Effects of Oxidative Aging on Asphalt Mixture Properties

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ABSTRACT

Aging has long been recognized as a contributing factor to fatigue distress of asphalt concrete pavement. Several research studies have been undertaken to gain fundamental understanding of the aging phenomenon at the asphalt binder level. However, relatively little effort has been made to understand and quantify the effects of aging on fundamental characteristics of asphalt mixtures.

In this paper, the phenomenon of oxidative aging is examined in terms of its effects on the dynamic modulus and fatigue performance of asphalt mixtures. For this purpose, an asphalt mixture is aged in the laboratory at four different aging levels. Mechanical tests for the four aged mixtures are performed to characterize the linear viscoelastic and damage properties. Such characterization is investigated in order to incorporate the aging effects into a more comprehensive analytical framework for predicting the performance of asphalt concrete pavements. Finally, this framework is used to evaluate the aging effects on an example asphalt concrete pavement. It is found that aging can significantly change the performance of an asphalt concrete pavement depending on the location evaluated within the pavement structure as well as climate conditions.

Keywords: Oxidative aging, asphalt mixture, viscoelastic continuum damage, fatigue performance, asphalt concrete pavement
INTRODUCTION

The effects of aging in asphalt binders on the fatigue performance of asphalt concrete pavement are well recognized. Aging causes the asphalt to stiffen and become brittle, which leads to a higher potential for cracking. The term aging has been applied to describe multiple mechanisms in asphalt mixtures. For some researchers, it may be applied to indicate the overall deterioration of an asphalt pavement from exposure to both climatological and load factors. In other cases, the term is applied to describe only the effects of climate, which include oxidative aging, ultraviolet radiation, and moisture-related damage. The most common usage of the term aging is to describe the process of oxidative aging only, and it is this definition that is applied in this paper.

Traditionally, the effects of binder aging on mixture performance have been investigated using two approaches. The first is to subject different asphalt binders to various aging conditions and measure the resultant changes in physical properties to assess the aging potential of the different binders. However, this approach does not account for the effect of aggregate particles and does not yield accurate and realistic information about the performance of the mixtures. The other approach is to subject the asphalt mixtures to various aging conditions and then measure the physical properties of the aged mixtures. Although this second method is more realistic because the aging process is conducted directly on the mixtures, little work has been done to determine the best method for incorporating these changes in mixture properties due to aging into the framework of constitutive modeling for fatigue performance. The original viscoelastic continuum damage (VECD) constitutive model is based on the assumption that the material is a non-aging system. This study focuses on establishing an experimental and analytical methodology for incorporating the effects of aging in the current constitutive model.

In this paper, an asphalt mixture is aged in the laboratory at four different aging levels. Mechanical tests for the four aged mixtures are performed to characterize the linear viscoelastic and damage properties. Such characterization is investigated in order to incorporate the aging effects into a more comprehensive analytical framework for predicting the performance of asphalt concrete pavements. Finally, this framework is used to evaluate the aging effects on an example asphalt concrete pavement.

OBJECTIVES

The objectives of this paper are to report the effects of laboratory induced oxidative aging on the linear viscoelastic (LVE) response and damage characteristics of an asphalt mixture, to explain the analytical approach that is taken to incorporate the aging effect into the LVE and VECD model, and to show how these effects can be incorporated into a suitable analytical framework to predict the effects of aging on in-service asphalt concrete pavements.

LABORATORY TEST METHOD

Materials and Specimen Fabrication

Findings from the Strategic Highway Research program (SHRP) suggest that the aging susceptibility of asphalt mixtures is dependent on the asphalt binder as well as the aggregates, even though the effect of asphalt binder is more significant than that of the aggregate. This effect appears to be related to the chemical interactions between the aggregate and the asphalt, which may be related to adhesion: the greater the adhesion, the greater the mitigation of aging.
this research the team wanted to choose a mixture that best amplified these interactive effects and based on the SHRP report’s recommendations this could be achieved by combining limestone aggregates with the SHRP AAD-1 asphalt binder.

The AAD-1 binder (PG 58-28) was obtained from the Materials Reference Library (MRL) and combined with a local North Carolina limestone aggregate to create the study mixture. The aggregate structure for this mixture is a fine 9.5 mm Superpave mixture comprised of 50% #78M stone, 33% 2S-sand, 14.5% dry screenings, and 2.5% baghouse fines. A Superpave mix design procedure was performed, and the optimal asphalt content is 6.2% by weight of total mix. The mixing and compaction temperatures are 147°C and 135°C, respectively.

All specimens were compacted by the Servopac Superpave gyratory compactor, manufactured by IPC Global of Australia, to dimensions of 178 mm in height and 150 mm in diameter. To obtain specimens of uniform quality for testing, these samples were cored and cut to a height of 150 mm and a diameter of 75 mm. The air voids for all tests in this study are between 3.5% and 4.5%.

**Laboratory Aging Method of Asphalt Mixture**

NCHRP 9-23 (7) reports that the laboratory aging method devised during the SHRP project is not sufficient to simulate field-aging behavior in the laboratory because of its inability to account for variables present in the field such as incidence of sunshine, UV radiation, or precipitation. Nevertheless, the SHRP method has some advantages to be considered for this study: 1) it is simple to implement; 2) it provides a general relationship between laboratory and field-aging behavior; and 3) it has been used successfully for previous studies conducted at North Carolina State University (NCSU) (6). In addition, this study focuses on developing a general relationship for the aging effects in the current VECD model rather than matching the laboratory aging to that of the field. Therefore, the aging process for the asphalt mixture in this study follows the SHRP protocol. Four levels of asphalt mixture aging were simulated, as follows (5):

- **Short-term aging (STA):** The loose, uncompacted mixture is conditioned at 135°C for 4 hours and then compacted. Specimens are cored and cut for testing.
- **Long-term aging, Level 1 (LTA1):** The aging procedure is the same as for STA, except the specimens are conditioned at 85°C for 2 days before testing after coring and cutting.
- **Long-term aging, Level 2 (LTA2):** The aging procedure is the same as for STA, except the specimens are conditioned at 85°C for 4 days before testing after coring and cutting.
- **Long-term aging, Level 3 (LTA3):** The aging procedure is the same as for STA, except the specimens are conditioned at 85°C for 8 days before testing after coring and cutting.

These aging processes for the asphalt mixture follow the AASHTO R30 specification (8), with the exception that three different long-term aging times are used. To minimize slump in the specimens during the oven aging portion, the method suggested by the NCHRP 9-23 project (9) is adopted whereby the specimens are wrapped in wire mesh, and the mesh is held in place by three steel clamps. The diameter, height, weight, and air void percentage of all specimens was measured before and after oven aging. No apparent damage due to the aging procedure was found.

**Testing Method**

Three different types of laboratory testing were performed: the dynamic modulus (|E*|) test, the constant crosshead rate (monotonic) test, and the cyclic fatigue test. The |E*| test and constant crosshead rate test were carried out with the aim of capturing the aging effects in the current
VECD model. For a more direct investigation of the aging effects, cyclic fatigue tests were performed in controlled crosshead (CX) and controlled stress (CS) modes.

The $|E^*|$ test was performed in stress-controlled uniaxial tension-compression mode. The test was performed at frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz and temperatures of -10°C, 5°C, 20°C, 40°C, and 54°C. The load level was adjusted for each condition to produce total strain amplitudes of about 50 to 75 microstrains. The constant crosshead rate test was conducted in uniaxial tension mode at 5°C until failure. Tests were conducted at three different rates with one replicate per rate. Both CX and CS tests were conducted only in tension mode with a haversine loading of 10 Hz at 5°C and 19°C for low and high amplitudes of load level.

LVE CHARACTERIZATION OF AGED MIXTURES

Three replicates for each different aging level of mixture were tested and the results were processed to create sigmoidal $|E^*|$ mastercurves at a reference temperature of 5°C. FIGURE 1 (a) and (b) present the replicate averaged $|E^*|$ mastercurves of the aged mixtures in semi-log and log-log scales. It is observed that, in general, the stiffness increases with aging time over all of the frequency ranges. Moreover, a clearer trend with regard to aging time is observed at low reduced frequencies (physically representing warm temperatures and/or slow loading frequencies). Such a trend is expected because it is known that, as temperature increases or frequency reduces, the modulus gradient between the asphalt binder and aggregate particles becomes larger. As a result, the effect of the asphalt binder properties on the total mixture behavior may become more noticeable. With respect to the phase angle mastercurves presented in FIGURE 1 (c), the maximum phase angle is delayed to a slower reduced frequency upon further aging, which causes the elasticity to be greater at intermediate temperatures but less at high temperatures.

In order to determine the significance of the graphical observations, statistical analysis of the $|E^*|$ data at different aging levels is performed by using the step-down bootstrap method. This method is used in lieu of multiple paired t-tests due to the effect of experiment-wise error rates, which can result in incorrect conclusions when making multiple comparisons. Failing to account for this error rate increases the probability of finding significance when none is present. The statistical analysis results are shown by temperature and frequency in TABLE 1 with conditions under which the means are statistically similar (based on a 95% significance level) are highlighted.

From TABLE 1 the first comparisons to review are those between adjacent aging level test results, i.e., STA versus LTA1, LTA1 versus LTA2, and LTA2 versus LTA3. Overall, statistically different values are found between each adjacent aging level, except at the extreme conditions, i.e., a fast frequency at a low temperature and a slow frequency at a high temperature. A comparison of the two extreme aging conditions, STA versus LTA3, shows that significant differences exist for almost all the conditions, except 0.1 Hz at 54°C. This result may be explained by the higher degree of replicate variation under extreme conditions as compared to that under less extreme conditions. Therefore, it is reasonable to conclude that overall a statistically significant effect on the dynamic modulus exists due to the laboratory aging procedures.
FIGURE 1  LVE properties of STA, LTA1, LTA2, and LTA3 aged mixtures: (a) $|E^*|$ mastercurves in semi-log space, (b) $|E^*|$ mastercurves in log-log space, and (c) phase angle mastercurves.
**TABLE 1  Statistical Analysis Results of \(|E*|\) Data**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Frequency (Hz)</th>
<th>p-value</th>
<th>STA vs. LTA1</th>
<th>LTA1 vs. LTA2</th>
<th>LTA2 vs. LTA3</th>
<th>STA vs. LTA3</th>
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<tr>
<td>-10</td>
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<td>0.486</td>
<td>0.070</td>
<td>0.100</td>
<td>0.019</td>
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<td>10</td>
<td>0.589</td>
<td>0.071</td>
<td>0.105</td>
<td>0.005</td>
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<tr>
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<td>0.694</td>
<td>0.047</td>
<td>0.087</td>
<td>0.004</td>
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<tr>
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<td>0.034</td>
<td>0.005</td>
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<td>0.001</td>
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<tr>
<td>5</td>
<td>25</td>
<td>0.241</td>
<td>0.008</td>
<td>0.031</td>
<td>0.009</td>
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</tr>
<tr>
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<td>10</td>
<td>0.194</td>
<td>0.012</td>
<td>0.026</td>
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<td>0.002</td>
<td>0.040</td>
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<td>0.021</td>
<td>0.001</td>
<td>0.033</td>
<td>0.008</td>
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<td>0.031</td>
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<td>0.011</td>
<td>0.006</td>
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</tr>
<tr>
<td>20</td>
<td>10</td>
<td>0.047</td>
<td>0.003</td>
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<tr>
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<td>0.002</td>
<td>0.013</td>
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<td>0.003</td>
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<td>0.000</td>
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<td>0.015</td>
<td>0.002</td>
<td>0.011</td>
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<tr>
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<td>0.021</td>
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<td>0.132</td>
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<td>0.419</td>
<td>0.265</td>
<td>0.507</td>
<td>0.132</td>
<td></td>
</tr>
</tbody>
</table>

Shaded cell: statistically similar (based on a 95% significance level).

**VECD CHARACTERIZATION OF AGED MIXTURES**

**Constant Crosshead Rate Test Results**

The damage characteristics for aged mixtures are obtained using the original VECD analysis method. A full description of this procedure is beyond the scope of this paper; however, excellent reviews are available elsewhere and a great deal of literature has been produced on the topic (10, 11, 12). Three replicates of each aged mixture were independently analyzed, and then, the representative damage characteristic curve for the four different aging levels of the mixture were obtained by fitting the replicate damage characteristic curves using Equation (1).
\[ C = e^{as} \]  

where; \( C \) is the pseudo stiffness, \( S \) is the damage parameter, and \( a \) and \( b \) are the fitting coefficients for the exponential model.

FIGURE 2 presents the representative damage characteristic curves for the aged mixtures. From this figure, the damage characteristic curve for the LTA3 mixture is positioned the highest, followed by LTA2 and LTA1 mixtures, and finally, by the STA mixture. The differences among the aged mixtures are significant, but care should be taken in concluding from these observations that aging affects the mixture properties relative to performance. Aging effects on the performance of asphalt mixtures must be evaluated in terms of the combined effects of stiffness, damage, and failure criteria. Hence, a series of cyclic fatigue tests has been conducted to investigate the effects of aging on these characteristics further.

![Damage characteristic curves for STA, LTA1, LTA2, and LTA3 aged mixtures.](image)

**FIGURE 2** Damage characteristic curves for STA, LTA1, LTA2, and LTA3 aged mixtures.

**Cyclic Fatigue Test Results**

Cyclic fatigue tests were conducted for all four aged mixtures under CS and CX cyclic conditions. Two amplitudes, high and low, were applied at two temperatures, 5°C and 19°C. Each test was done at different conditions, i.e., no replicate under the same condition. The test conditions and some important results, especially the number of cycles to failure \((N_f)\), are summarized in TABLE 2.

To define the \( N_f \), the phase angle criterion suggested by Reese (13) is utilized because it works well under both CX and CS test conditions. The phase angle quickly drops in the CX tests and suddenly increases in the CS tests once the specimen fails. One example from the test results for the STA mixture is shown in FIGURE 3. Overall, the dynamic modulus decreases and the phase angle increases according to the number of cycles until the specimen fails, which is when the localization of on-specimen strain starts.

Comparisons of the cyclic test results lead to the following conclusions:

- Regardless of testing mode, temperature, and aging level, fatigue resistance decreases as the magnitude of the input increases;
From the CX test results and from comparisons at a similar initial strain magnitude, as the temperature decreases or the aging time increases, the resulting initial stress magnitude increases and the $N_f$ decreases; and

- From the CS test results and from comparisons at a similar initial stress magnitude, as the temperature decreases or the aging time increases, the resulting initial strain magnitude decreases and the $N_f$ increases.

Overall, the different testing modes result in the opposite fatigue performance; e.g., the STA mix shows better performance in the CX tests, but the LTA3 mix shows better performance in the CS tests. It is known, based on energy principles that stiff materials tend to perform better in CS test protocols, whereas soft materials yield better performance in CX tests, all other factors being equal. Additionally, such results correspond to the findings from other researchers. Kutay et al. (14) report that, depending on the mode of loading (i.e., stress- or strain-controlled), the ranking of the mixtures can be quite different. Kutay et al. also found that stress-controlled push-pull tests reveal a reverse trend when compared to field fatigue data obtained from the Federal Highway Administration’s Accelerated Load Facility (FHWA-ALF) whereas strain-controlled tests provide the correct trend.

**TABLE 2 Cyclic Fatigue Test Summary**

<table>
<thead>
<tr>
<th>Aging Level</th>
<th>Test Designation</th>
<th>Initial Stress Amplitude in Tension (kPa)</th>
<th>Initial Peak-to-Peak Strain (Microstrain)</th>
<th>$N_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STA</td>
<td>19-CX-H</td>
<td>1,700</td>
<td>582</td>
<td>3,091</td>
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<tr>
<td></td>
<td>5-CX-H</td>
<td>2,870</td>
<td>274</td>
<td>3,498</td>
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<tr>
<td></td>
<td>5-CX-L</td>
<td>980</td>
<td>87</td>
<td>&gt;280,000</td>
</tr>
<tr>
<td></td>
<td>5-CS-H</td>
<td>1,500</td>
<td>120</td>
<td>4,000</td>
</tr>
<tr>
<td></td>
<td>5-CS-L</td>
<td>900</td>
<td>76</td>
<td>44,700</td>
</tr>
<tr>
<td>LTA1</td>
<td>19-CX-H</td>
<td>1,790</td>
<td>466</td>
<td>3,613</td>
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<tr>
<td></td>
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<td>259</td>
<td>3,100</td>
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<tr>
<td></td>
<td>5-CX-L</td>
<td>920</td>
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<td>&gt;280,000</td>
</tr>
<tr>
<td></td>
<td>5-CS-L</td>
<td>900</td>
<td>66</td>
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<tr>
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<td></td>
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<td></td>
<td>5-CS-H</td>
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<td></td>
<td>5-CS-L</td>
<td>900</td>
<td>64</td>
<td>97,200</td>
</tr>
<tr>
<td>LTA3</td>
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<td></td>
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<td>800</td>
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<td>5-CX-L</td>
<td>1,810</td>
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<td>8,900</td>
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<tr>
<td></td>
<td>5-CS-L</td>
<td>900</td>
<td>52</td>
<td>167,000</td>
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</table>

* Test temperature in degrees Celsius; $^b$ Test mode; $^c$ Relative magnitude: H = high, L = low
Cyclic fatigue data are analyzed using the simplified VECD model (S-VECD) formulation recently developed by Underwood et al. (11) in order to obtain the damage characteristics. The major difference between this S-VECD model and the more rigorous VECD model is the use of a simplified pseudo strain calculation methodology for the cyclic portion. The overall effect of such a simplification on the value of pseudo strain is found to be small, but the simplification saves a great deal of computational time without causing a large amount of error in the calculations. In addition, the resulting formulation unifies the results of the CS, CX, and monotonic testing and supports earlier findings that the damage characteristic curve is a material property independent of temperature and test type. A complete review of the S-VECD modeling is beyond the scope of this paper; however, interested readers are directed to (11, 12) for a more thorough review and for citations to additional resources.

FIGURE 4 shows the damage characteristic curves of all four aged mixtures obtained from the monotonic, CX, and CS tests. The collapse among different tests is good for all cases examined, except for the discrepancy between the monotonic and cyclic results of the LTA1 mixture. These results confirm that the S-VECD model can be applied to asphalt mixtures subjected to the laboratory aging process.
FIGURE 4 Damage characteristic curves of: (a) STA, (b) LTA1, (c) LTA2, and (d) LTA3 aged mixtures.

Failure Criterion as a Function of Aging and Temperature

One important finding from the cyclic fatigue test is that the failure of the specimen occurs at different degrees of damage, depending on the aging level of the mixture and the test temperature. In FIGURE 5, the averaged pseudo stiffness (C) values at failure obtained from the CX tests for all aged mixtures are plotted against the test temperatures. It is observed that the C values at failure decrease as the temperature increases for all aging levels. It is also found that the aging effect on failure is most noticeable at 19°C. Such a trend can be expected because of the tendency of asphalt concrete to become brittle with age. On the other hand, all the aging mixes failed at similar C values at 5°C. This result is believed to be caused by the fact that asphalt concrete is brittle enough at low temperatures to mitigate the aging effect such that the aging effect is not significant.

Because of limited test data, it is assumed that the failure criterion varies linearly between 5°C and 19°C and is constant beyond this range. It is also noted that the C at failure for all aging levels at 5°C is averaged to obtain the representative value, and that the LTA1 and LTA2 data are averaged at 19°C because they show similar values. The failure criterion is formulated by the ratio of the aged value to the original (un-aged) value so that it can be universally applied to other mixtures according to aging effect.
FIGURE 5  Failure criterion as a function of temperature and aging.

A scaled parameter, referred to as the condition index ($CI$) and defined by Equation (2), is computed to interpret the loss in material integrity. As this equation indicates, the $CI$ is a variable that ranges from 0 to 1, with 0 being failure and 1 representing a completely intact body.

$$CI = \frac{C_i - C_{f,i}}{C_{intact} - C_{f,i}}$$  \hspace{1cm} (2)

where,

- $CI$ = the condition index,
- $C_{intact}$ = the intact pseudo stiffness value,
- $C_i$ = pseudo stiffness at instant $i$, and
- $C_{f,i}$ = failure pseudo stiffness at instant $i$.

INCORPORATION OF AGING EFFECTS INTO THE VECD MODEL

To incorporate the effects of aging into the VECD model, two major parameters must be evaluated: the viscoelastic property and the damage characteristics. It is analytically possible to include the effects of aging in the formulation of the current constitutive model using another time variable that accounts for the aging time, as shown in Equations (3) and (4). The major advantage of this approach is that the interaction between loading and aging can be modeled realistically, thus allowing a more accurate evaluation of the effects of oxidative aging on mixture performance. Accounting for the effects of aging on the damage growth of asphalt-aggregate mixtures using fundamental principles is probably the best approach to simulate the interaction between damage and aging that occurs simultaneously in actual pavements.

The pseudo strain of an aged material under uniaxial conditions is represented by the hereditary integral shown in Equation (3).
Two time variables are used in this integral: the aging time, \( t \), or the time that has elapsed since the sample was fabricated, and the loading time, \( \xi \). From this equation, the relaxation modulus accounts for the aging effects. The relaxation modulus is a function of aging time, loading time, and temperature, and is given as

\[
E = E(t, t - \tau, T) = E(t, \xi)
\]  

where \( \xi = (t - \tau)/a_T \) and \( a_T \) is the time-temperature \((t-T)\) shift factor. Theoretically, Equation \( (4) \) results in the mastercurves for the different aging times at a specific reference temperature. However, the relaxation mastercurves of the different aged mixtures cannot simply be shifted horizontally or vertically to construct a single mastercurve that includes the effects of aging. Moreover, solving Equation \( (3) \) with the two-dimensional relaxation modulus, Equation \( (4) \), is analytically difficult. Thus, an alternative, quasi-static approach is followed that takes advantage of the relatively long time scale of aging as compared to the time of loading.

All coefficients involved in the \(|E^*|\) curve and damage characteristics curve are plotted against aging time. For the aging time, the laboratory-to-field aging times suggested by SHRP \( (5) \) are selected. This relationship is as follows: 1 year for the STA mix, 4 years for the LTA1 mix, 7.5 years for the LTA2 mix, and 18 years for the LTA3 mix. As a result of analytical investigation, it is found that the sigmoidal coefficients, shift factor coefficients, and the damage evolution rate \((\alpha)\) vary as a function of aging time in power relationships. On the other hand, the damage coefficients are found to change with aging time by following the sigmoidal type of the function.

FIGURE 6 presents the relationship between the sigmoidal coefficients of \(|E^*|\) mastercurve shown in Equation \( (5) \) and aging time as an example. From the equations in the figure, it can be observed that the models are formulated using the ratio of the aged values to the original (un-aged) values. This normalized formulation is chosen so that the final function can be applied universally to other mixtures to simulate aging effects. A more thorough investigation into the correlation between the oven aging and field aging times for LVE and VECD characteristics is beyond the scope of the current research.

\[
\log |E^*| = a + \frac{b}{1 + \frac{1}{e^{d_\log(f_s)}}}
\]  

---

1. \( \varepsilon_R = \frac{1}{E_R} \int_0^{\xi} E(t, \xi) \frac{dE}{d\xi} d\xi \) (3)
FIGURE 6 Relationship of sigmoidal function coefficients to aging time.

4 STRUCTURAL AGING MODEL

The time scale used for the material level aging model corresponds physically only to that used for the top layer of a real pavement cross-section. To apply this model to other depths, the age of each sublayer relative to that of the surface must be found. This goal is achieved by coupling the principles of the Global Aging System (GAS), first proposed by Mirza and Witczak (15), with an effective time concept. The GAS model is probably the most well-known mixture-based aging model, which was developed using viscosity data from field cores obtained throughout the United States and Canada. This empirical model includes functional relationships to predict the change in viscosity within an asphalt mixture both with time and with depth in an asphalt pavement structure.

Due to the time and resource limitations of this study, the GAS model is used to determine the effective time of a given pavement structure. The GAS model predicts the viscosity of the asphalt binder as a function of depth, mean annual air temperature (MAAT) representing the effect of geographical location, and rolling thin film oven (RTFO) binder viscosity. The effective time is determined by finding, for some physical time and depth, the time that gives the same viscosity for the binder at the pavement surface. A flow chart of the structural aging model, including the equiviscosity concept as well as the plot of effective time versus depth for a typical simulation, is shown in FIGURE 7. Detailed explanation of FIGURE 7 could be found in elsewhere (12).
A ten-year-old pavement can serve as an example of the effective time concept whereby after ten years of service, the surface layer has aged ten years, but the material at a depth of three inches may behave as the surface layer behaved when the pavement was only four years old. In this example then, the effective time of the sublayer three inches from the surface is four years. To compute the material properties of this sublayer at year ten, material aging models can be used to find the value of the coefficients at four years.

\[
\eta_{\text{equil},t} = \frac{\eta_{\text{equil}}(4 + A) - A\eta_{\text{equil}}(1 - 4z)}{4(1 + Az)}
\]

\[
\eta(t, d) = \eta(t_e, d_0)
\]

\[
|E^*|(t_i, d_i) = |E^*|(t_e, d_0) = \text{ratio function (}|E^*|_{\text{STA}}\text{)}
\]

\[
\alpha(t_i, d_i) = \alpha(t_e, d_0) = \text{ratio function (}\alpha_{\text{STA}}\text{)}
\]

\[
C(S)(t_i, d_i) = C(S)(t_e, d_0) = \text{ratio function (}C(S)_{\text{STA}}\text{)}
\]

**FIGURE 7** Structural aging model conceptual map.
AGING EFFECT ON PAVEMENT PERFORMANCE

To investigate the effects of aging on fatigue performance in asphalt pavement, pavement simulations are performed using viscoelastic continuum damage finite element program (VECD-FEP++) software (16). This software is the finite element model developed at NCSU. The aging model has been implemented into the VECD-FEP++. The pavement structure is a 304.8 mm (12 in) thick asphalt concrete layer over semi-infinite subgrade. The control mix from the FHWA-ALF study is used for the asphalt concrete layer and the elastic modulus of the subgrade is assumed to be 83 MPa (12 ksi). Pavement temperature profiles were obtained from the enhanced integrated climatic model (EICM) for two regions (Tallahassee, Florida and Laramie, Wyoming) to represent relatively hot and cold climates. The temperatures vary in accordance with time and depth within a given asphalt concrete layer. A moving load is simulated by applying a 0.1 second haversine loading pulse with a magnitude of 40 kN (9 kip) and contact pressure of 689 kPa (100 psi) on the pavement surface, followed by 62.2 seconds of rest period. For the simulations, a single year run was performed, but the input material properties correspond to either the un-aged properties (denoted as No Aging) or the 20 year-aged properties (denoted as Aging). TABLE 3 shows the contour plots after one year simulation. In these contours, the areas with a gray-scale value closest to white correspond to heavily damaged areas, i.e., where the normalized pseudo stiffness values are close to zero. Note that only the asphalt concrete layers are shown. The following observations can be made from the contours shown in TABLE 3:

- Aging can have a noticeable effect on the damage growth in a pavement, particularly at the pavement surface;
- The effects of aging are more significant in climates with higher annual pavement temperatures (Florida) than in cooler climates (Wyoming);
- Although the effects of aging are most noticeable at the pavement surface, aging affects the way stress distributes throughout the pavement and, thus, the way damage accumulates throughout the whole pavement structure.
- Embrittlement due to aging is found to be a major effect, which is captured through an increase in the $C$ at failure.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>FL</th>
<th>WY</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Aging</td>
<td><img src="image1" alt="Contour Plot No Aging Florida" /></td>
<td><img src="image2" alt="Contour Plot No Aging Wyoming" /></td>
</tr>
<tr>
<td>Aging</td>
<td><img src="image3" alt="Contour Plot Aging Florida" /></td>
<td><img src="image4" alt="Contour Plot Aging Wyoming" /></td>
</tr>
</tbody>
</table>

TABLE 3 Aging Effect in Florida and Wyoming Pavements

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CONCLUSIONS

Oxidative aging of asphalt concrete mixtures has been studied at four different laboratory simulated levels. At each level of aging, the mechanical properties were determined via dynamic modulus testing, monotonic direct tension testing, and cyclic fatigue testing. Based on these test results, the effects of aging on the linear viscoelastic and damage properties have been investigated. It is found that the stiffness of an asphalt mixture increases with aging time over all of the frequency ranges and a statistically significant effect on the dynamic modulus exists due to the laboratory aging procedures. With respect to damage properties, aging clearly differentiates the damage characteristic curves of the aged mixtures. From the cyclic fatigue tests, it is found that the S-VECD model can be applied to characterize the damage properties of aged asphalt mixtures and fatigue failure in the asphalt mixture is a function of temperature as well as aging level.

Along with the laboratory test results, the aging effect was incorporated into the existing analytical model in both a material-level and a structural-level form, and finally, the resultant aging model was implemented to the VECD-FEP++. One example simulation was performed by using the developed aging model framework, and the results show that aging clearly affects the fatigue performance, especially at the pavement surface, and is more significant under warm climate conditions.

Further research associated with the aging model for asphalt pavement should include investigation into the relationship between the laboratory aging method and field aging. The laboratory aging method used for this research follows the SHRP method whose aging levels roughly match those of field aging. However, such a relationship may be heavily dependent on material type, environmental conditions, traffic conditions, pavement structure, etc. In addition, the extent to which the laboratory aging levels used in this research age the asphalt mixtures has not yet been proven.

REFERENCES


