Comparison of Conventional, Polymer, and Rubber Asphalt Mixtures Using Viscoelastic Continuum Damage Model

Waleed Zeiada¹, Shane Underwood², Tina Pourshams¹, Jeffrey Stempilhar¹ and Kamil Kaloush³

¹Graduate Research Associate
²Assistant Professor
³Associate Professor
Arizona State University
Department of Civil and Environmental Engineering
PO Box 875306
Tempe, AZ 85287-5306 USA
wzeiada@asu.edu; wzeiada@mans.edu.eg

ABSTRACT. In this study, a laboratory experimental program was conducted to compare the material properties and fatigue performance characteristics for reference, polymer-modified and rubber-modified gap graded mixtures. These mixtures were placed on E18 highway between the interchanges Järva Krog and Bergshamra in the Stockholm area of Sweden. The advanced material characterization tests included: dynamic (complex) modulus for stiffness evaluation and the uniaxial tension-compression for fatigue assessment. The data was used to compare the performance of the rubber-modified gap graded mixture to the reference and the polymer-modified gap mixtures using the viscoelastic continuum damage (VECD) approach. Different researchers have successfully applied the VECD model to describe the fatigue behavior of asphalt concrete mixtures. The damage characteristic (C-S) curves were established for each of the three mixtures. The fatigue behavior for the three mixtures was ranked based on the C-S curve results and the rubber-modified mixture showed the best fatigue damage resistance followed by the polymer-modified mixture and the reference mixture. The VECD approach provides a more comprehensive analysis to evaluate fatigue resistance compared to tradition fatigue evaluation using a number of cycles at a given stiffness reduction.

KEYWORDS: Fatigue, rubber-modified, polymer-modified, dynamic modulus, viscoelastic continuum damage
1. Introduction

Load-associated fatigue cracking is considered to be one of the most significant distress modes in flexible pavements besides thermal cracking and rutting. The action of repeated loading, caused by traffic induced tensile and shear stresses in the bound layers, will eventually lead to a loss in the structural integrity of a stabilized layer material. Fatigue cracking is a progressive distress and can be distinguished into three different stages. An early stage of fatigue cracking consists of intermittent longitudinal wheel path cracks. An intermediate stage of fatigue cracking called alligator cracking because the cracking pattern resembles an alligator’s skin. In some extreme cases, the final stage of fatigue cracking is disintegration when potholes form.

Different test methodologies have been developed over the past few decades for measuring the fatigue behavior of asphalt concrete mixtures. One of the most popular fatigue testing methods is the flexural beam fatigue to measure the fatigue life of a compacted asphalt beam subjected to a repeated flexural bending. The AASHTO T-321 is the standard procedure for the beam fatigue test [1]. Other fatigue tests have been developed such as such as diametral test [2], cantilever rotating beam test [3], trapezoidal fatigue test [4], direct tension, or tension-compression [5]. The prediction quality of the fatigue life using any of these test methods will depend on how exact the method simulates the condition of loading, support, stress state and environment. Moreover, selecting any of these test methods can be influenced by the availability and cost of the equipment, in addition to ease of use [6].

In general, there are two main approaches that can be utilized to characterize the fatigue behavior of asphalt concrete mixtures: phenomenological and mechanistic. The phenomenological approach usually relates the stress or strains in the Hot Mix Asphalt (HMA) layer to the number of load repetitions that cause failure [7]. A mechanistic approach is inherently more complex than the phenomenological one but it is more widely accepted because it uses material properties based on stress-strain relationships. The mechanistic approach can be implemented through dissipated energy [8, 9], fracture mechanics [10, 11], or continuum damage mechanics [12-20].

A Continuum Damage Mechanics Approach (CDM) was developed through research efforts at North Carolina State University and Texas A&M University. This approach utilizes the viscoelastic correspondence principle and Work Potential Theory (WPT) described by Schapery [21] to remove viscous effects in monitoring changes in pseudo-stiffness in repeated uniaxial tensile tests. Therefore, physical variables were replaced by pseudo variables based on the extended elastic-viscoelastic correspondence principle to transform a viscoelastic (linear and/or nonlinear) problem to an elastic case. In 1990-1991, Schapery [22, 23] developed a series of damage models for elastic and viscoelastic media based on
thermodynamics of irreversible process and work potential theories with internal state variable to describe evolution of micro-structural changes.

The Swedish Transport Administration, Trafikverket, has aggressively utilized asphalt-rubber mixtures on highways within Sweden to mitigate pavement distresses such as fatigue cracking [24]. However, the majority of the rubber-modified pavement sections have been tested and evaluated mainly for noise and rolling resistance [25]. To date, adequate information regarding fatigue behavior of the Swedish rubber-modified mixtures pertinent to its regional climatic conditions is not available.

In 2009, Arizona State University (ASU) and Trafikverket engaged in a joint effort to understand the fundamental materials properties of the different gap graded, unmodified and modified mixtures placed on the E18 highway in the Stockholm area of Sweden [24,26]. As part of this project, advanced mixture material characterization tests were performed that included rutting evaluation, fatigue and thermal cracking evaluation, and crack propagation phenomenon assessment. The test results and analysis of the advanced characterization tests are presented in another paper submitted to the 2012 asphalt rubber conference [27]. In 2012, the uniaxial tension-compression test was added to further evaluate fatigue damage utilizing the viscoelastic and continuum damage model.

This paper presents results of the fatigue evaluation of the reference, polymer-modified and asphalt rubber, gap-graded asphalt mixtures placed the E18 highway in the Stockholm area of Sweden. The uniaxial tension compression test was used along with the viscoelastic continuum damage model to evaluate resistance to fatigue damage.

2. Objective

The main objective of this study was to compare fatigue behavior of gap-graded mixtures; reference, polymer-modified and rubber-modified placed in the Stockholm area of Sweden using the viscoelastic and continuum damage model

3. VEC Model Background

Continuum damage theories ignore specific micro-scale behaviors and instead characterize a material using macro-scale observations. The VEC model consists of three concepts:

a) the elastic-viscoelastic correspondence principle;

b) the continuum damage mechanics-based work potential theory; and

c) the temperature-time superposition principle.
Schapery (1984) proposed the extended elastic-viscoelastic correspondence principle (CP) which can be applicable to both linear and nonlinear viscoelastic materials [21]. Schapery suggested that constitutive equations for certain viscoelastic media are identical to those for the elastic cases, but stresses and strains are not necessarily physical quantities in the viscoelastic body. Instead, they are pseudo variables in the form of convolution integrals. The uniaxial pseudo strain ($\varepsilon^p$) is defined according to Equation 1.

$$\varepsilon^p = \frac{1}{E_R} \int_0^t E(t-\tau) \frac{d\varepsilon}{d\tau} d\tau$$

where:

- $E_R$ = reference modulus
- $E(t)$ = relaxation modulus and creep compliance, respectively;
- $t$ = elapsed time from specimen fabrication and time of interest;
- $\tau$ = time when loading began; and
- $\varepsilon$ = measured strain.

Schapery (1990) applied the method of thermodynamics of irreversible processes and the observed phenomenon of path independence of work in damage-inducing processes to develop the work potential theory to describe the mechanical behavior of elastic composite materials with growing damage [22]. The theory is general enough to allow for strong nonlinearities and to describe a variety of mechanisms including micro- and macro-crack growth in monolithic and composite materials. Three fundamental elements comprise the work potential theory: the pseudo strain energy density function (Equation 2), the stress-pseudo strain relationship (Equation 3) and the damage evolution law (Equation 4).

$$W^p = f(\varepsilon^p, S)$$

$$\sigma = \frac{\partial W^p}{\partial \varepsilon^p}$$

$$\frac{dS}{dt} = \left(-\frac{\partial W^p}{\partial S}\right)^\alpha$$

The work potential theory specifies an internal state variable ($S$) to quantify damage, which is defined as any microstructure changes that result in stiffness reduction. Kim (1997) characterized the growing damage for a controlled-strain testing mode through the following constitutive equations (Equations 5-6) [28]:

4   Zeiada, Underwood, Pourshams, Stempihar, and Kaloush
\[ W^R = \frac{1}{2} C(S)(\varepsilon^R)^2 \]  
\[ \sigma = IC(S)e^R \]  

Where I is the initial pseudo stiffness, and C is the normalized pseudo stiffness via dividing the pseudo stiffness by I. Daniel and Kim (2002) developed a simplified numerical model to calculate \( S \) from measured data as a function of time shown in Equation 8 [16].

\[ S(t) = \sum_{i=1}^{N} \left[ -\frac{I}{2} (C_i - C_{i-1})(\varepsilon^R)^2 \right] \frac{\alpha}{(i^{1+\alpha})} \left( t_i - t_{i-1} \right)^{\frac{1}{1+\alpha}} \]  

Chehab et al. (2002) and Underwood et al. (2006) verified that the time-temperature superposition (t-TS) principle at high levels of damage is equally significant [17, 29]. Based on this validation, Equation 8 can be modified to produce Equation 9.

\[ S(\xi) = \sum_{i=1}^{N} \left[ -\frac{I}{2} (C_i - C_{i-1})(\varepsilon^R)^2 \right] \frac{\alpha}{(i^{1+\alpha})} (\xi_i - \xi_{i-1})^{\frac{1}{1+\alpha}} \]  

Where \( \xi \) is the reduced time. Equation (8 or 9) can also be written in the following form:

\[ S_{i+1} = S_i + \left[ -\frac{I}{2} (C_i - C_{i-1})(\varepsilon^R)^2 \right] \frac{\alpha}{(i^{1+\alpha})} \Delta \xi_i^{\frac{1}{1+\alpha}} \]  

Underwood et al. (2010) developed a simplified VECVD modeling technique based on the analysis of cyclic data. This method allows for the prediction of the fatigue life of asphalt concrete at various strain-stress amplitudes under different temperatures using the dynamic modulus master curve and the cyclic fatigue data from a single temperature and single stress or strain amplitude [18]. The proposed S-function takes on the form shown in Equation 11.

\[ S_{N+1} = S_N + \left[ -\frac{DMR}{2} (C_N - C_{N-1})(\varepsilon^R)^2 \right] \frac{\alpha}{(N^{1+\alpha})} (\Delta \xi_N)^{\frac{1}{1+\alpha}} (K_i)^{\frac{1}{1+\alpha}} \]  

where:

DMR  = Dynamic Modular Ratio = \(|E^*|_{fp}/|E^*|_{LVE}\) and \(|E^*|_{LVE}\) is the fingerprint modulus,

\( \Delta \xi \)  = the change in the average reduced time between analysis cycles,

\( K_i \)  = a developed functional parameter to account for the analysis of
The parameter $\alpha$ is believed to be a material property. It was recommended to correlate $\alpha$ to the slope, $m$, in the central part of the dynamic modulus master curve for the $\log E(t)$-$\log(t)$ relationship where $\alpha = 1/m$ for the stress-controlled tests and $\alpha = 1/m + 1$ for the cross-head strain tests [28]. The C-S curve is a unique relationship for each mixture where all the different curves for tests conducted at different strain levels, temperatures, stress or strain-controlled, and monotonic or dynamic are supposed to collapse on only one curve named the damage characteristic (C-S) curve. The C-S relationship can be also fitted to an analytical form represented by Equation 12, where $C_0$ are regression coefficients and $C_0$ is equal to 1.0 [30].

$$C(S) = C_0 - C_1(S)^{C_2} \tag{12}$$

4. Description of the Project, Mixtures, and Specimen Preparation

The test sections constructed as part of this project include: a reference mixture (ABS 16 70/100), polymer-modified mixture (ABS 16 Nypol 50/100-75) and a rubber-modified mixture (Gap 16). The polymer modified mixture contained 3-6% polymer and the rubber-modified mixture contained approximately 20% ground tire rubber. Base bitumen was Pen 70/100 and all mixture designs were accomplished using the Marshall method. Air voids in the field for all three mixtures were approximately 3% [26]. Figure 1 presents the section of E18 where the project was constructed along with a schematic test section layout. Table 1 and Table 2 display the mixture characteristics and gradation, respectively.

![Figure 1. Project location and schematic of test section layout [26].](image-url)
Comparison of Conventional, Polymer, and Rubber Asphalt Mixtures

<table>
<thead>
<tr>
<th>Mix</th>
<th>Binder Content (%)</th>
<th>Air Voids (%)</th>
<th>Max. Theoretical Density ($G_{mm}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference ABS 16 70/100</td>
<td>5.9</td>
<td>2.6</td>
<td>2.4642</td>
</tr>
<tr>
<td>Polymer ABS 16 Nypol 50/100-75</td>
<td>5.9</td>
<td>2.6</td>
<td>2.4558</td>
</tr>
<tr>
<td>Rubber GAP 16</td>
<td>8.7</td>
<td>2.4</td>
<td>2.3588</td>
</tr>
</tbody>
</table>

Table 1. Field mixture characteristics, Stockholm test section

<table>
<thead>
<tr>
<th>Sieve Size (mm)</th>
<th>Reference-Gap</th>
<th>Polymer-Modified</th>
<th>Rubber-Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.4</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>11.2</td>
<td>65</td>
<td>65</td>
<td>68</td>
</tr>
<tr>
<td>8</td>
<td>38</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>0.063</td>
<td>10.5</td>
<td>10.5</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 2. Average aggregate gradations, Stockholm Highway.

The three variants of asphalt gap-graded mixtures and the associated binders were sampled from the project sites during construction. At the ASU laboratories, cylindrical gyratory samples were compacted for both dynamic modulus and uniaxial tension-compression fatigue test. Two different specimen geometries were manufactured for each test. For the dynamic modulus test, gyratory plugs were compacted into 150 mm (6 inches) diameter and 170 mm (6.7 inches) tall specimens. Then, one 100 mm (4 inches) diameter sample was cored from each gyratory plug. The sample ends were sawn to arrive at typical test specimens of 150 mm in height. For uniaxial tension-compression fatigue test, the compaction height was increased to 180 mm (7.1 inches) and the final specimen dimensions were 150 mm (6 inches) height and 75 mm (3 inches) in diameter. The main reason to increase the compaction height was to allow for larger end cuts to produce a more homogeneous air void distribution which increases the chances to have a middle failure in the uniaxial fatigue test. Figure 2 shows cored specimens for the uniaxial tension-compression fatigue test.
During compaction of the uniaxial tension-compression test, a large difference in compaction effort to achieve the target air void level was noticed between mixture types. The reference mixture required approximately 500 gyrations followed by the polymer-modified (~160 gyrations) and the rubber-modified (~12 gyrations). This trend is reasonable given the higher binder content of the rubber-modified mixture. However, the lower compaction effort required for the rubber-modified mixtures may influence fatigue behavior as discussed in a latter section of this paper.

5. Test Methods

5.1 Dynamic Modulus Test

The dynamic modulus (|E*|), per AASHTO TP 62-07 [31] was performed in the laboratory at five temperatures -10, 4.4, 21.1, 37.8, 54.4 °C (14, 40, 70, 100, and 130 °F) and six load frequencies: 25, 10, 5, 1, 0.5 and 0.1 Hz. The stress levels were varied with the frequency to keep the specimen response within a linear viscoelastic limit (recoverable microstrain below 150 microstrain). The test parameter values; dynamic modulus and phase angle, were measured at different temperatures and frequencies. The average dynamic modulus and phase angle values were summarized based on three replicates for each mixture. Figure 3 shows a typical instrumented test specimens and the applied wave shape.
5.2 Uniaxial Tension-Compression Test

The first step prior to running the test included gluing end plates to the specimen using the jig shown in Figure 4. The applied glue is Devcon plastic steel 5 minutes epoxy putty. The test specimen was then instrumented with three LVDTs to monitor material response. The uniaxial tension-compression fatigue test is conducted to evaluate the fatigue damage of the Swedish gap-graded mixtures using the viscoelastic and continuum damage model. A servo hydraulic testing machine was used to load the specimens under an on-specimen strain-control mode of loading. A dynamic sinusoidal strain (continuous wave) was applied. The test software is capable of achieving and maintaining the target on-specimen strain based on the outputs from the three LVDTs by dynamically changing the actuator strain level to solve the machine compliance issue. New software was developed for Arizona State University by IPC (Industrial Process Control) company and is designated as UST032-v1.01b S-VECD fatigue test. The uniaxial tension-compression fatigue tests were conducted using two specimens from each mixture type where two different strain levels (low and high) were applied to each specimen. The uniaxial tension-compression fatigue test was run until the specimen reached 50% of its initial modulus. For a regular fatigue test, the initial modulus or stiffness is measured at cycle number 50. In this particular study, the initial modulus was measured at cycle number 100 as to allow enough time for the software to reach the target on-specimen strain. At each loading cycle, the software calculates the dynamic modulus and the phase angle plus the stress and the strain values from the actuator and the three LVDTs.
6. Test Results

6.1 Dynamic Modulus Test

Using the E* values obtained in this study, [E*] master curves were constructed for the three gap-graded mixtures. The shift factors at different temperatures were first computed from the master curve of the storage modulus [E' = |E*| cos(φ), where φ is the phase angle in degrees] then the same values were used to construct the E* master curve and the phase angle master curve. The main reason for this is that the storage modulus considers both the dynamic modulus and phase angle, which completely describe the material behavior. In general, the master modulus curve can be mathematically modeled by a sigmoidal function described as:

\[ \log|E'| = \delta + \frac{\alpha}{1 + e^{\beta \gamma (\log f_r)}} \]  

where:

- \( f_r \) = reduced frequency of loading
- \( \delta \) = minimum value of \( \log |E'| \)
- \( \delta + \alpha \) = maximum value of \( \log |E'| \)
- \( \beta, \gamma \) = parameters describing the shape of the sigmoidal function

Figures 5 and 6 present the dynamic modulus and phase angle master curves for the reference, polymer-modified and rubber-modified mixtures, respectively. At
low test temperatures, the polymer-modified mixture expressed the highest stiffness followed by the reference and rubber-modified mixtures. In comparison, at low temperatures, the rubber-modified mixture had the highest stiffness followed by reference and polymer-modified. The rubber-modified mixture exhibited the lowest stiffness compared to the other two mixtures at 21°C (70°F) which is the test temperature used for the uniaxial tension-compression test.

It can be observed from Figure 6 that the phase angle increases with decreasing reduced frequency till a certain point where it starts to decrease. This can be explained that at low temperature and high loading frequency, the asphalt binder dominates the behavior of asphalt mixtures and the mixture is more elastic resulting in a reduced phase angle. By increasing temperature or decreasing loading frequency, the asphalt mixture becomes more viscous as the binder becomes softer and thus, phase angle increases. This trend is observed until a point when the asphalt binder becomes very soft and the aggregates dominate the behavior of asphalt mixture. At this point, the asphalt mixture exhibits more elastic behavior resulting in a decrease in phase angle.

![Figure 5. Dynamic modulus master curves of the Swedish gap-goaded mixtures.](image-url)
6.2 Uniaxial Tension-Compression Test

During this experiment a cylindrical asphalt concrete undergoes a controlled on-specimen strain cyclic loading until failure point. The applied stress and on-specimen axial strains are measured. These values are used to calculate pseudo strain and pseudo secant modulus (pseudo stiffness), internal state damage parameter and construct the damage characteristic curve.

Two specimens from each mixture type were tested at different strain levels: 300 and 250 microstrains on the reference-gap mixture, 300 and 400 microstrains on the rubber-modified mixture and the polymer-modified mixture. However, it is important to note that one specimen from each of the three mixtures were tested under the same target on-specimen strain value (300 microstrain). The results are shown in Table 3.

<table>
<thead>
<tr>
<th>Mixture Type</th>
<th>Specimen ID</th>
<th>Air Voids %</th>
<th>Strain Level μs</th>
<th>FP Modulus MPa</th>
<th>Machine Compliance Factor</th>
<th>Initial Stiffness MPa</th>
<th>Initial φ Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference-Gap</td>
<td>SWC03</td>
<td>3.65</td>
<td>250</td>
<td>10,978</td>
<td>6.78</td>
<td>8,609</td>
<td>25.3</td>
</tr>
<tr>
<td></td>
<td>SWC02</td>
<td>3.82</td>
<td>300</td>
<td>10,310</td>
<td>6.45</td>
<td>7,435</td>
<td>28.6</td>
</tr>
<tr>
<td>Polymer-Modified</td>
<td>SWP05</td>
<td>3.55</td>
<td>300</td>
<td>8,479</td>
<td>5.08</td>
<td>6,707</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>SWP06</td>
<td>3.65</td>
<td>400</td>
<td>8,913</td>
<td>5.43</td>
<td>6,214</td>
<td>24.1</td>
</tr>
<tr>
<td>Rubber-Modified</td>
<td>SWR04</td>
<td>2.81</td>
<td>300</td>
<td>6,710</td>
<td>4.45</td>
<td>5,296</td>
<td>24.9</td>
</tr>
<tr>
<td></td>
<td>SWR06</td>
<td>3.11</td>
<td>400</td>
<td>7,123</td>
<td>4.63</td>
<td>5,134</td>
<td>25.5</td>
</tr>
</tbody>
</table>

Table 3. Fingerprint modulus (FP) and uniaxial fatigue test results.
From Table 3, it appears that the reference mixture has the highest modulus value compared to the modified mixture types. At 300 microstrain levels, both polymer-modified mixture and the rubber-modified mixture, undergo higher load cycles before failure compared to the reference mixture. This appears to be reasonable since for strain-controlled test, the lower the modulus the higher the fatigue life.

Moreover, the polymer-modified mixture appears to have slightly higher number of cycles until failure compared to the rubber-modified mixture; however it was expected that the rubber-modified mixtures would show relatively higher fatigue life. This might be due to the fact that the rubber-modified mixture required much less compaction effort (gyrations) compared to the polymer-modified mixture to reach the target air void level. This might decrease the fatigue resistance of the rubber-modified below what was expected. Based on that, the mixture design for the rubber-modified mixture might need to be modified to allow more voids in mineral aggregate (VMA) to accommodate the excess amount of the asphalt rubber.

6. Viscoelastic Material Properties

The viscoelastic material properties were estimated through the relaxation modulus calculation. The relaxation modulus values were calculated for each mixture type using the exact inter-conversion method [32]. This method requires the storage modulus, $E'$ master curve. It is based on the Prony series representation of $E'$ to allow simple inter-conversion between the frequency and time domains. The relaxation modulus values along desired time range are fitted to the Prony series function using the collocation method. The Prony series function can be expressed using the following formula:

$$E(t) = E_\infty + \sum_{i=1}^{N} E_m \exp^{-\rho_m t}$$

(14)

where:
- $E(t)$ = the relaxation modulus as a function of time, t, (kPa or psi).
- $E_\infty$ = the long-time equilibrium modulus (kPa or psi);
- $E_m$ = the modulus of Prony term number m (kPa or psi);
- $\rho_m$ = the relaxation time of Prony term m (s); and
- $N$ = the number of Prony terms used.

Table 4 summarizes the three asphalt mixtures’ Prony series coefficients for different term values required for relaxation modulus.
Table 4. Prony series parameters for the Swedish gap-graded mixtures.

7. Damage Characteristic Curve

The construction of C-S curves in this paper followed the most updated procedure developed by Underwood et al., 2010 [20] to calculate the internal state damage, S as shown in Equation 12. The pseudo stiffness or modulus was calculated simply by calculating the pseudo strain from cyclic data divided by the applied stress [20]. Then the pseudo stiffness was normalized via dividing the pseudo stiffness at each cycle by the initial pseudo stiffness at the first cycle. For each mixture, two C-S curves were established from the two tested specimens. Then a single model using Equation 12 was fitted through the collapsed two curves to represent the model C-S curve for the mixture. Figure 7 demonstrates an example of the C-S curve for the polymer-modified mixture while Figure 8 shows the C-S curves for the three mixtures together.
Comparison of Conventional, Polymer, and Rubber Asphalt Mixtures

Figure 7. An example of S-C curve fitting model for the polymer-modified mixture.

Figure 8. Comparison of damage characteristic curves for study mixtures.

From Figure 8 it can be observed that the most favorably positioned damage characteristic curves are obtained from the reference-gap and polymer-modified mixtures. A more favorable damage characteristic curve is the one that has the greatest damage level for a given pseudo stiffness. This condition is more favorable because, as seen in Equations 2 through 5, it means that the rate of damage growth for a given pseudo energy input will be less and thus the incremental loss in pseudo stiffness will also be less. However, one cannot, or should not, use this curve alone to judge the fatigue resistance of the three mixtures.
While the damage characteristic curve constitutes an important component of the overall mixture fatigue resistance, it is not the only characteristic that should be considered. In addition, one must also consider the material’s resistance to deformation, i.e., how much pseudo energy will be generated for any given strain input. The resistance to deformation can vary as much or more between materials than their differences in damage resistance. An example of how this interplay between resistance to deformation and resistance to damage may affect the fatigue life can be observed by considering the following hypothetical case. Suppose that there are two mixtures, and that the first (Mixture 1) has low damage sensitivity, but the second (Mixture 2) has high damage sensitivity (i.e., the C-S curve for Mixture 1 is positioned above the C-S curve for Mixture 2). Ignoring the modulus effect, one would immediately conclude that Mixture 1 is the better material with regards to fatigue resistance. However, now suppose that the modulus for Mixture 1 is greater than that of Mixture 2 by a factor of 4, and further suppose that both materials are subjected to controlled strain loading at the same input level. According to the damage theory (Equations 2 through 5), under these loading conditions Mixture 1 would generate 16 times more pseudo energy than would Mixture 2. Such an increase in pseudo energy may very easily overcome the differences in C-S curves and result in overall poorer fatigue performance from Mixture 1.

It can also be theoretically shown [33] that S is an internal state variable that relates to a physical change within the material (microcrack formation, internal dislocations, etc.), but does not necessarily give direct quantification of that change. Consider the case where the physical transformation responsible for any observed softening is microcracking. The S variable will increase as those microcracks grow or multiply, but one cannot convert the value of S to, the number of microcracks, cumulative crack area, etc. without some additional theoretical assumptions. This constraint means that across different materials, the same S value does not necessarily represent the same internal physical change. The practical implication of this theoretical constraint is simply that in order to gain useful information on fatigue cracking one must perform simulated predictions of the fatigue life at specific conditions of interest. Underwood et al. [34] derived the formulas for predicting the material response to fully reversed constant stress and constant strain loadings (Equation 15 and 16 respectively) and verified these formulations using independent laboratory experiments [35]. Here, these equations are used to predict the fatigue performance of the three study mixtures at the temperatures of 5, 20, and 27 °C (41, 68, and 80 °F) and the results are summarized in Figure 9 and Figure 10.

\[
N_{\text{failure}} = \frac{(f_c)(2^{\alpha C_{\text{r, failure}}})}{(\alpha - \alpha C_{\text{r}} + 1)(C_{\text{r}} C_{\text{f}})^\alpha \left[ (\varepsilon_{0,pp}) \left[ \frac{|E^\prime|}{LVE} \right] \right]^2 K_1}
\]  

(15)
Comparison of Conventional, Polymer, and Rubber Asphalt Mixtures

\[ N_{\text{failure}} = \frac{f_r \# 2^{3\alpha} |E^*|^{2\alpha}}{K_1} \left( \int_0^{S_{\text{failure}}} \left( 1 - \hat{C}_1 \left( \frac{\hat{S}}{C} \right) \right)^2 d\hat{S} \right)^{\frac{1}{\alpha}} \]  

(16)

where:

- \( N_{\text{failure}} \) = predicted cycle number of cycles to failure;
- \( f_r \) = reduced frequency for the condition being simulated;
- \( |E^*| \) = dynamic modulus for the condition being simulated;
- \( \varepsilon_{0,pp} \) = peak-to-peak strain level for simulation;
- \( \sigma_{0,pp} \) = peak-to-peak stress level for simulation;
- \( S_{\text{failure}} \) = damage level at failure; and
- other variables are given by Equation 17 and Equation 18.

\[ \hat{S}_{\text{failure}} = \frac{S_{\text{failure}}}{|E^*|^{2\alpha}} \]  

(17)

\[ \hat{C}_{11} = C_{11} \left( |E^*|^{\frac{1}{2\alpha}} \right)^{\frac{1}{2}} \]  

(18)

Figure 9. Simulation results for controlled strain test at 10 Hz loading frequency and at: (a) 5 °C, (b) 20 °C, and (c) 27 °C.
Figure 10. Simulation results for controlled stress test at 10 Hz loading frequency and at; (a) 5 °C, (b) 20 °C, and (c) 27 °C.

Note that although the stress controlled function has been used to generate the data in Figure 10, the simulation results are plotted against the initial strain instead of the input stress level based on the typical convention [6, 7]. From these two figures it is observed that overall the asphalt rubber mixture is expected to yield a longer laboratory fatigue life. The results also show the complexities involved with fatigue assessment as the asphalt rubber and polymer modified mixtures are expected to show similar fatigue resistance at 5 °C (41 °F), but different results at 20 °C and 27 °C (68 and 80 °F) particularly at small strain amplitudes. This behavior can be related to the complex interaction between modulus and damage resistance that was mentioned earlier. The same trend holds in the case of controlled stress testing when the mixtures are compared at consistent initial strain levels. None of the results directly conflict the basic findings from the laboratory experiment, which concluded that the asphalt rubber and polymer modified mixtures have similar fatigue resistance, and that the reference-gap mixture has worse fatigue resistance. One interesting finding is that the fatigue life predicted through the continuum damage analysis using the uniaxial fatigue test showed similar results and trends, when compared to the fatigue life measured by the beam fatigue test [26]. This shows the power of the continuum damage analysis to predict the fatigue life relationships using only limited amount of tests.

One caveat in this analysis is that the controlled stress simulations are shown with respect to initial strain level and not with respect to the input stress condition. Since the reference mixture is stiffer than either the polymer modified or rubber
Comparison of Conventional, Polymer, and Rubber Asphalt Mixtures

modified mixtures, when comparisons are made at the same stress level the reference mixture would appear to outperform the other two. However, conventional based on historical correlations [6 and references from 6] suggests that more useful insight on in-service fatigue performance is gained by examining controlled stress laboratory tests in the manner performed herein. It should also be mentioned that laboratory fatigue tests of the type simulated with the VECD model do not generally take explicit consideration of differences in the fracture characteristics of the materials. However, these characteristics may have important implications in rigorously relating laboratory fatigue tests to pavement cracking performance. Since the rubber-modified asphalt mixture has been shown to outperform either of the other two study mixtures in this regard, it is expected that the differences identified through this investigation likely underestimate the overall net benefits of asphalt rubber in mitigating or reducing the cracking phenomenon in asphalt concrete pavements.

8. Conclusions

This paper presented research performed to compare properties and fatigue performance characteristics for reference, polymer-modified and rubber-modified gap graded mixtures placed on the E18 highway in the Stockholm area of Sweden. The advanced material characterization tests included: dynamic (complex) modulus for stiffness evaluation and the uniaxial tension-compression for fatigue assessment. The data were used to compare the performance of the rubber-modified gap graded mixture to the reference and the polymer-modified gap mixtures using the viscoelastic continuum damage (VECD) approach.

Dynamic modulus test results indicate that, at low test temperatures, the polymer-modified mixture expressed the highest stiffness followed by the reference and rubber-modified mixtures. In comparison, at low temperatures, the rubber-modified mixture had the highest stiffness followed by reference and polymer-modified. The rubber-modified mixture exhibited the lowest stiffness compared to the other two mixtures at 21°C (70°F) which is the test temperature used for the uniaxial tension-compression test.

According to the uniaxial tension-compression fatigue test (300 μɛ), both the polymer-modified mixture and rubber-modified mixtures, undergo higher load cycles before failure compared to the reference-gap mixture. This appears to be reasonable since for strain-controlled test, the lower the modulus the higher the fatigue life. Moreover, the polymer-modified mixture appears to have slightly higher number of cycles till failure compared to the rubber-modified mixture. However it was expected that the rubber-modified mixture would show relatively higher fatigue life and this discrepancy may be the result of differences in compaction effort.

Damage characteristic (C-S) curves were formulated and used along with the measured linear viscoelastic characteristics to predict the fatigue performance of
the three study mixtures over a range of temperatures. This data clearly showed the benefits of the rubber modified mixture in terms of laboratory fatigue resistance. This VECD analysis presents a more powerful tool to evaluate fatigue resistance. Instead of only looking at the number of cycles at a certain stiffness reduction, this method considers internal state damage. Results indicate that VECD is a much more comprehensive approach to access resistance to fatigue damage than the traditional number of cycles at a certain stiffness reduction. The rubber-modified mixture exhibits the greatest fatigue resistance followed by the polymer-modified and reference.

Finally, results obtained from this study will be compared to actual field performance of the test sections once this information becomes available from Trafikverket. At this time, ranking of mixtures from lab tests will be compared to field ranking to validate the results of the VECD approach.

9. Bibliography


