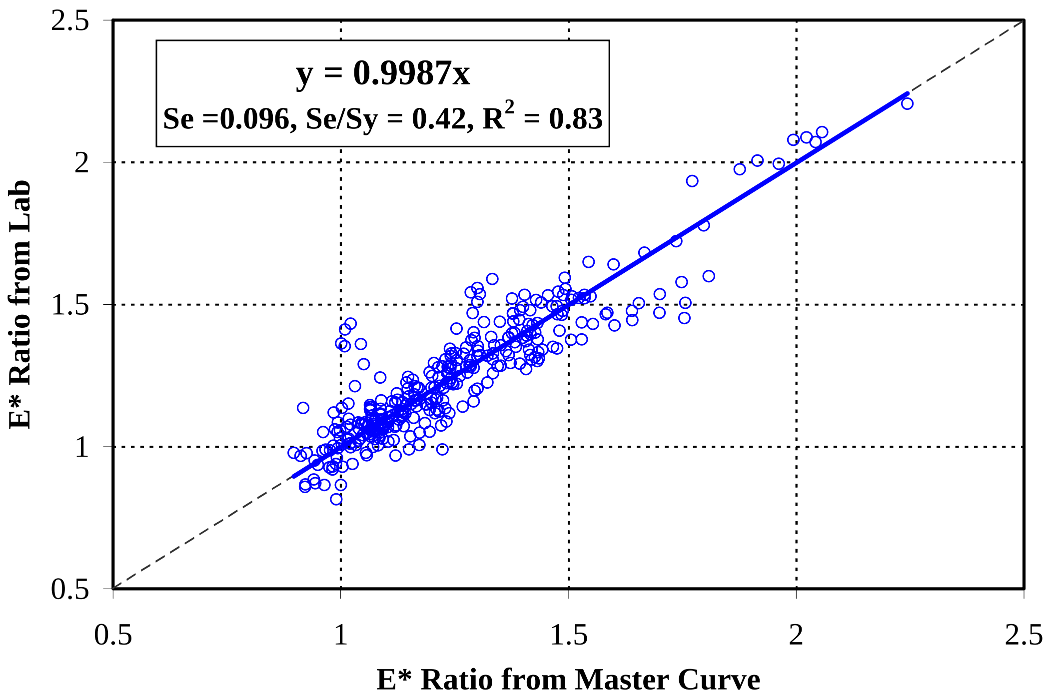


Figure 9. Comparison of Lab E* Ratio vs. Master Curve E* Ratio

CHAPTER-6 : CONCLUSIONS

The objectives of this research were to: (i) establish an initial database of E* for lime modified asphalt mixtures; (ii) assess any changes in the HMA stiffness (E*) that are observed with the addition of lime in the HMA, and if a change occurs; (iii) assess how sensitive the change is, (iv) compare the test results of the E* testing of the lime modified HMA mixtures to predicted results from the Witczak E* equation; and (v) outline recommended protocols for lime modified HMA mixtures to use with the procedures described in the new M-E PDG. This research used a wide range of aggregate types and gradations from five different project sites across the U.S. to prepare seventeen different mixtures with hydrated lime contents from 0 to 3 percent (by aggregate weight).

Based upon the range of lime modified mixtures evaluated:

1. Lime modified HMA mixtures have a higher E* (dynamic modulus) than unmodified mixtures.
2. On average, E* for lime-modified mixes was 25 percent greater than unmodified mixes. Across all lime percentages tested, the increase varied from near 0 to 120 percent. This quantitative increase in the E* value for lime modified mixtures, was found to be true for a range of lime percentages from 1% to 3% (percent based on aggregate weight). The variation undoubtedly reflects the complex interaction of hydrated lime with binder type, binder quality, and aggregate characteristics and gradation.
3. Direct laboratory E* test results correlated well with the E* values obtained from the Master Curves. This demonstrates that the Master Curve accurately encompasses the temperature-time rate of loading effects of lime modified HMA mixtures.
4. No systematic change in the E* ratio (E* with lime divided by E* without lime) was found to occur as either temperature and/or time rate of loading was varied. In general, the E* ratio appeared to be independent of the reduced time and the performance grade (type) used.

5. The fraction of lime that interacts with the binder to increase the binder viscosity (and hence mixture E*) varies. The variation undoubtedly reflects the complex interaction of hydrated lime with binder type, binder quality, and aggregate characteristics and gradation.

Protocol for Characterizing the E* of Lime Modified HMA Mixtures

The NCHRP 1-37A Draft Test Method DM-1 (*11*) is the most recent version of the E* test protocol. This is the protocol (provisional) that is being contemplated for use in the new M-E PDG. Based upon the findings in this study, recommended protocols for lime modified HMA mixtures, to use in conjunction with the pavement design procedures described in the new M-E PDG follow:

Recommended Protocol for the Level-1 Input

a) Heat the virgin binder at 275ºF (135ºC) only until it is pourable and mixable (typically an hour).
b) For mixtures to be modified with 1% lime (by aggregate weight), add 2.8% hydrated lime (by asphalt weight) directly into this hot virgin binder and mix thoroughly. If the lime percentage is 2% (by aggregate weight), add 3.2% hydrated lime (by asphalt weight).
c) Prior to testing, short-term oven age (STOA) this lime modified asphalt in the Rolling Thin Film Oven (RTFO), according to the AASHTO T 240 test protocol.
d) After the STOA process is completed, conduct asphalt characterization testing to determine the binder viscosity at the temperatures that will be used for dynamic modulus testing. Asphalt characterization can be done either by Dynamic Shear Rheometer Test (AASHTO TP5) or by a series of conventional tests (e.g. Penetration, Ring and Ball softening point, Brookfield™, Absolute Viscosity, Kinematic Viscosity) at a wide variety of temperatures, preferably from 15 to 177°C (59 to 350°F).
e) Convert the asphalt test data to Log Log viscosity (in cP) and plot them against Log temperature (in °Rankine).

f) By linear regression, obtain the viscosity-temperature susceptibility parameters (“A” and “VTS”) of the ASTM A_i-VTS_i equation.

g) Using this ASTM A_i-VTS_i equation, determine the HMA mixing and compaction temperature and compute the binder viscosity at the E* test temperatures.

h) Add the desired level of lime (typically 1 to 3% hydrated lime) directly to the dry aggregates and mix thoroughly.

i) Add the required amount of virgin tank aged binder (not modified with lime) into the lime-aggregate mixture and wet mix thoroughly at the proper mixing temperature.

j) Perform short-term oven aging of the loose hot mix for 4 hours at 275ºF (135ºC), according to the AASHTO Test Method AASHTO PP2 – Standard Practice for Short and Long Term Aging of Hot Mix Asphalt.

k) Compact the loose mix with a gyratory compactor in a 6-in (≈ 150-mm) diameter mold to approximately 6.7-in (≈ 160-mm) height.

l) Follow the E* test protocol for final sample preparation and E* testing (*11*).

m) Use the E* test data of the lime modified mixture and the computed viscosity values of the RTFO-aged, lime-modified binder to obtain the final master curve of the particular HMA mixture. Use this master curve in the Level-1 input procedures of the new M-E PDG.

Recommended Protocol for the Level-2 Input

a) Follow the steps (a) through (f) of the provisional protocol outline for the Level-1 Analysis.

b) Use the ASTM A_i-VTS_i equation to compute the binder viscosity at the temperatures of interest.

c) Compute the reduced time (t_r) from these viscosity values.

d) Use the computed t_r in the Witczak E* predictive equation to obtain the final E* master curve. Use this master curve in the Level-2 input procedures of the new M-E PDG.

Potential Guideline for Level-3 Input

The E* of a lime modified mixture (with typical hydrated lime percentages of 1% to 2+%, based on weight of aggregate) will be approximately 25% greater than a HMA mixture with no lime (i.e. $E^*_{lime} = 1.25\ E^*_{no\ lime}$). This increase appears to be independent of temperature and/or time rate of load.

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