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16. Abstract <p>Fatigue cracking is a primary form of distress in hot-mix asphalt. The long-term nature of fatigue due to repeated loading and aging and its required tie to pavement structure present challenges in terms of evaluating mixture resistance. This project focused on comparing stiffness and fatigue life output from two recently developed approaches that use repeated direct tension tests: the Modified Calibrated Mechanistic with Surface Energy (CMSE*) approach and the Push-Pull Viscoelastic Continuum Damage (PP-VECD) approach.</p> <p>The CMSE* and the PP-VECD approaches were applied to both laboratory and field specimens for two mixtures, one from SH 24 in the Paris (PAR) District and one from US 277 in the Laredo (LRD) District of the Texas Department of Transportation, and the results were compared. Both approaches can be used to characterize mixture fatigue resistance with relatively low variability. Based on stiffness, both approaches predict better resistance (lower stiffness) for the PAR mixture based on laboratory results but that the mixtures would have equivalent resistance based on field results for the CMSE* approach. There was also good agreement between laboratory and field specimens for the LRD mixture.</p> <p>The two approaches define fatigue failure in different ways, and thus the rankings of mixture resistance may be different. For the CMSE* approach, the stiffer LRD mixture based on laboratory specimens results in a longer fatigue life, while for the PP-VECD approach, this mixture results in a shorter fatigue life. In addition, the PP-VECD approach outputs significantly lower fatigue lives than the CMSE* approach does due to differences in the analysis including critical strain values and accumulation of damage.</p> <p>The CMSE* approach only requires a single test sequence, and thus fewer resources in terms of specimens and time are needed. However, the PP-VECD approach is more user friendly in terms of the analysis, and some of the required inputs (E*) can be used to evaluate mixture resistance to other distresses. Field specimens can be tested and analyzed using both approaches. Ultimately, the laboratory approach used should tie to field performance.</p>					
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COMPARISON OF FATIGUE ANALYSIS APPROACHES FOR HOT-MIX ASPHALT TO ENSURE A STATE OF GOOD REPAIR

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TABLE OF CONTENTS

LIST OF FIGURES	vi
LIST OF TABLES	vii
DISCLAIMER.....	viii
ACKNOWLEDGMENTS	ix
1 INTRODUCTION.....	1
1.1 Project Problem Statement and Research Objectives	1
1.2 Background.....	1
1.3 Description of Contents	2
2 MATERIALS, MIXTURES, PAVEMENT STRUCTURES, AND SPECIMEN FABRICATION	3
2.1 Materials, Mixtures, and Pavement Structures	3
2.2 Specimen Fabrication.....	4
3 MODIFIED CALIBRATED MECHANISTIC WITH SURFACE ENERGY APPROACH.....	7
3.1 Laboratory Testing and Outputs	7
3.2 Other Inputs and Assumptions.....	8
4 PUSH-PULL VISCOELASTIC CONTINUUM DAMAGE APPROACH.....	11
4.1 Laboratory Testing and Outputs	11
Step 1. Load $ E^* $ Data.....	12
Step 2. Load Peak Stress-Strain Data	12
Step 3. Smooth Peak Stress-Strain Data	12
Step 4. Calculate C and S.....	12
Step 5. Fit Exponential Curve to C versus S Data	13
Step 6. Predict N_f at Different Temperatures, Frequencies, and Strain Levels....	13
Outputs	13
4.2 Other Inputs and Assumptions.....	13
5 RESULTS AND DISCUSSION	15
6 CONCLUSIONS AND RECOMMENDATIONS.....	19
REFERENCES.....	21

LIST OF FIGURES

	Page
Figure 1. Vertical Gluing Jig for Cylindrical LMLC Specimens (a) and Magnetic Gluing Vice for Prismatic Field Specimens (b).....	5
Figure 2. Test Setup for Cylindrical LMLC Specimens (a) and for Prismatic Field Specimens (b).....	7
Figure 3. CMSE* and PP-VECD Approach Results for E_{ve} (1 Hz and 20 °C).	16
Figure 4. CMSE* and PP-VECD Approach Results for Fatigue Life at 1 Hz and 20 °C (Critical Shear Strain Levels of 262 and 198 for CMSE* and Critical Tensile Strain Levels of 145 and 147 for PP-VECD for LRD and PAR, Respectively).	17

LIST OF TABLES

Page

Table 1. CMSE* and PP-VECD Approach Results..... 15

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EXECUTIVE SUMMARY

Fatigue cracking is a primary form of distress in hot-mix asphalt (HMA). With a better understanding of mixture resistance to this form of distress, state departments of transportation and other transportation agencies can better plan and use the most economical methods for extending the life of the pavement to provide a safer, efficient, and sustainable transportation system. The long-term nature of fatigue cracking due to repeated loading, the complication of aging that makes HMA mixtures more susceptible to this form of distress, and the required tie to pavement structure present challenges in terms of evaluating and predicting mixture resistance. Many different approaches have been used to capture mixture durability in terms of fatigue resistance, including analysis of repeated load tests by flexural bending beam, semi-circular bending, direct uniaxial tension, and indirect tension; although few studies have compared these approaches. This project focused on comparing stiffness and fatigue life output from two recently developed approaches that use repeated direct tension tests: the Modified Calibrated Mechanistic with Surface Energy (CMSE*) approach and the Push-Pull Viscoelastic Continuum Damage (PP-VECD) approach.

The CMSE* and the PP-VECD approaches for evaluating mixture fatigue resistance were applied to both laboratory and field specimens for two mixtures, one from SH 24 in the Paris (PAR) District and one from US 277 in the Laredo (LRD) District of the Texas Department of Transportation, and the results were compared. Both approaches that use direct uniaxial tension testing can be used to characterize HMA mixtures in terms of fatigue resistance with relatively low variability, especially if three replicate specimens are tested. Based on stiffness as an index parameter to indicate susceptibility to fatigue cracking, both approaches predict that the PAR mixture would have better resistance (lower stiffness) based on the laboratory results but that the mixtures would have approximately equivalent resistance based on the field results for the CMSE* approach. There was also good agreement between laboratory specimens and corresponding stiffness values for the field specimens for the LRD mixture. But for the PAR mixture, the results indicated a difference in specimen types that may be due to aging during the production and construction processes.

The two approaches define fatigue failure in different ways, and thus the rankings of mixture performance may be different. For the CMSE* approach, the stiffer LRD mixture based

on laboratory specimens results in a longer fatigue life, while for the PP-VECD approach, this same stiffer LRD mixture results in a shorter fatigue life. In addition, the PP-VECD approach outputs significantly lower fatigue lives than the CMSE* approach does due to differences in the analysis including the critical strain values and accumulation of damage in the analysis.

The CMSE* approach only requires a single test sequence (RDT*), and thus fewer resources in terms of number of specimens and testing time are needed when using this approach. However, the PP-VECD approach is more user friendly in terms of the analysis, and some of the required inputs (E^*) can be used to evaluate mixture resistance to other distresses. Field specimens can be tested and analyzed using both the CMSE* and the PP-VECD approaches. Ultimately, the laboratory approach used should tie to field performance.

1 INTRODUCTION

Fatigue cracking is a primary form of distress in hot-mix asphalt (HMA), but the long-term nature of fatigue from repeated loading with aging and its required tie to pavement structure present challenges in terms of evaluating and predicting mixture resistance. Many different approaches have been used to capture mixture durability in terms of fatigue resistance, including analysis of repeated load tests by flexural bending beam, semi-circular bending, direct uniaxial tension, and indirect tension; although few studies have compared these approaches (Walubita et al. 2005a, 2007, 2010, 2011). This project focused on comparing stiffness and fatigue life output from two recently developed approaches that use repeated direct tension tests: the Modified Calibrated Mechanistic with Surface Energy (CMSE*) approach and the Push-Pull Viscoelastic Continuum Damage (PP-VECD) approach.

1.1 PROJECT PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Mix design and analysis of HMA mixtures can be further improved to better guarantee adequate fatigue resistance. With a better understanding of mixture resistance to fatigue, state departments of transportation and other transportation agencies can plan and prepare the most economical methods for extending the life of the pavement, which can provide a safer, more economical, and sustainable transportation system. The objectives of this project were to apply two advanced approaches for evaluating mixture fatigue resistance to both laboratory and field specimens, compare the results for two mixtures, and identify advantages and disadvantages for both approaches.

1.2 BACKGROUND

Assessment of the HMA fatigue resistance and quantification of the effects of aging on this resistance have been a research focus at the Texas A&M Transportation Institute and Texas A&M University over the past decade. Three multi-year projects that addressed these issues were sponsored by the Texas Department of Transportation (TxDOT) and include TxDOT Project 0-4468, Evaluate the Fatigue Resistance of Rut Resistant Mixes; TxDOT Project 0-4688, Development of a Long-Term Durability Specification for Modified Asphalt; and TxDOT Project 0-6009, Development and Calibration of a Laboratory Test to Assess Binder Aging and

Treatments to Reduce Aging of Binders. TxDOT Projects 0-4468 and 0-4688 were completed after three years in 2005 and after two years in 2006, respectively, and TxDOT Project 0-6009 concluded in 2012 after a five-year effort. TxDOT Project 0-4468 recommended a fatigue analysis system for HMA mixtures based on a comparison of the fatigue resistance of two commonly used mixtures determined using four approaches (Walubita et al. 2006a, 2006b, 2006c, 2006d). These approaches included a mechanistic-empirical approach with flexural fatigue testing, the *Proposed 2002 Mechanistic-Empirical Pavement Design Guide* model using dynamic modulus testing, and calibrated mechanistic approaches that use uniaxial creep, tensile strength, and repeated uniaxial direct tensile tests with and without surface energy measurements of the component materials. This project also focused on quantitatively incorporating the effects of aging on mixture fatigue resistance. TxDOT Project 0-4688 further examined the effects of binder aging on mixture durability in terms of fatigue resistance (Woo et al. 2007).

More recently, the Asphalt Research Consortium sponsored by the Federal Highway Administration further developed the CMSE* approach that was applied in a parallel effort in TxDOT Project 0-6009 (Glover et al. 2009, 2013; Luo et al. 2013a, 2013b, 2013c, 2013d, 2013e). In both of these projects, the main objectives were to continue to quantify the effects of aging on HMA durability as measured by fatigue resistance. In TxDOT Project 0-6009, the effects of aging on the fatigue resistance of laboratory-produced specimens used for mix design was compared with those for field samples whose testing methodology was also developed in the project. In addition, the effects of trafficking and aging on mixture fatigue resistance were explored by examining field samples taken from the wheel path and the shoulder, and the effects of chip seals on aging and fatigue resistance were explored by examining field samples taken from adjacent treated and untreated field sections.

1.3 DESCRIPTION OF CONTENTS

Following this introduction section, the report describes the materials, mixtures, and specimens used. Next, the CMSE* and the PP-VECD approaches are described including laboratory tests, inputs, assumptions, and outputs. Then the results are provided for both laboratory and field specimens in terms of stiffness and fatigue life, and a discussion comparing these results is offered. A summary and conclusions complete the report.

2 MATERIALS, MIXTURES, PAVEMENT STRUCTURES, AND SPECIMEN FABRICATION

2.1 MATERIALS, MIXTURES, AND PAVEMENT STRUCTURES

Materials for this project were selected from those used in two field sections in Texas on US 277 in the Laredo District of TxDOT and SH 24 in the Paris District of TxDOT. At the time of construction, raw materials from each section were collected for the fabrication of laboratory mixed-laboratory compacted (LMLC) specimens. Field cores were taken immediately following construction.

US 277 was constructed in 2008 with the Laredo (LRD) District mixture that was designed as a dense-graded coarse TxDOT Type C mixture (TxDOT 2004) in the following pavement structure with assumed material properties as noted:

- 3-inch (75-mm) TxDOT Type C surface course ($E=500,000$ psi [3448 MPa], $\nu=0.33$) on top of a chip seal.
- 12 inches (300 mm) of cement-treated base (CTB) ($E=100,000$ psi [690 MPa], $\nu=0.35$).
- 6 inches (150 mm) of flexible base ($E=50,000$ psi [345 MPa], $\nu=0.35$).
- Existing subgrade ($E= 10,000$ psi [69 MPa], $\nu=0.45$).

Aggregates for this mixture consisted of a blend of three different aggregate fractions from a limestone quarry and a fourth fraction of manufactured sand from a second source. Binder for this mixture consisted of a PG 70-22 binder with an optimum asphalt content of 4.5 percent by weight of mix using the Superpave volumetric mix design method. In addition, 0.5 percent liquid anti-stripping agent by weight of binder was also added to this mixture. The climate is dry and warm at this field section with an annual average high temperature of 86.3 °F (30.2 °C) and annual average precipitation of 21.5 inches (545 mm) (Belsoft and Styleshout 2012).

SH 24 was constructed in 2009 with the Paris (PAR) mixture that was designed as a dense-graded finer TxDOT Type D mixture (TxDOT 2004) in the following pavement structure with assumed material properties as noted:

- 2-inch (50-mm) TxDOT Type D surface course ($E=500,000$ psi [3448 MPa], $\nu=0.33$) on top of a chip seal.

- 2 inches (50 mm) of a coarser Type B mixture ($E=500,000$ psi [3448 MPa], $\nu=0.33$).
- 11 inches (275 mm) of CTB ($E=100,000$ psi [690 MPa], $\nu=0.35$).
- 8 inches (200 mm) of lime-treated subgrade ($E=30,000$ psi [345 MPa], $\nu=0.40$).
- Existing subgrade ($E= 10,000$ psi [69 MPa], $\nu=0.45$).

Aggregates for this mixture consisted of a blend of three different aggregate fractions from a sandstone source. Binder for this mixture consisted of a PG 64-22 binder with an optimum asphalt content of 5.4 percent by weight of mix using the Superpave volumetric mix design method. In addition, 1.0 percent liquid anti-stripping agent by weight of binder was also added to this mixture. The climate is wet and cool at this field section with an annual average high temperature of 74.0 °F (23.4 °C) and annual average precipitation of 47.8 inches (1214 mm) (Belsoft and Styleshout 2012).

2.2 SPECIMEN FABRICATION

Aggregates used for the LMLC specimens were placed in an oven at the mixing temperature of 149° C and were left overnight in order to remove any moisture. The binder was also heated to the same mixing temperature for 2 hours just prior to mixing. The mixture was then short-term oven aged at the compaction temperature of 135 °C for 4 hours as prescribed by American Association of State Highway and Transportation Officials (AASHTO) R30 for performance testing. LMLC specimens were fabricated using the Superpave gyratory compactor to 152 mm in diameter by 152 mm in height, and then cored and trimmed to a 102-mm diameter and 102-mm height for a more uniform air void (AV) distribution with a target AV content between 5 and 7 percent. The LMLC specimens were next placed in vertical gluing jigs to attach and align steel platens to the ends of the specimens such that eccentricities during direct tension testing were minimized (Figure 1). Following sufficient drying time, three linear variable displacement transducers (LVDTs) with a gauge length of 51 mm were glued vertically and equidistant around the cylindrical specimen.

Field cores were trimmed into a prismatic shape to allow the specimens to be tested in the same direction that they would experience tension in the field. Special care was taken during cutting to ensure that the specimen sides were as close to parallel as possible. A horizontal magnetic gluing vice was used to align and glue steel platens to the ends of the specimens to

again minimize eccentricities during direct tension testing that could be caused by small discrepancies in the specimen introduced during the trimming process (Figure 1). LVDTs were placed with a 51-mm gauge length on each of the long sides of the specimen to measure vertical displacement during testing.

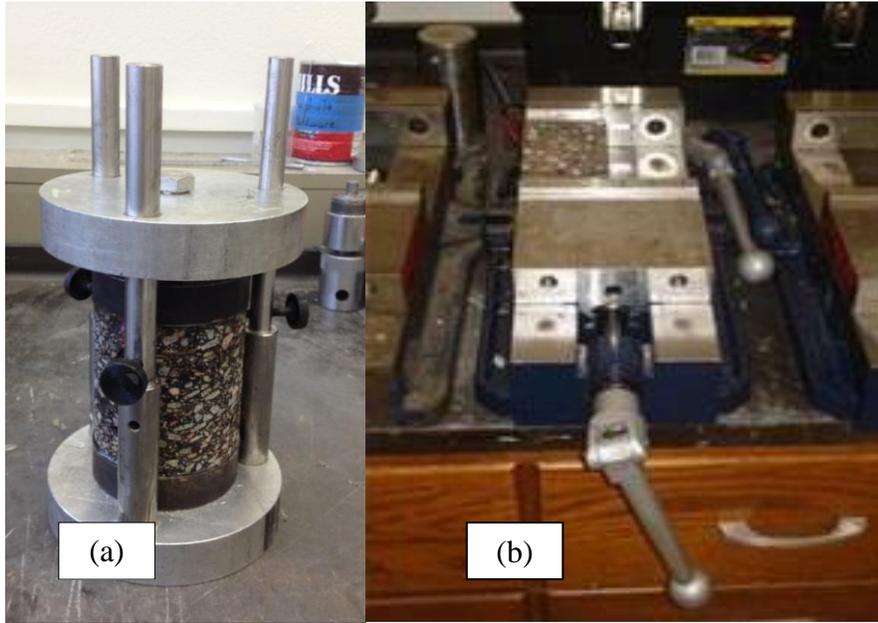


Figure 1. Vertical Gluing Jig for Cylindrical LMLC Specimens (a) and Magnetic Gluing Vice for Prismatic Field Specimens (b).

3 MODIFIED CALIBRATED MECHANISTIC WITH SURFACE ENERGY APPROACH

3.1 LABORATORY TESTING AND OUTPUTS

In order to calculate the stiffness and fatigue properties of LMLC and field specimens by the CMSE* approach, two mixture tests were performed. Viscoelastic characterization (VEC) and repeated direct tension (RDT*) tests were performed using a servo-hydraulic testing machine. A ball and socket joint was used to minimize the effects of specimen eccentricity and undesirable moments for both types of specimens that were carefully fabricated to also minimize eccentricities (Figure 2).

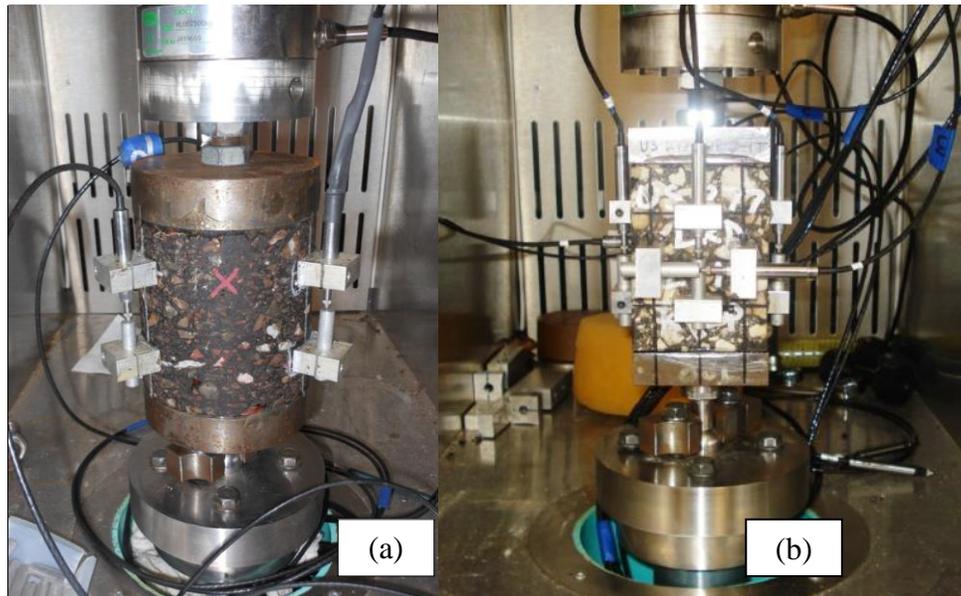


Figure 2. Test Setup for Cylindrical LMLC Specimens (a) and for Prismatic Field Specimens (b)

The VEC test and analysis were originally developed at Texas A&M University for application to LMLC specimens (Luo et al. 2008, Luo and Lytton 2010). Modifications were later made to this test for application to field specimens cut from cores (Lawrence 2009, 2012). The VEC test was performed by applying a monotonically increasing tensile load to a specimen at a displacement rate of $50.8 \mu\text{m}$ per minute. The test continued at this rate until one of the measuring LVDTs reached a strain level of $100 \mu\epsilon$. It is assumed that at this small strain level, no damage occurs, and the specimen can be used in further testing (Luo and Lytton 2010). The

specimen was initially conditioned and tested at 10 °C. Once the test was completed, the specimen was reconditioned for a minimum of 2 hours and retested at 20 °C and 30 °C using the same procedure. Recorded load and displacement data from the LVDTs for each temperature were used to calculate stress and strain. These values were averaged and defined using a fitting curve at each temperature. Fitting parameters from these curves were then used, in conjunction with Laplace transformations and calculated shift factors, to determine the relaxation modulus (E_r) master curve and the complex modulus (E^*) master curve at 20 °C.

The RDT* test was also developed at Texas A&M University originally for LMLC specimens and then further refined for application to field specimens (Luo et al. 2008; Lawrence 2009, 2012). The RDT* test was performed on a specimen preconditioned at 20 °C. The specimen was exposed to a haversine load in displacement control mode with a maximum vertical strain level of 30 $\mu\epsilon$ for 50 cycles at a frequency of 1 Hz. For a 51-mm LVDT gauge length, this small strain of 30 $\mu\epsilon$ is a change in gauge length of approximately 1.5 μm . This portion of the test was used to calculate the undamaged viscoelastic phase angle and the undamaged dynamic modulus (E_{ve}) of the mixture. Following the 50 cycles at 30 $\mu\epsilon$, a 1000-cycle haversine loading was applied at a frequency of 1 Hz with a maximum strain level of 175 $\mu\epsilon$. For a 51-mm LVDT gauge length, this higher strain of 175 $\mu\epsilon$ is a change in gauge length of approximately 8.9 μm . At the completion of the test, the specimen was damaged and could not be retested. Data obtained from the RDT* test were averaged and filtered using a low-pass filter to remove machine noise and facilitate automated data processing. The damaged portion of the RDT* test (a higher strain level of 175 $\mu\epsilon$) was used in combination with the results of the undamaged portion of the test to determine fracture properties, such as Paris' law fracture coefficient, A ; Paris' law exponent, n ; and the rate of damage accumulation, b . These were then used in the CMSE* model to calculate N_f (Luo et al. 2008, Walubita et al. 2005b).

3.2 OTHER INPUTS AND ASSUMPTIONS

In the CMSE* approach, N_f is determined when cracks have propagated through the thickness of the surface pavement layer. In addition, the CMSE* approach considers pavement structure through the maximum shear strain at the edge of the tire because this approach assumes that the shear strains that occurs before and after the bending strain as a wheel load passes are dominant and propagate fatigue cracks. This maximum shear strain was calculated under a single

tire of an equivalent single axle load (ESAL) using the pavement analysis software WinJULEA and the assumed pavement layer material properties provided in the previous section. For the LRD and PAR mixtures, the calculated maximum shear strains were 262 $\mu\epsilon$ and 198 $\mu\epsilon$, respectively.

Furthermore, the CMSE* approach accumulates damage in terms of crack propagation only in tension and separates the damage that accumulates during tensile loading and the damage during compressive loading used to push the specimen back to its original position in the controlled strain RDT* test. This repeated load test in direct uniaxial tension has relatively small variability for a repeated load test with a coefficient of variation (COV) of $\ln N_f$ of 3 percent (Walubita et al. 2005a).

4 PUSH-PULL VISCOELASTIC CONTINUUM DAMAGE APPROACH

4.1 LABORATORY TESTING AND OUTPUTS

A uniaxial tension compression or push-pull fatigue test has been used to apply the VECD theory in a simple, efficient, and less expensive fashion as compared to the traditional fatigue beam test (Kutay et al. 2008, Kutay 2011). The PP-VECD approach consists of the following steps and uses the same test setup as the RDT* in the CMSE* approach (Figure 2a):

- 1) Run $|E^*|$ tests per AASHTO TP-79 (or AASHTO T-342).
- 2) Run push-pull tests at various temperatures and strain levels.
- 3) Analyze the data using the PP-VECD software.
- 4) Calibrate the fatigue life formulation:

$$N_f = a(\varepsilon)^b(E)^c \quad \text{(Equation 1)}$$

where a , b , and c are regression constants.

Although each pull-push test is performed at a constant frequency, strain, and temperature; the PP-VECD approach recommends conducting several push-pull tests at different temperatures and strain levels to calibrate the damage characteristic curve and predict fatigue performance at other strain levels and temperatures. In the PP-VECD approach, the fatigue life formulation (number of cycles to fatigue failure, N_f) shown in Equation 1 is defined as 50 percent reduction in stiffness.

The selected temperatures and strain levels for the LMLC specimens used in this project were:

- 15 °C, 1 Hz, 150 $\mu\varepsilon$, and 1000 load cycles.
- 20 °C, 1 Hz, 200 $\mu\varepsilon$, and 1000 load cycles.

Two replicates were tested at each condition. The push-pull tests were preceded by a 1-Hz, 30- $\mu\varepsilon$, 50-load-cycle tension-only cyclic RDT* test at the same temperature that the push-pull tests were performed. A rest period of 5 minutes was introduced between the tension-only and push-pull tests. The objective of the low-strain tension-only test was to compare the E_{ve} obtained with the set of specimens subjected to the PP-VECD approach versus the E_{ve} obtained with the

specimens subjected to the CMSE* approach, and to capture any differences between the specimens that were tested over a long 2- to 3-year period.

The PP-VECD software is a user-friendly interface that facilitates processing and analyzing the laboratory data. It is designed as a step-by-step approach to make it easy to follow. The steps are as follows.

Step 1. Load $|E^*|$ Data

This step is performed by copying/pasting from a spreadsheet or other database the following information: temperature ($^{\circ}\text{C}$), frequency (Hz), modulus (MPa), and phase angle (deg). Once the data are input, the user selects a reference temperature for the $|E^*|$ master curve. The software then develops the $|E^*|$ and phase angle master curves. It also converts $|E^*|$ to $E(t)$ (i.e., relaxation modulus master curve) to obtain α , the slope of the maximum $E(t)$ versus time curve, which is a key input in the VECD approach.

Step 2. Load Peak Stress-Strain Data

This step is performed by loading an asphalt mixture performance tester device datafile (.csv file) or by copying/pasting from a spreadsheet or other database the cycle number, loading stress (kPa), and microstrain values. Each replicate is loaded and saved separately, and the user inputs the temperature and frequency of each replicate data set.

Step 3. Smooth Peak Stress-Strain Data

The objective of this step is to eliminate machine noise from the peak stress-strain data. The user selects which portion of the data is used for the calculation.

Step 4. Calculate C and S

In this step the default damage exponent, α , calculated in Step 1 or a different user-specified value is used to generate the C and S curves. One C versus S curve is generated for each set of peak stress-strain data. C represents a reduction in modulus due to S, which is the damage internal state variable that represents microcrack development within the mixture. In other words, C versus S is a representation of how the modulus of the mixture changes as microcracks develop. Since C versus S is proposed as a fundamental material property that governs damage growth under all conditions—regardless of stress level, strain level, frequency/rate, or temperature—the C versus S curves obtained from the stress-strain data

collected at various temperatures and strain levels should collapse to a single curve. If that is not the case, different α values are input until this objective is met.

Step 5. Fit Exponential Curve to C versus S Data

The exponential function shown in Equation 2 is fit to the C versus S data. The two constants, a and b , in Equation 2 are the VECD calibration constants:

$$C = \exp(aS^b) \quad \text{(Equation 2)}$$

Step 6. Predict N_f at Different Temperatures, Frequencies, and Strain Levels

The user inputs the desired frequency, temperature, and microstrain levels to predict N_f . The software then generates a three-dimensional damage or failure surface showing microstrain, temperature, and number of cycles to failure. In addition, a spreadsheet is also generated, which is used to calibrate the fatigue life and obtain the constants for the fatigue life formulation (Equation 1).

Outputs

The PP-VECD approach can be used to compare HMA pavements of different thicknesses or in forensic investigations to evaluate mixtures in terms of N_f . Other features include exporting E^* and phase angle master curves, relaxation modulus master curves, smoothed push-pull data, and C versus S curves. Although field specimens were not tested for analysis by the PP-VECD approach in this project, they can be (Kutay et al. 2009).

4.2 OTHER INPUTS AND ASSUMPTIONS

The main output of the PP-VECD software is the number of cycles to failure, N_f , at one or a number of selected temperatures, frequencies, and strain levels. For comparison with the CMSE* data, a temperature of 20 °C, frequency of 1 Hz, and strain level based on the pavement structure were selected. The maximum tensile strain that occurs under a single tire of an ESAL using WinJULEA with the assumed pavement layer material properties provided previously was considered. For the LRD and PAR mixtures, the calculated maximum tensile strains were 145 $\mu\epsilon$ and 147 $\mu\epsilon$, respectively.

As previously noted, in the PP-VECD approach N_f is calculated assuming failure occurs when there is a 50 percent reduction in stiffness. Another important assumption of the PP-VECD

approach is that damage occurs in both tension and compression, and thus the analysis uses the entire compression and tension portions of the cyclic test.

5 RESULTS AND DISCUSSION

Results for laboratory and field specimens for both the CMSE* and the PP-VECD approaches are shown in Table 1. Results for the laboratory specimens represent the recommended protocols as described in the previous sections. Estimates of the variability and the number of replicates for which data were available are also provided.

Table 1. CMSE* and PP-VECD Approach Results.

Mixture	Approach	Specimen Type (Number of Replicates)	E_{ve} (MPa) Avg. (COV)	N_f Avg. (COV of Ln N_f)
LRD	CMSE*	Laboratory (n=2)	4758 [@] (5.2%)	2.98 * 10 ^{6#} (9.2%)
		Field (n=2)	4552 [@] (11.7%)	5.46 * 10 ^{6#} (3.2%)
		PP-VECD specimens (n=2)	5475 [@] (1.1%)	N/A
	PP-VECD	Laboratory (n=2)	5829 [§] (N/A)	8.74 * 10 ^{4*} (18%) (n=3)
PAR	CMSE*	Laboratory (n=2)	2855 [@] (10.3%)	1.11 * 10 ^{7#} (0.1%)
		Field (n=3)	4764 [@] (2.0%)	2.41 * 10 ^{7#} (2.3%)
		PP-VECD specimens (n=2)	3497 [@] (8.9%)	N/A
	PP-VECD	Laboratory (n=2)	3670 [§] (N/A)	9.29 * 10 ^{3*} (12%) (n=4)

[@] E_{ve} at 1 Hz, 20 °C from cyclic tension-only RDT* test run at 30 $\mu\epsilon$ for 50 load cycles

[§] E_{ve} at 1 Hz, 20 °C from compression-only |E*| test (AASHTO TP-79) reported by the PP-VECD software

[#] N_f to propagate through surface pavement layer with critical shear strain values of 262 $\mu\epsilon$ and 198 $\mu\epsilon$ for LRD and PAR, respectively

^{*} N_f to 50% reduction in stiffness with critical tensile strain values of 145 $\mu\epsilon$ and 147 $\mu\epsilon$ for LRD and PAR, respectively

Based on the results shown in Table 1, the COV for the parameters output from the CMSE* approach were low, especially considering the use of a repeated load test. As illustrated in Figure 3, when comparing the E_{ve} results for the laboratory specimens that were both analyzed

using CMSE* protocols, the PP-VECD approach results are higher than those from the CMSE* approach. This difference likely reflects aging of the specimens over the multi-year period between testing by the different approaches. For these stiffness values, there is good agreement between laboratory specimens and corresponding values for the field specimens for the LRD mixture. But the same is not true for the PAR mixture, with the results indicating a difference in specimen types that may be due to aging during the production and construction processes. If stiffness was used as an index parameter to indicate susceptibility to fatigue cracking, the ranking of these two mixtures for both approaches would predict that the PAR mixture would have better resistance (lower stiffness) based on the laboratory results but that the mixtures would have approximately equivalent resistance based on the field results for the CMSE* approach. It should be noted that the E_{ve} value used for this comparison of rankings is tensile for the CMSE* approach and compressive for the PP-VECD approach. These stiffness values are not equivalent as shown by Luo et al. (2013a). The COV values for E_{ve} also highlight the importance of increasing the number of replicates from two to three.

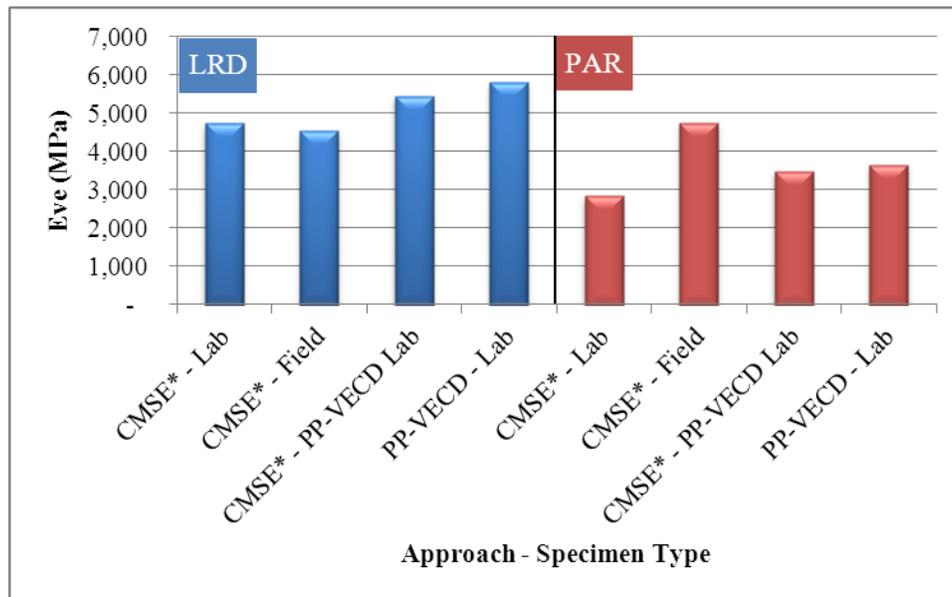


Figure 3. CMSE* and PP-VECD Approach Results for E_{ve} (1 Hz and 20 °C).

The results in Table 1 and Figure 4 also show the interrelationship between stiffness and N_f for the two approaches. For the CMSE* approach, the stiffer LRD mixture based on laboratory specimens results in a longer fatigue life, while for the PP-VECD approach, this same stiffer LRD mixture results in a shorter fatigue life. Thus, if fatigue life was used as a durability

parameter to indicate susceptibility to fatigue cracking, the ranking of these two mixtures would be different for both approaches, with the PAR mixture predicted to have longer fatigue life for the CMSE* approach and the LRD mixture predicted to have longer fatigue life for the PP-VECD approach. In addition, the PP-VECD approach outputs significantly lower fatigue lives than the CMSE* approach does. These differences result from differences in the analysis including the critical strain values (shear strain at the edge of the tire in the CMSE* approach and tensile strain at the bottom of the HMA layer in the PP-VECD approach), accumulation of damage (in tension only in the CMSE* approach and in both tension and compression in the PP-VECD approach), and definition of failure (propagation through the surface pavement layer in the CMSE* and 50 percent reduction in stiffness in the PP-VECD approach).

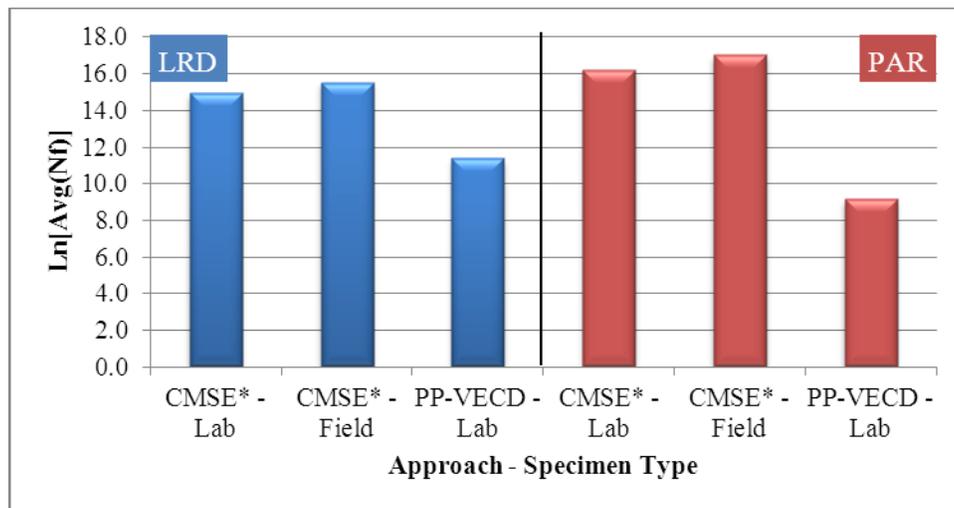


Figure 4. CMSE* and PP-VECD Approach Results for Fatigue Life at 1 Hz and 20 °C (Critical Shear Strain Levels of 262 and 198 for CMSE* and Critical Tensile Strain Levels of 145 and 147 for PP-VECD for LRD and PAR, Respectively).

An attempt was made to analyze the CMSE* approach laboratory results collected for field specimens with the PP-VECD approach to highlight the difference between the approaches. However, the CMSE* approach does not require testing to determine E* and estimates this value from VEC tests described previously. Therefore, the E* estimate from the CMSE* approach yields testing temperatures and frequencies that are not equivalent to standard E* testing conditions. From the trials performed in this study, it was found that the PP-VECD approach fatigue life formulation is highly dependent on the E* input (perhaps due to the definition of

failure), and thus, no reasonable N_f values were obtained when the E^* estimates from the CMSE* approach were used in the analysis.

6 CONCLUSIONS AND RECOMMENDATIONS

This project compared the CMSE* and the PP-VECD approaches for evaluating HMA mixture fatigue resistance. The following conclusions and recommendations are based on these analysis approaches with laboratory test data for two mixtures gathered for both laboratory and field specimens:

- Either approach that uses direct uniaxial tension testing can be used to characterize HMA mixtures in terms of fatigue resistance with relatively low variability.
- The CMSE* approach only requires a single test sequence (RDT*), and thus fewer resources in terms of number of specimens and testing time are needed when using this approach.
- The PP-VECD approach is more user friendly in terms of the analysis, and some of the required inputs (E^*) can be used to evaluate mixture resistance to other distresses.
- The two approaches define fatigue failure in different ways, and thus the user must be aware of the implications on the rankings of different mixtures due to this difference. Ultimately, the laboratory approach used should tie to field performance.
- Field specimens can be tested and analyzed using both the CMSE* and the PP-VECD approaches (even though field samples were not tested using the PP-VECD approach in this project).

REFERENCES

- Belsoft and Styleshout (2012). U.S. Climate Data, Temperature-Precipitation-Sunshine. <http://www.usclimatedata.com/>, accessed July 3, 2012.
- Glover, C. J., A. Epps Martin, A. Chowdhury, R. Han, N. Prapaitrakul, X. Jin, and J. Lawrence (2009). Evaluation of Binder Aging and Its Influence on Aging of Hot Mix Asphalt Concrete: Literature Review and Experimental Design. Research Report 0-6009-1, Texas Transportation Institute, February.
- Glover, C. J., N. Prapaitrakul, R. Han, X. Jin, Y. Cui, A. Rose, J. Lawrence, M. Padigala, E. S. Park, E. Arambula, and A. Epps Martin (2013). Evaluation of Binder Aging and Its Influence in Aging of Hot Mix Asphalt Concrete: Technical Report. Research Report 0-6009-2, Texas A&M Transportation Institute.
- Kutay, E. (2011). “Practical Fatigue Characterization of Asphalt Mixtures Using PP_VECD (Push-Pull Test Based Viscoelastic Continuum Damage Analysis) Software.” In *Advanced Models to Characterize and Design Asphalt Pavements: Implementation and Application Examples*, webinar, Transportation Research Board, the National Academies, October.
- Kutay, M. E., N. Gibson, and J. Youtcheff (2008). “Conventional and Viscoelastic Continuum Damage (VECD)-Based Fatigue Analysis of Polymer Modified Asphalt Pavements.” *Journal of the Association of Asphalt Paving Technologists*, Vol. 77, pp. 395–434.
- Kutay, M. E., N. H. Gibson, J. Youtcheff, and R. Dongre (2009). “Use of Small Samples to Predict the Fatigue Lives of Field Cores: Newly Developed Formulation Based on Viscoelastic Continuum Damage Theory.” *Transportation Research Record* 2127, pp. 90–97.
- Lawrence, J. L. (2009). *Advanced Tools for Characterizing HMA Fatigue Resistance*. M.S. Thesis, Texas A&M University.
- Lawrence, J. L. (2012). *Application of Direct Tension Testing to Field Samples to Investigate the Effects of HMA Aging*. Ph.D. Dissertation, Texas A&M University.
- Luo, R., and R. L. Lytton (2010). “Characterization of the Tensile Viscoelastic Properties of an Undamaged Asphalt Mixture.” *Journal of Transportation Engineering*, Vol. 136, No. 3, p. 173–80.

- Luo, X., A. Epps Martin, R. Luo, R. L. Lytton, and C. J. Glover (2008). Aging Experiment Design Including Revised CMSE* Testing Protocols and Analysis to Characterize Mixture Fatigue Resistance. Report No. FHWA-DTFH61-07H-0009, U.S. Department of Transportation, Federal Highway Administration.
- Luo, X., R. Luo, and R. L. Lytton (2013a). “Characterization of Asphalt Mixtures Using Controlled-Strain Repeated Direct Tension Test.” *Journal of Materials in Civil Engineering*, ASCE, Vol. 25, No. 2, pp. 194–207.
- Luo, X., R. Luo, and R. L. Lytton (2013b). “Characterization of Fatigue Damage in Asphalt Mixtures Using Pseudo Strain Energy.” *Journal of Materials in Civil Engineering*, ASCE, Vol. 25, No. 2, pp. 208–218.
- Luo, X., R. Luo, and R. L. Lytton (2013c). “Energy-Based Mechanistic Approach to Characterize Crack Growth of Asphalt Mixtures.” *Journal of Materials in Civil Engineering*, ASCE, Vol. 25, No. 9, pp. 1198–1208.
- Luo, X., R. Luo, and R. L. Lytton (2013d). “Characterization of Recovery Properties of Asphalt Mixtures.” *Construction and Building Materials*, Vol. 48, pp. 610–621.
- Luo, X., R. Luo, and R. L. Lytton (2013e). “A Modified Paris’ Law to Predict Entire Crack Growth in Asphalt Mixtures.” *Transportation Research Record*, accepted for publication.
- TxDOT (2004). Texas Department of Transportation Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges.
- Walubita, L. F., A. Epps Martin, S. Jung, C. Glover, E. S. Park, A. Chowdhury, and R. Lytton (2005a). Comparison of Fatigue Analysis Approaches for Two Hot Mix Asphalt Concrete (HMAC) Mixtures. Research Report 0-4468-2, Texas Transportation Institute, August.
- Walubita, L. F., A. Epps Martin, S. H. Jung, C. J. Glover, R. L. Lytton, and G. S. Cleveland (2005b). “Fatigue Characterization of Asphalt Concrete Using Mechanistic Empirical and Calibrated Mechanistic Approaches Including the Effects of Aging.” *Asphalt Concrete GSP 146*, R. Lytton Symposium, June 1–3, p. 11.
- Walubita, L. F., A. Epps Martin, G. Cleveland, and R. Lytton (2006a). “Computation of Pseudo Strain Energy and Paris Law Fracture Coefficients from Surface Energy and Uniaxial Strain-

- Controlled Tension Test Data.” *International Journal of Pavement Engineering*, Vol. 7, No. 3, pp. 167–178.
- Walubita, L. F., A. Epps Martin, C. Glover, S. Jung, G. Cleveland, R. Lytton, and E. S. Park (2006b). “Application of the Calibrated Mechanistic Approach with Surface Energy (CMSE) Measurements for Fatigue Characterization of Asphalt Mixtures.” *Journal of the Association of Asphalt Paving Technologists*, Vol. 75, pp. 457–490.
- Walubita, L. F., A. Epps Martin, C. Glover, S. Jung, G. Cleveland, and R. Lytton (2006c). “Modeling the Fatigue Resistance of Hot-Mix Asphalt Concrete (HMA) Mixtures Including the Effects of Aging.” *Proceedings of the 10th International Conference on Asphalt Pavements*, Quebec, Canada, August 12–17.
- Walubita, L. F., A. Epps Martin, S. Jung, C. Glover, and E. S. Park (2006d). *Application of Calibrated Mechanistic Fatigue Analysis with Aging Effects*. Research Report 0-4468-3, Texas Transportation Institute, July.
- Walubita, L. F., A. Epps Martin, and M. Mikhail (2007). “Investigation of a Surrogate Fatigue Test Protocol for Asphalt Mix-Design and Mixture Screening.” *Proceedings of the International Conference on Advanced Characterization of Pavement and Soil Engineering Materials*, Athens, Greece, June 20–27.
- Walubita, L. F., V. Umashankar, X. Hu, B. Jamison, F. Zhou, T. Scullion, A. Epps Martin, and S. Dessouky (2010). *New Generation Mix-Designs: Laboratory Testing and Construction of the APT Test Sections*. Research Report 0-6132-1, Texas Transportation Institute, March.
- Walubita, L. F., B. P. Jamison, G. Das, T. Scullion, A. Epps Martin, D. Rand, and M. Mikhail (2011). “Search for a Laboratory Test to Evaluate Crack Resistance of Hot Mix Asphalt.” *Transportation Research Record* 2210, p. 73–80.
- Woo, W. J., E. Ofori-Abebrese, A. Chowdhury, J. Hilbrich, Z. Kraus, A. Epps Martin, and C. J. Glover (2007). *Polymer Modified Asphalt Durability in Pavements*. Research Report 0-4688-1, Texas Transportation Institute, July.