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Implementation of the Linear Amplitude Sweep Test to Evaluate Fatigue Resistance of Highly Polymerized Asphalt Binders

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Abstract: Highly polymerized asphalt binders (HPABs) such as PG 64-40 have been increasingly used in cold regions such as Alaska in recent years. However, there are currently considerable data gaps when it comes to the characterizations of the HPABs, especially their fatigue behaviors. The objective of this study is to apply the linear amplitude sweep (LAS) test with the viscoelastic continuum damage (VECD) model to assess the fatigue resistance of HPABs. Three HPABs (PG 52-40, PG 64-40, and PG 52-46) and one unmodified binder (PG 52-28) were used in the study. The fatigue failure during LAS tests on HPABs was defined, and an analysis protocol using the VECD model was proposed based on the experimental results. The analysis protocol was validated by the agreements of the predicted and measured number of cycles to failure in the time sweep (TS) test. The results indicated that the LAS test with the selected analysis protocol can effectively predict the fatigue lives of HPABs. Both the LAS and TS test results showed that the HPABs had higher fatigue resistance than the unmodified asphalt binder. Among the four binders, the PG 64-40 binder exhibited the longest fatigue lives under repeated loadings. **DOI: 10.1061/(ASCE)MT.1943-5533.0004212.** © *2022 American Society of Civil Engineers.*

Author keywords: Highly polymerized asphalt binders (HPABs); Viscoelastic continuum damage (VECD) model; Fatigue characterizations; Linear amplitude sweep (LAS) test.

Introduction

Modification of asphalt binders have become prevalent during the last few decades. Various modifiers (such as polymers, ground tire rubber, chemicals, and recycled engine oils) have been used to produce modified asphalt binders to improve mixture durability against pavement distress (Brown et al. 2009). Among these modifiers, polymers, consisting of clusters of small molecules (monomers) or large molecules with long chains, are commonly used (Brown et al. 2009). Several state transportation agencies, including Alaska Department of Transportation and Public Facilities (ADOT&PF), have recognized the benefits of using polymer-modified asphalt in flexible pavements (Liu and Liu 2019). ADOT&PF has recently become interested in the potential use of the highly polymerized asphalt binders (HPABs) in asphalt pavements. HPABs are defined as modified asphalt binders with high polymer concentration (about 7% by the weight of the neat binder) to suit its specific climatic conditions. Several projects with HPABs have been constructed in Alaska in recent years (Liu and Liu 2019; Liu et al. 2020). A mixture with PG $64-40$ was placed in downtown Anchorage to address the rutting and wearing concerns in high-traffic areas and moderate low-temperature cracking–related distresses. As HPABs have become popular, however, the current understanding about the mechanical properties and behaviors of the HPABs among researchers and practitioners is limited.

Fatigue damage is one of the primary distresses on asphalt pavements. It typically occurs in the form of cracking underneath the wheel path due to repeated traffic loading. The fatigue resistance of asphalt binder has been found to have great contributions to the fatigue performance of asphalt concrete (Ameri et al. 2017; Cao et al. 2018; Liu et al. 2018; Abdollahi et al. 2020; Shan et al. 2020). As such, it is crucial to appropriately characterize the mechanical properties of asphalt binders that are related to fatigue damage. One of the common methods to evaluate the fatigue performance of asphalt binder is the Superpave fatigue factor (i.e., $G^* \cdot \sin\delta$), which was proposed during the Strategic Highway Research Program (SHRP) and was based on the linear viscoelastic properties of asphalt binder. However, $G^* \cdot \sin\delta$ has been reported to lack the capability to characterize the fatigue resistance of asphalt binders dominated by nonlinear behaviors under loading, especially modified asphalt binders (Hintz et al. 2011; Wang et al. 2015; Cao and Wang 2018). To overcome the limit of the Superpave fatigue factor and introduce the concept of damage accumulation, during the National Cooperative Highway Research Program (NCHRP) 9-10 research project, researchers developed the time sweep (TS) test (Bahia et al. 2001). In the TS test, the asphalt sample is subjected to repeated cyclic shear loading in either the stress-controlled or the strain-controlled mode applied by a dynamic shear rheometer (DSR). The test results from the NCHRP 9-10 study indicated that the TS tests showed significant correlation with fatigue damage in asphalt concrete and was a promising method to evaluate the fatigue performance of asphalt binders (Bahia et al. 2001). However, previous studies (Anderson et al. 2001; Shenoy 2002) pointed out that the TS test is not applicable for binders with a modulus lower than 5 MPa because the asphalt sample could flow out from the

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DSR plates during testing. In addition, the TS test was time consuming (Brown et al. 2009; Cao and Wang 2018; Hintz and Bahia 2013). Recently, the linear amplitude sweep (LAS) test was introduced to overcome the limitations of the TS test (Johnson 2010). Like the TS test, the LAS test is also conducted with DSR using the 8-mm parallel plate geometry. Unlike the repeated cyclic shear loading in the TS test, the LAS test involves oscillatory shear loads with increasing strain amplitudes under strain-control mode, which reduces the testing time from several hours down to minutes.

In 2011, Hintz et al. (2011) adopted the viscoelastic continuum damage (VECD) model to analyze the LAS test results. The model has been successfully used to model the fatigue behaviors of asphalt mixtures (Kim and Little 1990; Underwood et al. 2012; Wang et al. 2018, 2020). Research studies have reported that the predicted fatigue lives of binders from the LAS test with the VECD model correlate well with the field observations of fatigue cracking on asphalt pavements (Hintz et al. 2011; Wang et al. 2015). One merit of VECD theory is that the fatigue behaviors of asphalt materials at various loading conditions can be predicted from one single test at a certain testing condition (Johnson 2010; Notani et al. 2019; Abdollahi et al. 2020). However, although the LAS test and the VECD model have been successfully applied to characterize the fatigue behaviors of some asphalt binders, they have not been applied on the HPABs. One of the challenges is to define the fatigue failure of the HPAB binder during the fatigue test. This study was conducted to address these difficulties and propose an implementable LAS test and analysis protocol to evaluate HPAB binders.

Objectives

The objectives of this study are to (1) develop an appropriate the VECD model analysis protocol for the HPABs, (2) validate the proposed analysis protocol by comparing the predicted fatigue life of the HPABs with the measured fatigue life from the TS test, and (3) evaluate fatigue resistance of HPABs using LAS with the VECD model.

Viscoelastic Continuum Damage Model

The analysis of LAS test data is usually performed using the VECD model. The model can predict the fatigue life of asphalt binder at various loading conditions from a single test (Hintz et al. 2011). Schapery's theory of work potential [Eq. (1)] is applied to model the fatigue damage accumulation (Schapery 1984)

$$\frac{dS}{dt} = \left(\frac{\partial W}{\partial S}\right)^{\alpha} \quad (1)$$

where t is time; S is the damage intensity; α is a material constant that represents damage evolution rate, which is one of the essential parameters that impacting the VECD analysis results, and will be discussed specifically in the following sections; and W is the work quantified by the dissipated energy, which is represented by Eq. (2)

$$W = \pi \cdot \gamma_0^2 \cdot |G^*| \sin \delta \quad (2)$$

where, γ_0 is the shear strain, G^* is the complex shear modulus (MPa), and δ is the phase angle (degrees).

Substitute Eq. (2) into Eq. (1), the damage intensity (S) can be represented by

$$S(t) \cong \sum_{i=1}^{N} [\pi \gamma_0^2 (C_{i-1} - C_i)]^{\frac{\alpha}{(1+\alpha)}} (t_i - t_{i-1})^{\frac{1}{(1+\alpha)}} \quad (3)$$

where i indicates the cycle number, t_i is the time at the end of the cycle i, and the material integrity (C) is given by normalized $|G^*| \sin \delta$. A power law is used to model the relationship between the damage intensity (S) and the material integrity (C)

$$C = 1 - C_1 (S)^{C_2} \quad (4)$$

where C_1, and C_2 are curve-fit coefficients.

Combining Eqs. (1)–(4), a closed-form solution between fatigue life (N_f) and the expected strain amplitude for the loading condition of interest (γ) can be obtained

$$N_f = \frac{f(S_f)^{1+(1-C_2)\alpha}}{k(\pi C_1 C_2)^{\alpha}} (\gamma)^{-2\alpha} \quad (5)$$

$$k = 1 + (1 - C_2)\alpha \quad (6)$$

where f is the loading frequency (i.e., 10 Hz); and S_f is the damage intensity at specimen's failure per the specification AASHTO T 391 (AASHTO 2020), which is closely related to the definition of the sample failure of the test.

Materials and Testing Details

The asphalt binders evaluated in this study include one unmodified asphalt binder (PG 52-28) and three HPABs (i.e., PG 52-40, PG 64-40, and PG 52-46). The binders were collected from a supplier in Alaska. Each asphalt binder was conditioned to three aging extents: short-term aging with rolling thin film oven (RTFO) [AASHTO T 240 (AASHTO 2021a)], long-term aging with pressure aging vessel (PAV) [AASHTO R 28 (AASHTO 2021b)], and prolonged aging, during which the RTFO residual was subjected to PAV aging at 100°C and 2.1 MPa for 40 h. The 40-h PAV conditioning was applied to simulate the prolonged aging time in the field (Anderson et al. 2011). Table 1 presents the low-temperature rheological properties of the studied binders. More detailed information about the binders can be found in the recently published technical report (Liu and Liu 2019).

The frequency sweep tests at different temperatures (i.e., 5°C, 15°C, 15°C, and 35°C) were conducted using a DSR on binders at three different aging states (i.e., RTFO, 20-h PAV, and 40-h PAV). The testing frequency ranged from 0.1 rad/s to 100 rad/s. The 8-mm parallel plate geometry with a 2-mm gap was adopted. The binders were tested under the strain-controlled mode within the linear viscoelastic range. The complex modulus data at various

Table 1. Bending beam rheometer results of the studied binders at 20-h PAV

	−12°C		−18°C		−24°C		−30°C		−36°C		−40°C	
Binder	S (MPa)	m	S (MPa)	m	S (MPa)	m	S (MPa)	m	S (MPa)	m	S (MPa)	m
PG 52-28	85	0.39	200	0.33	434	0.27	—	—	—	—	—	—
PG 52-40	—	—	—	—	67	0.38	149	0.33	352	0.28	—	—
PG 64-40	—	—	—	—	60	0.38	150	0.34	329	0.30	—	—
PG 52-46	—	—	—	—	—	—	87	0.38	209	0.33	466	0.28

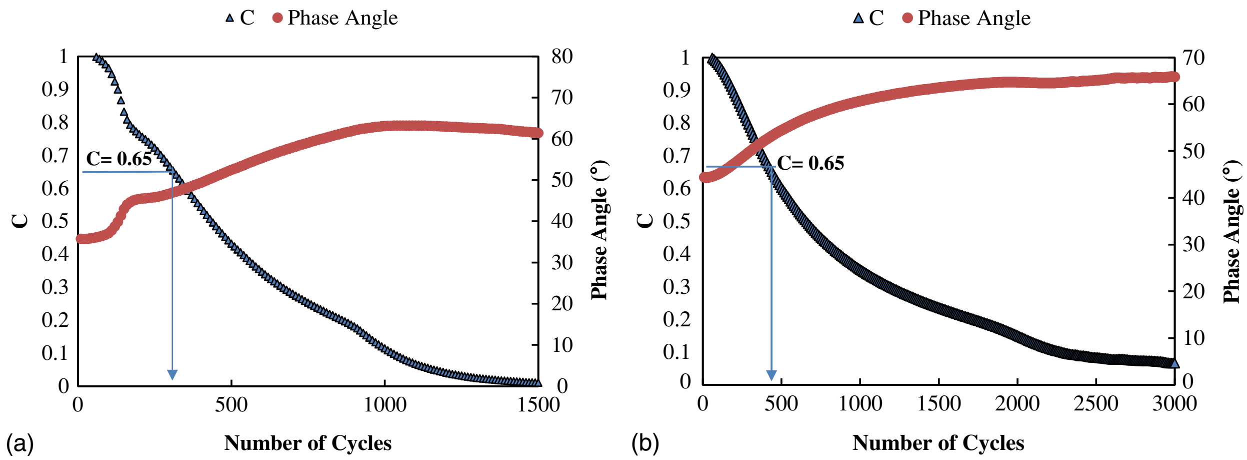

Fig. 1. Phase angle response under repeated loading: (a) unmodified binder; and (b) HPAB (PG 52-40).

frequencies were collected to construct the master curve. The master curve was used to calculate the damage evolution rate, α, in the VECD model.

The standard LAS tests were conducted on the binders with three different aging states (i.e., RTFO, 20-h PAV, and 40-h PAV) at 10°C following the procedure in AASHTO T 391 with the same DSR. The 8-mm parallel plate geometry with a 2-mm gap was adopted. The LAS test consists of two parts: the frequency sweep test and the amplitude sweep test. The frequency sweep test was performed with 0.1% strain amplitude over a range of frequency from 0.2 to 30 Hz. The amplitude sweep test was conducted by applying an oscillatory shear load linearly increased from zero to 30% over the course of the 3,100 cycles of loading at a frequency of 10 Hz. Further, the TS test was performed at 10°C under the strain-controlled mode to validate the proposed VECD analysis protocol. The chosen strain levels for this study are 2.5% and 5%. For each test, two duplicates were used.

Results and Analysis

A damage characteristic curve can be obtained from the LAS test data when analyzed using the VECD model. This damage characteristic curve indicates the relationship between the loss of the material integrity (C) and the growth of the damage intensity (S). Theoretically, each asphalt binder has a unique damage characteristic curve that is independent of testing conditions (i.e., mode of loading, load amplitude, frequency, temperature, and loading history). According to Eq. (5), the S_f, defined as the damage intensity at specimen's failure, and the damage evolution rate (α) are two important parameters that can impact the model prediction results dramatically. To apply the appropriate analysis protocol for HPABs, the study focuses on the identification of the specimen fatigue failure during LAS tests and the computation of the damage evolution rate.

Specimen Failure Definition

Appropriately defining asphalt failure under repeated loading during the fatigue test is important for asphalt fatigue characterization. As for HPABs, the definition of the failure point is critical because the HPABs usually do not exhibit sudden drops in modulus and phase angle at the end of fatigue tests, as presented in Figs. 1(a and b). One conventional fatigue failure definition for asphalt mixtures is the reduction in stiffness of mixtures to a certain level [for example, 50% drop in flexural stiffness in the four-point bending beam test (AASHTO 2017)]. When the LAS test was first introduced (Johnson 2010), the asphalt fatigue failure was defined as 35% drop in material integrity (i.e., $C = 0.65$). According to Johnson (2010), this failure definition was selected based on the good correlation between the predicted fatigue life of asphalt binders and field fatigue performance and has been incorporated into the AASHTO T 391 specification. However, studies pointed out that this failure definition was determined arbitrarily and based on a limited number of asphalt binders (Hintz et al. 2011; Cao and Wang 2018). Fig. 2 presents the predicted fatigue life (at strain level of 2.5%) of the HPABs using the VECD model with fatigue failure defined as 35% drop in material integrity. The damage evolution rate (α) was defined as $1 + 1/m$ with m defined as the slope of the best-fit straight line with log ω on the horizontal axis and log storage modulus (G') on the vertical axis. It has been well accepted that the asphalt binders with more aging extent are more susceptible to fatigue damage than the ones with less aging extent. However, as presented in Fig. 2, for the HPABs, the predicted fatigue lives did not follow this trend. For PG 52-40 and PG 64-40, the binder subjected to 40-h PAV showed longer predicted fatigue life than that with 20-h PAV aging extent. The disagreement between the predictions and the accepted expectations can be attributed to the fact that some binder was able to retain its structural integrity after C decreased to 0.65. This observation indicates using $C = 0.65$ because the failure indicator may not be a suitable approach for HPABs.

Alternatively, the peak in phase angle and the peak in shear stress have also been used to define failure for asphalt mixtures and have

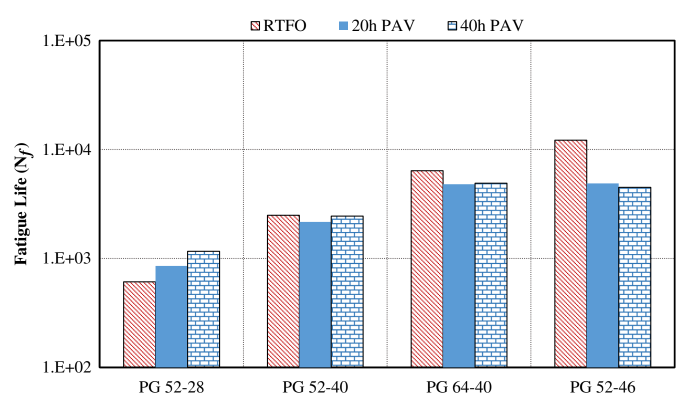

Fig. 2. Predicted fatigue life of the HPAB from the LAS test based on AASHTO T 391: failure defined as 35% drop in material integrity.

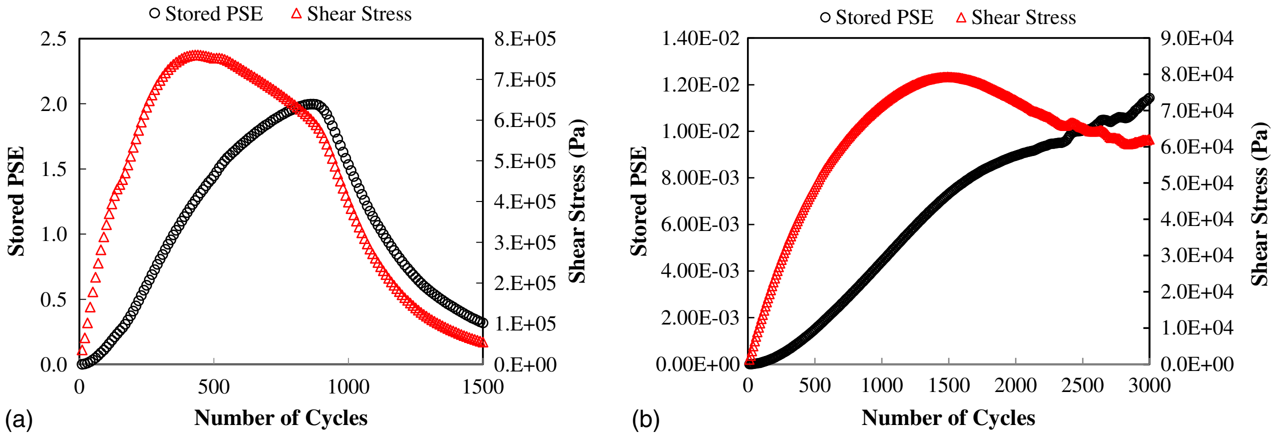

Fig. 3. PSE response under repeated loading: (a) unmodified binder; and (b) HPAB (PG 52-46).

been shown to correlate well with the onset of macro cracking of asphalt mixtures (Wang et al. 2015; Castelo Branco et al. 2008; Zhang et al. 2013; Safaei et al. 2014; Wang and Kim 2017). The peak in phase angle can be understood as the point that corresponds to the maximum load repetitions that the asphalt binder can bear (Zhang et al. 2013; Safaei et al. 2014). For the HPABs, however, the peak in phase angle, as shown in Figs. 1(a and b), is hard to detect.

In recent years, the concept of pseudo strain energy (PSE) has also been used to define failure in the LAS test (Wang et al. 2015). Figs. 3(a and b) illustrate the schematic of PSE. The accumulated dissipated PSE has been utilized to define the fatigue failure for asphalt binders and mixtures during fatigue tests (Wang et al. 2015; Zhang et al. 2013; Wang and Kim 2017; Sabouri and Kim 2014). The stored PSE in each cycle in this study is calculated based on the definition presented in Eq. (7), which represents the PSE that is stored at each loading cycle

$$PSE = \frac{\tau_p}{2 \times \gamma_p^R \times DMR}(\gamma_p^R)^2 \tag{7}$$

$$\gamma_p^R = \gamma_{pi} \times |G^*|_{LVE} \tag{8}$$

where τ_p is the effective (measured) peak shear stress in a given cycle; DMR is the dynamic modulus ratio, equal to $|G^*|_{\text{fingerprint}}/|G^*|_{\text{LVE}}$; and $|G^*|_{\text{LVE}}$ is the linear viscoelastic dynamic shear modulus at a given temperature and loading frequency.

In some studies, the peak of the PSE versus N curve, as presented in Fig. 3(a), has been used to indicate the fatigue failure (Wang et al. 2015). However, for the HPABs, the stored PSE peak value cannot be detected in some cases [as shown in Fig. 3(b)].

The peak in the shear stress versus N curve has been interpreted as the yield threshold of asphalt binder under repeated traffic loading (Wang et al. 2015). The peaks in the shear stress versus N curve and the phase angle versus N curve are believed to be superposition to some extent (Wang et al. 2015). For HPABs, while the number of cycles to failure corresponding to phase angle peak could not be obtained, it can be observed that the measured shear stress exhibited a clear peak during the test [Figs. 4(a and b)]. As shown in Fig. 4(a), for unmodified binder, the number of cycles to failure corresponding to shear stress peak was close to the cycle where C was equal to 0.65. However, for HPABs [Fig. 4(b)], the C was much lower than 0.65 when the shear stress reached the peak point. In other words, the HPAB specimens did not fail when C dropped to 0.65. In summary, using the peak in shear stress to define asphalt binder failure under repeated loading during the LAS test can be considered as a more suitable failure definition for HPABs than other approaches (i.e., 35% drop in C, the peak of phase angle, and peak in stored PSE).

Fig. 5 presents the numbers of cycles to failure of the asphalt binders based on the shear stress peak failure definition measured in the LAS tests. The results were validated by the generally accepted rule: for each asphalt binder, the sample with more severe

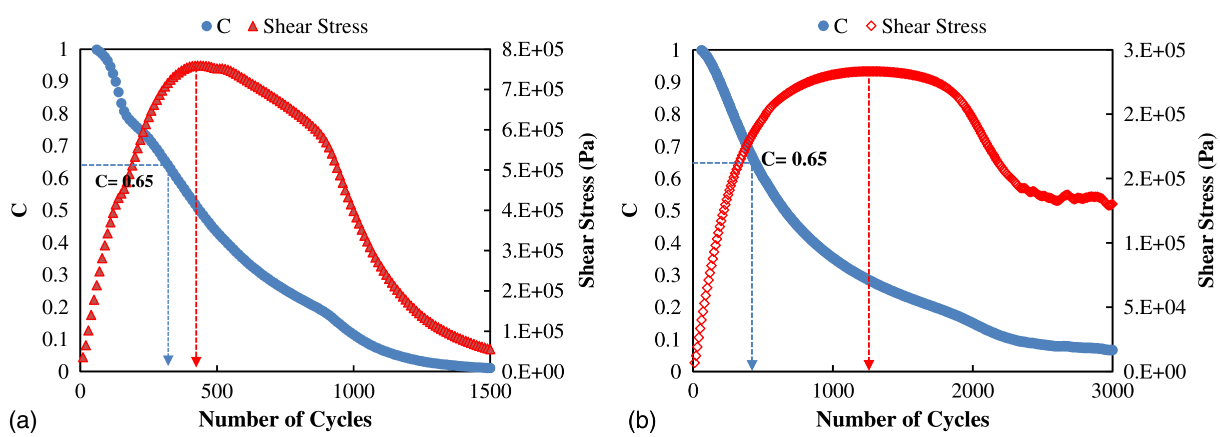

Fig. 4. Shear stress response under repeated loading: (a) unmodified binder; and (b) HPAB (PG 52-40).

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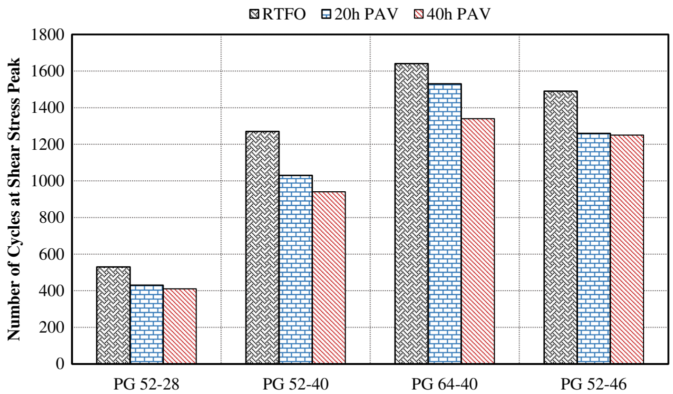

Fig. 5. Number of cycles corresponding to the peak of shear stress in LAS tests.

aging conditions usually has lower number of cycles to failure. It can be seen from Fig. 5 that the number of cycles to failure of a given asphalt binder decreased with asphalt aging level increased. Based on this observation, the peak in shear stress versus N can be considered as a reasonable fatigue failure definition for HPABs in the LAS tests.

Definition of Damage Evolution Rate

The damage evolution rate (α) is defined as a material-dependent parameter, and it is a key element to appropriately characterize fatigue performance of asphalt binder in the LAS test. AASHTO T 391 defines α as $1 + 1/m$ with using the following procedures to obtain the m parameter:

1. A frequency sweep test with the strain-controlled mode (0.1% strain) is conducted at the desired temperature (the same as the temperature used in the LAS test). The testing frequency ranges from 0.2 to 30 Hz, including 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 4.0, 8.0, 10, 20, and 30 Hz.
2. The storage modulus (G') values at different frequency (ω) are collected.
3. The storage modulus (G') versus frequency (ω) is plotted in a log-log scale, and a slope of best-fit line is obtained as m parameter

$$Log(G') = m \log \ \log(\omega) + k \tag{9}$$

However, studies reported that α calculated based on AASHTO T 391 was dependent on the testing temperature and loading history, which was contrary to the precondition of VECD theory that α should be a material-dependent parameter and independent on testing conditions (Cao and Wang 2018). Safaei et al. (2016) recommended a new definition of α parameter. Researchers proposed that the m parameter can be obtained from the complex modulus master curve by fitting the data using the Christensen–Anderson–Marasteanu (CAM) model (Marasteanu and Anderson 1999)

$$G^*_{(\omega)} = \mathrm{G}_g \left[1 + \left(\frac{\omega_c}{\omega}\right)^{(\log 2)/R}\right]^{-mR/(\log 2)} \tag{10}$$

where $G^*(\omega)$ is complex modulus; G_g is glass modulus assumed equal to 1 GPa; ω is the reduced frequency (rad/s); ω_c is crossover frequency; and R is rheological index.

The α computed based on the complex modulus master curve is independent of testing conditions and can reveal the damage evolution rate of asphalt binder. Cao and Wang (2018) also indicated that defining the α parameter as $1 + 1/m$ with m obtained from the CAM model could result in damage characteristic curves independent of testing temperatures and loading history.

Figs. 6(a and b) present the fatigue lives in the TS tests predicted using the VECD model coefficients obtained from the LAS tests. The prediction results with α computed from the CAM model master curve [Fig. 6(b)] exhibits higher correlation with the measured N_f in the TS tests than those with α defined in AASHTO T 391. Therefore, the α defined using the CAM model master curve is considered as a reasonable damage rate definition for HPABs. Note that the failure in the TS test was determined by the number of cycles at the stiffness (complex modulus) reduced by 50%, which is the most commonly used specimen failure definition for the TS test (Hasan et al. 2019). Other failure definitions for the TS test, such as the peak in shear, the peak in phase angle, and the peak in PSE, were evaluated in the study; however, for HAPBs, the peaks of such curves from the TS tests could not be observed. Figs. 6(a and b) present the comparisons of the predicted and measured fatigue lives of HPABs at 10°C with two strain levels (i.e., 2.5% and 5%). It should be noted that the data for PG 64-40 at a strain level of 2.5%

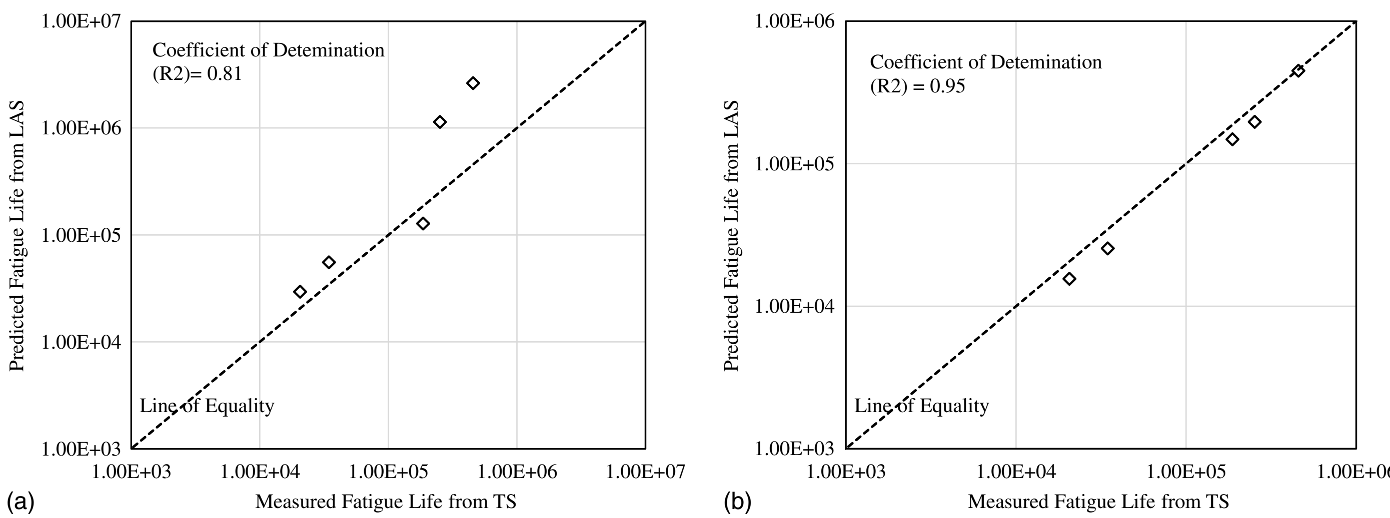

Fig. 6. Comparison of predicted and measured fatigue lives of HPABs in TS tests: (a) definition of α in AASHTO T 391; and (b) definition of α based on the CAM model.

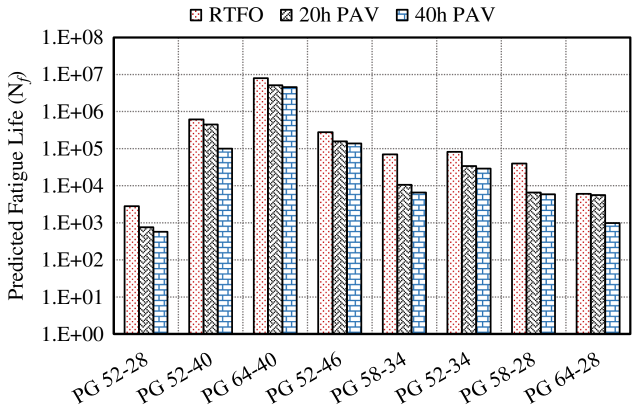

Fig. 7. Predicted fatigue lives of the commonly used polymer modified asphalt binders in Alaska.

was excluded from the figure because the specimens never reached failure under that strain level during the tests. As shown in Fig. 6(b), the predicted fatigue lives of the HPABs correlated well with the measured fatigue lives from the TS tests with a coefficient of determination (R^2) of 0.95, indicating that the selected analysis protocol could effectively predict the fatigue lives of the studied HPABs.

The recommended VECD analysis protocol (peak in shear stress as failure definition; $\alpha = 1 + 1/m$ with m parameter obtained from the CAM model) has also been phenomenally validated through assessing its sensitivity to aging using the polymer-modified asphalt binders in Alaska (HPABs along with PG 58-34, PG 52-34, PG 58-28, and PG 64-28). Fig. 7 presents the predicted fatigue lives of the other commonly used polymer modified binders at a strain level of 2.5% and 10°C. As shown in this figure, the fatigue lives of all the studied asphalt binders deceased with the increase of the aging extent, which was consistent with the well-accepted statement that the asphalt binder with more severe aging extent is more susceptible to fatigue damage. In addition, it can be observed from Fig. 7 that the modified asphalt binders showed higher predicted fatigue lives than the unmodified asphalt binders, which were consistent to the field observations reported in the reference (Liu and Liu 2019).

Fatigue Characterization of HPABs

Figs. 8(a–c) present the stress–strain relationships of the HPABs at different aging states from the LAS tests. It can be seen from this figure that the HPABs had different responses than the unmodified asphalt binder. The unmodified asphalt binder (PG 52-28) reached the stress peak at a much lower strain level and the peak stress value was much higher than the HPABs, regardless of aging states. In addition, it can be found from Figs. 8(a–c) that the HPABs had lower falling slopes than those of the unmodified asphalt binder, indicating lower damage evolution rates after the crack initiates. Figs. 9(a–c) present the damage characteristic curves of the HPABs at different aging states at a reference temperature of 10°C. As can be seen from Figs. 9(a–c), the unmodified asphalt binder (PG 52-28) had the lowest damage characteristic curve among all the studied

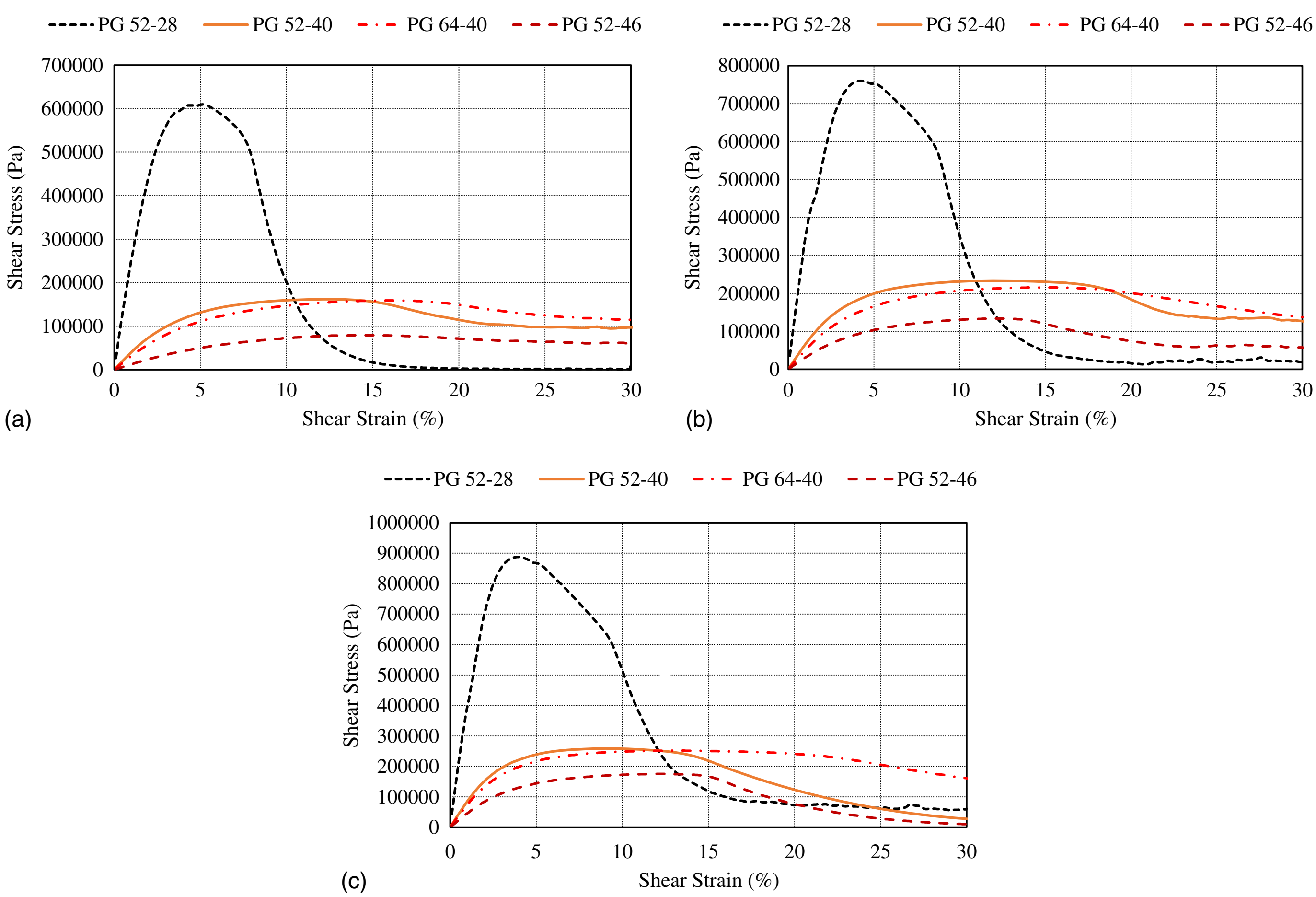

Fig. 8. Stress–strain relationships of the studied HPABs at different aging states: (a) RTFO; (b) 20-h PAV; and (c) 40-h PAV.

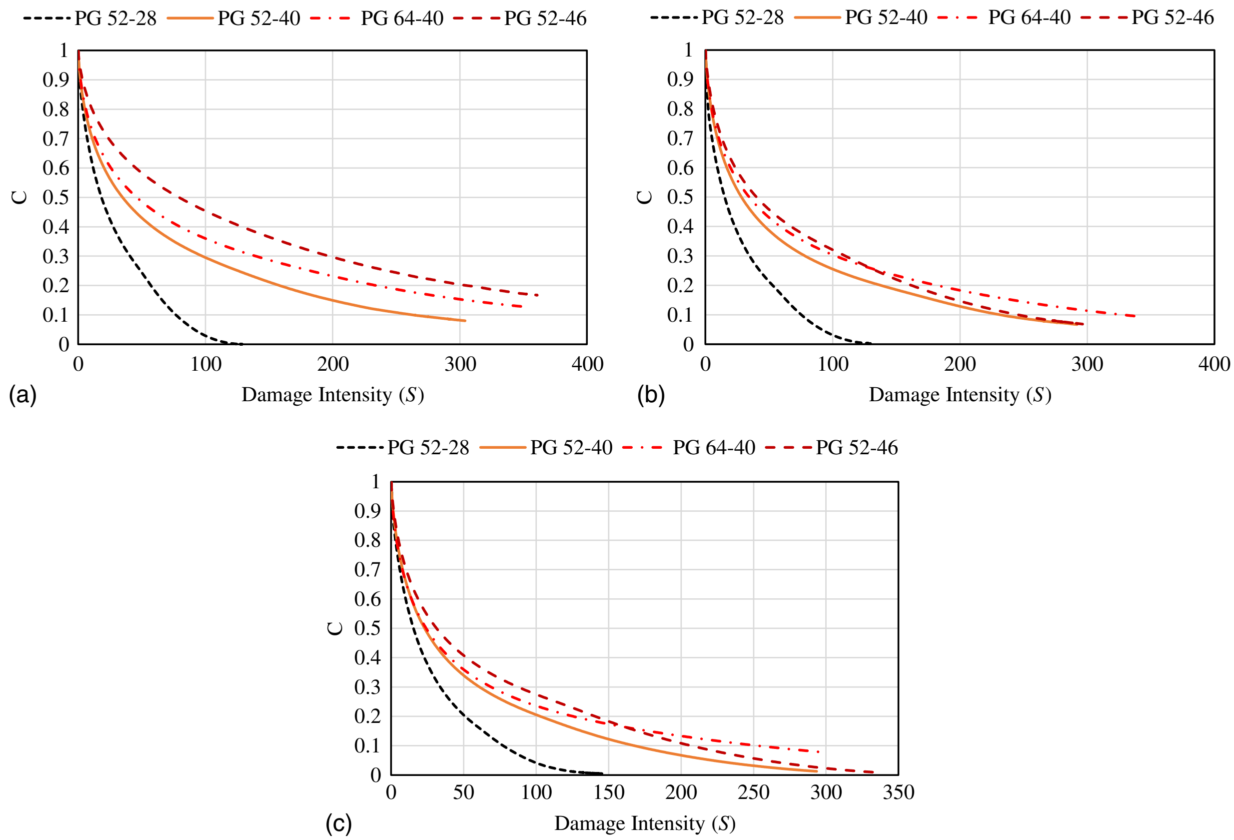

Fig. 9. Damage characteristic curves of the studied HPABs at different aging states: (a) RTFO; (b) 20-h PAV; and (c) 40-h PAV.

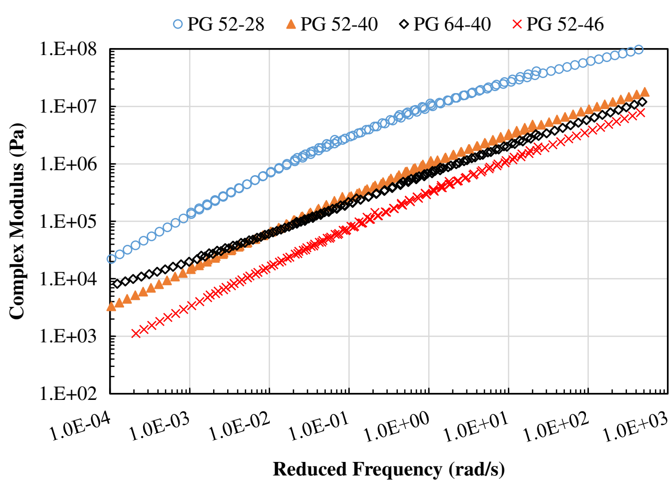

Fig. 10. Complex modulus master curves of HPABs.

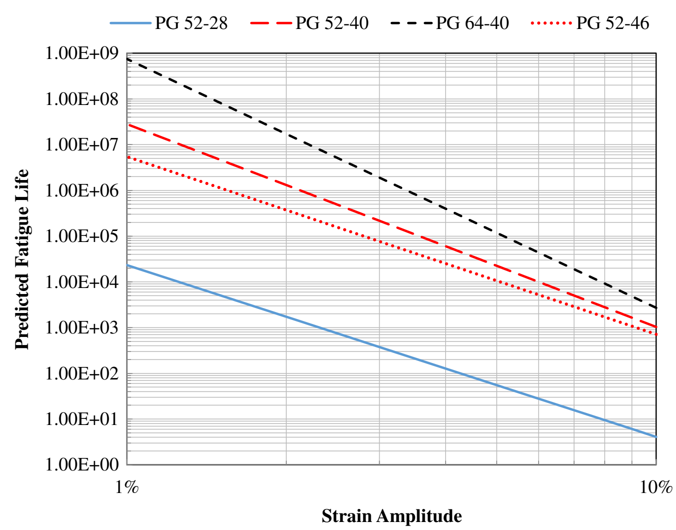

Fig. 11. Predicted fatigue lives of HPABs under different strain amplitudes based on the selected VECD analysis protocol.

asphalt binders at each aging state while the unmodified asphalt binder showed higher stiffness than the HPABs at 10°C (Fig. 10). This observation indicates that the HPABs exhibit lower integrity deterioration rate as damage accumulates.

Fig. 11 presents the predicted fatigue lives of HPABs along with unmodified asphalt binder (20-h PAV) at 10°C under different expect strain amplitudes, based on the recommended VECD analysis protocols. As shown in this figure, the HPABs showed higher fatigue lives than the unmodified asphalt binder at the same strain levels. Among all the studied HPABs, PG 64-40 showed the highest fatigue lives, followed by PG 52-40 and PG 52-46. The differences in fatigue lives for the HPABs could be attributed to either the variations on the polymer concentration or different interaction between polymer and asphalt binder.

Conclusions

This study characterizes the fatigue performance of the HPABs used in cold regions such as Alaska by using the LAS tests with the VECD model. Three HPABs (PG 52-40, PG 64-40, and PG 52-46) along with unmodified asphalt binder (PG 52-28) were evaluated. An appropriate VECD model analysis protocol in terms of the specimen failure definition and damage evolution rate computation was recommended based on the experimental results. The VECD model was validated through assessments on the commonly used polymer modified asphalt binders and via correlating the predicted fatigue lives with the measured fatigue lives from the TS tests. Based on the testing results, the following conclusions can be drawn:

- The peak in shear stress versus number of cycles (N) could be used to define asphalt binder specimen failure under repeated shear loading during the LAS test for the HPABs.
- The damage evolution rate (α) can be defined as $1 + 1/m$ with the m parameter obtained from the complex modulus master curve by fitting the data using the CAM model for HPABs.
- The LAS test with VECD model can effectively predict the fatigue lives of the studied HPABs. There was a good correlation between the predicted fatigue lives from the LAS test and measure fatigue lives from the TS tests for the HPABs.
- Both the LAS and TS test results showed that the HPABs had better fatigue resistance (longer fatigue lives) than the unmodified asphalt binder. The PG 64-40 performed the best in terms of fatigue resistance among all the studied asphalt binders due to its high polymer concentration.

Data Availability Statement

All data, models, and code that support the findings of this study are available from the corresponding author upon reasonable request.

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