Using New Pavement Design Procedures for Hot Mix Asphalt Mixtures Modified with Hydrated Lime

This technical brief answers questions that pavement and material designers may have in using the new Mechanistic-Empirical Pavement Design Guide (M-E PDG) [1] to evaluate asphalt pavements modified with hydrated lime:

1. What are the advantages of using hydrated lime?
2. How does lime affect long-term performance of hot mix asphalt (HMA) mixtures?
3. What is dynamic modulus and how is it used in pavement structural designs?
4. How does hydrated lime affect the dynamic modulus of HMA mixtures?

What are lime's advantages?

Hydrated lime has been used in HMA mixtures in the United States since 1910. The benefits of adding hydrated lime to HMA mixtures are:

- Reduces moisture damage and stripping for moisture sensitive aggregates.
- Reduces the design asphalt content.
- Improves toughness and resistance to fracture growth at low temperatures.
- Reduces age hardening of the asphalt binder.
- Increases mixture stability and durability.

These benefits have been discussed in many technical reports and publications [2-6]. Hydrated lime is best known as an anti-stripping additive in HMA, as recognized by the Federal Highway Administration and other State highway agencies (e.g., Georgia, Nevada, Oregon, South Carolina, Texas, and Utah [4]).

HIGHLIGHTS:

Hydrated lime increases dynamic modulus by 20-25%.

The Design Guide protocols can be used for lime-modified asphalts.

How does lime affect long-term pavement performance?

The major types of HMA pavement distresses affected by rheological asphalt properties are stripping, rutting, and cracking [6]. Many studies have proven that hydrated lime is very effective in preventing moisture damage and stripping [7], but in addition, lime has been shown to reduce the amount and severity of rutting and cracking.

Hydrated lime increases resistance to rutting because it produces a stiffer HMA mixture, as demonstrated by the higher dynamic modulus of lime-modified HMA mixtures. High modulus mixtures will deform less and thus rut less in the HMA layers. Higher modulus HMA layers will also reduce the irrecoverable deformation in the foundation layers because of reduced vertical stresses, resulting in less rutting in the lower layers as well.

Although stiffer mixtures would seem to be more prone to fatigue and thermal cracking at cold temperatures, lime also increases tensile strength and improves the resistance to fracture growth or fracture toughness, which is important at lower temperatures, when HMA is more prone to cracking due to higher stiffness [3, 9]. Therefore, lime increases the resistance to thermal and fatigue cracking at moderate to low temperatures, while reducing rutting at high temperatures.

What is dynamic modulus & how is it used in pavement design?

The M-E PDG, as well as other mechanistic-empirical pavement design procedures, have procedures to compute pavement responses, e.g., deflections, stresses, and strains within the pavement structure

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(including HMA layers). For practical reasons, the M-E PDG uses a layered elastic program to compute pavement responses. These computed responses are then used to predict the amount of cracking and rutting. Several inputs are required for computing pavement responses including HMA layer modulus. In the M-E PDG, the HMA layer modulus is characterized using the dynamic modulus (stiffness) - see box on p.4. The dynamic modulus at a given loading time and temperature is assumed to be the elastic modulus in the response computation. The M-E PDG incorporates an incremental damage accumulation process to predict pavement distresses from the computed responses. Each increment pertains to a unique combination of loading, materials properties, and climatic conditions. By selecting the appropriate dynamic modulus within each increment of the design life, the viscoelastic nature of the asphalt material behavior is accounted for in the M-E PDG.

Due to the complex nature of HMA mixtures, the dynamic modulus of HMA depends on various conditions including temperature, rate of loading, age, volumetric properties (air voids and binder content), and its component material characteristics (i.e.; binder stiffness and aggregate gradation). For this reason, dynamic modulus is determined using standardized testing conditions. ASTM D3497-79, “Standard Test Method for Dynamic Modulus of Asphalt Mixtures,” is one test method that has been used in past studies. Another is the NCHRP 1-37A (E*) Test Method DM-1, in which a sinusoidal (haversine) compressive stress is applied to the test specimen at different temperatures and loading frequencies [8].

The M-E PDG uses the E* test to determine the modulus of HMA layers. In addition, the E* test is the leading candidate for the Simple Performance Test for use in the Superpave mixture design procedure. Thus, the E* test will be play a significant role in the characterization of HMA materials in future structural and mixture designs.

Once the dynamic modulus is measured for different temperatures and loading frequencies, this data is used to create a <u>master curve</u> using the principle of time-temperature superposition. Specifically, the data at various temperatures are shifted with respect to load time until the curves merge into a single smooth sigmoidal function. The dynamic modulus at any temperature or loading rate can then be obtained from this master curve. The use of this dynamic modulus master curve permits the elastic modulus of the HMA layers to be varied by temperature, speed, and layer depth to represent the viscoelastic response.

How does lime affect modulus?

Although the E* test has been used to characterize <u>un</u>modified-HMA mixtures for the past 30 years, little E* testing has been performed on lime-modified HMA mixtures. To fill this knowledge gap, the National Lime Association sponsored a testing program to measure the E* of lime-modified and unmodified-HMA mixtures and determine the effect of adding hydrated lime to selected HMA mixtures [6].

Six different sets of HMA were produced from six aggregates and four asphalts. The amount of lime in the HMA mixtures was varied up to 3 percent by the weight of the total aggregates, resulting in seventeen different HMA mixtures that were tested. Current practice is to use 1 to 1 ½ % lime. Greater percentages were included in the study to see what effects it would have. Consistent mixture gradation was maintained throughout testing by adjusting the amount of filler in those mixtures with lime. The NCHRP 1-37A Test Method DM-1 was followed for the E* test specimen preparation and testing [8]. In this test method, three replicates are prepared for each mix and tested at 14, 40, 70, 100, and 130 °F at loading frequencies of 25, 10, 4, 1, 0.5, and 0.1 Hz.

The comparison between dynamic modulus of lime-modified and unmodified HMA mixtures indicates that the addition of lime increases the overall average dynamic modulus by about 25 percent based on 330 data points [6]. Figure 1 summarizes the effect of lime on the average dynamic modulus of all mixtures tested at each temperature and frequency. As noted above, every mix was not tested at every lime concentration; results for each of the seventeen tested combinations are presented in Figure 2.

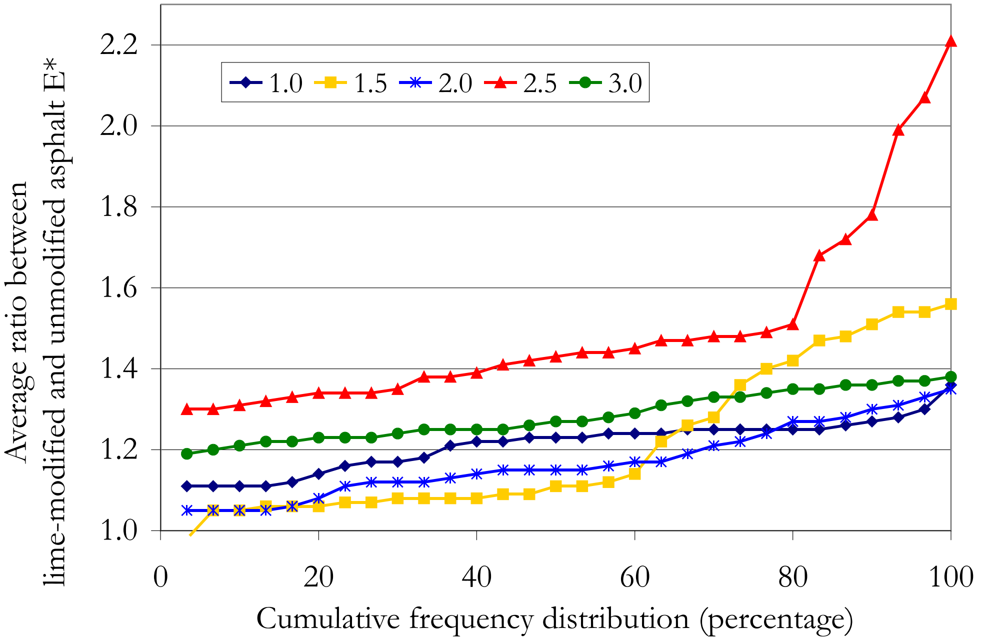

Figure 1. Effect of Lime on Dynamic Modulus

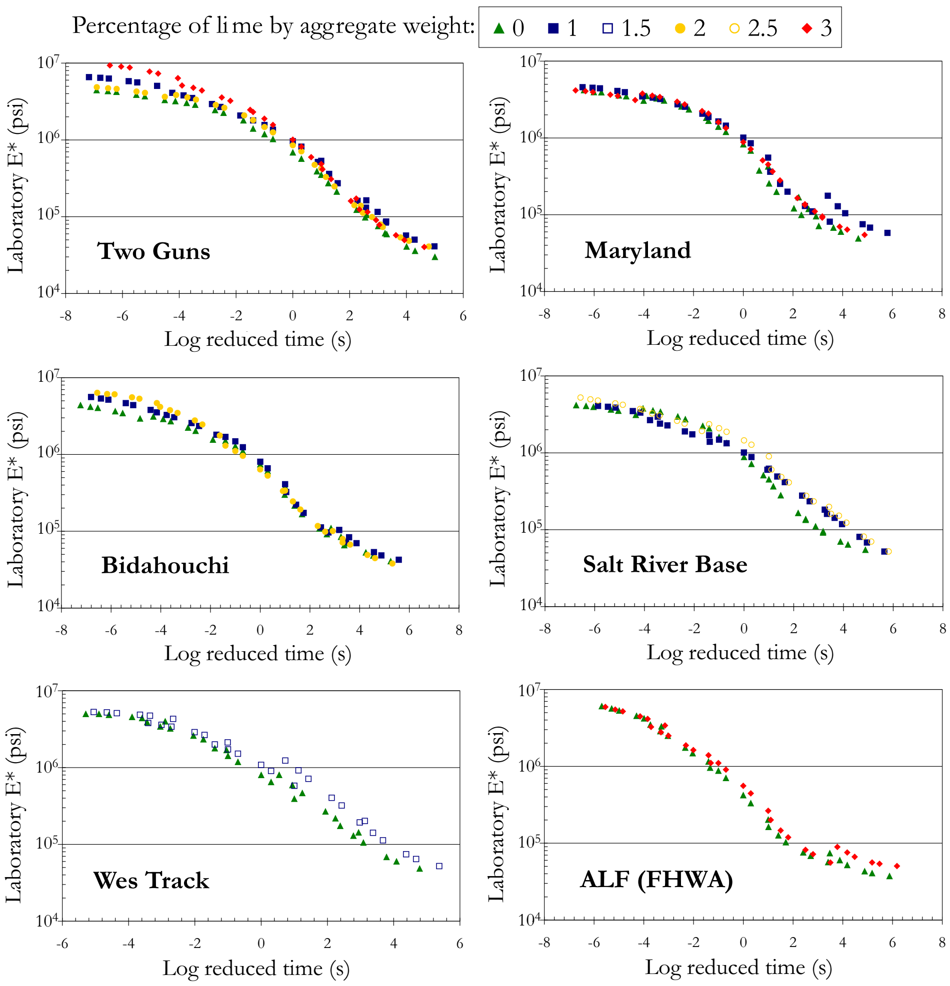

Figure 2. Master Curves for Lime-Modified Asphalt Mixtures

Across all mixtures and lime contents tested, the average E* ratio (lime modified to unmodified) is 1.25; in other words, lime modification increases dynamic modulus by an average of 25 percent. By mixture type, the increases ranged from 12 to 39 percent. At typical lime addition levels (1 and 1 ½ % by weight), dynamic modulus increases by an average of 21 percent.

The master curves of the average dynamic modulus for each mixture are shown in Figure 2. They illustrate that lime increases the dynamic modulus, especially when the load is applied over a short period of time or high frequency. The test results also confirm the hypothesis that the concept and use of the master curve are applicable to lime-modified HMA mixtures.

The M-E PDG uses a three level hierarchical input procedure for most inputs, including dynamic modulus. Level 1 inputs are the most comprehensive input level, using dynamic modulus obtained from a master curve constructed from laboratory dynamic modulus tests. Input levels 2 and 3 require asphalt binder and mixture volumetric properties to predict dynamic modulus using the Witczak predictive equation - see p. 4. The results from this study [6] show that with an easy adjustment in the asphalt viscosity, this equation can be used to accurately calculate the dynamic modulus of lime-modified HMA mixtures for different conditions.

Conclusions

Hydrated lime creates multiple benefits in asphalt mixtures. The recent study by Witczak and Bari demonstrates that the addition of lime to HMA enhances its dynamic modulus (E*), a primary material property used in the evaluation of the fatigue cracking, rutting, and thermal cracking behavior of flexible pavements in the M-E PDG. The study also demonstrates that the E* protocol proposed in the M-E PDG for unmodified HMA mixtures can be used to evaluate mixtures modified with hydrated lime at input Level 1. For input Level 2, the Witczak E* predictive equation can be used to compute the master curve of lime-modified mixtures from volumetric properties, gradation parameters, and lime-modified binder data. At input Level 3, the dynamic modulus for unmodified asphalts can be increased by a factor of 1.21 - 1.25 to reflect the expected benefits of lime modification.

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The Witczak Predictive Equation

The equation used in the new M-E PDG to calculate the dynamic modulus at different temperatures and loading frequencies for developing the master curve follows:

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

Where,
E* = dynamic modulus, 105 psi
η = asphalt viscosity at the age and temperature of interest, 106 Poise (use of RTFO aged viscosity is recommended for short-term oven aged lab blend mix)
f = loading frequency, Hz
Va = air void content, %
Vbeff = effective asphalt content, % by volume
ρ34 = cumulative % retained on 3/4 in (19 mm) sieve
ρ38 = cumulative % retained on 3/8 in 9.5 mm sieve
ρ4 = cumulative % retained on #4 (4.76 mm) sieve
ρ200 = % passing #200 (0.075 mm) sieve

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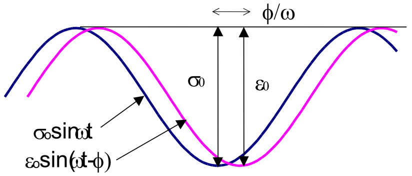
Dynamic Modulus

For linear viscoelastic materials, such as HMA mixtures, the stress-strain relationship under a continuous sinusoidal loading is defined by its complex dynamic modulus (E*). 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), $\sigma = \sigma_0 \sin(\omega\tau)$ and the amplitude of the sinusoidal strain $\varepsilon = \varepsilon_0 \sin(\omega\tau - \phi)$, at the same time and frequency, that results in a steady state response.



Thus, the complex dynamic modulus is mathematically expressed by the following equation:

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

Where:
σ_0 = Peak (maximum) stress
ε_0 = Peak (maximum) strain
φ = Phase angle, degrees
ω = Angular velocity
τ = Time, seconds

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 usually denoted as E* (not |E*|). HMA mixtures are viscoelastic and have both recoverable and irrecoverable responses, but only the recoverable strain is used to compute E*.