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Fatigue Performance of Rubberized Stone Matrix Asphalt by a Simplified Viscoelastic Continuum Damage Model

Zhaoxing Xie¹ and Junan Shen, Ph.D., M.ASCE²

Abstract: The study investigated the fatigue performance of rubberized stone matrix asphalt (SMA) in the dry process and compared its fatigue characterization with SMAs with other typical binders. Five SMA mixtures were used with the following asphalt binders: (1) virgin asphalt of PG 67-22, (2) crumb rubber modifier (CRM) modified in wet process, (3) CRM modified in dry process, (4) terminal-blend binder, and (5) styrene-butadiene-styrene (SBS) modified binder. Dynamic modulus and direct-tension fatigue tests were performed using the asphalt mixture performance tester (AMPT) system. In addition, improved linear amplitude sweep (LAS) tests were performed on the binders by a dynamic shear rheometer (DSR). The fatigue test data were analyzed by the simplified viscoelastic continuum damage (S-VECD) theory. The results showed that (1) dynamic modulus of the rubberized SMA in the dry process was similar to that of the wet process and higher than that of SMA with virgin asphalt, although a little lower than those of SMAs with terminal-blend binder or SBS binder at high temperatures; (2) the damage resistance and fatigue life of the rubberized SMA in the dry process are higher than those of SMA with virgin asphalt and similar or slightly higher than with the wet process, but lower than SMAs with terminal-blend binder or SBS binder; and (3) the virgin binder had lower damage resistance and fatigue life, followed by the CRM binder in the wet process, the terminal-blend binder and SBS binder had higher damage resistance and fatigue life. This is consistent with the mixture results for the direct-tension fatigue tests. DOI: 10.1061/(ASCE)MT.1943-5533.0001463. © 2015 American Society of Civil Engineers.

Author keywords: Stone matrix asphalt; Crumb rubber; Dry process; Fatigue performance; Viscoelastic continuum damage model.

Introduction

A crumb rubber modifier (CRM) is introduced into asphalt mixtures by a wet process or a dry process. Considerable research has indicated that rubberized mixtures in the wet process exhibited better resistance to permanent deformation and fatigue compared to conventional mixtures (Cooper et al. 2007; Hicks et al. 1995; Huang et al. 2002; Xiao et al. 2007). However, the performance properties of rubberized mixtures in the dry process have been inconsistent, with service life varying from 2 to 20 years (Rahman et al. 2004), depending on the type of mixture and paving method.

In the traditional dry process, a larger size (4–18 mesh) and higher dosage (1–3% by mass of the total aggregate) of CRM is mixed directly with aggregate and binder in the drum to produce a rubberized mix. Recently, CRM in a modified dry process was used in stone matrix asphalt (SMA) mix as a substitute for styrene-butadiene-styrene (SBS) in Georgia: the smaller size (30 or 40 mesh) and lower content of CRM (about 0.6% by mass of the total aggregate) as well as a cross-link agent [transpolyoctenamer (TOR) polymer] were used to produce rubberized mixtures. The field research showed that rubberized SMA pavement in this dry process exhibited good conditions after three years in service (Shen and Xie 2012; Xie and Shen 2013). However, the long-term performance (i.e., fatigue life) of rubberized SMA in this dry process is still unclear. It is also unclear how the introduction methods of CRM (wet process and dry process) affect the fatigue performance of SMA.

Accurate description and prediction of fatigue resistance in rubberized asphalt mixtures are extremely important to flexible pavement design and preservation, and pavement engineers can select the better introduction methods of CRM into rubberized SMA based on their fatigue properties. However, the relative research was scant, and how the differences in dry and wet methods for introducing CRM affect the fatigue performance of porous European mixture (PEM) and SMA mixtures was unclear. Therefore, a study comparing their fatigue performance was needed.

Objectives

• To investigate the fatigue performance of rubberized SMA in the dry process used in Georgia;
• To compare the fatigue performance of rubberized SMA in the dry process with that of SMAs with different binders (i.e., virgin asphalt, CRM binder in the wet process, and SBS-modified binder); and
• To examine the influence of the introduction methods of CRM into SMA on the fatigue-performance characteristics, i.e., in wet process and in dry process.

Scope

In this study, five types of binders were used in five SMA mixtures, respectively. Optimum asphalt contents (OAC) of five SMA mixtures were designed according to the specification of SMA design GDT 123. Dynamic modulus and direct-tension fatigue tests were conducted on SMA mixtures using an asphalt mixture performance tester (AMPT). In addition, the improved linear amplitude sweep (LAS) tests were performed on the binders by a dynamic shear

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rheometer (DSR) to determine the fatigue life of the binders used and to develop the fatigue life relationship between SMA mixtures and binders. The fatigue test data from direct-tension fatigue tests and LAS tests were analyzed by the simplified viscoelastic continuum damage (S-VECD) theory.

**S-VECD Theory**

The S-VECD model is based on the elastic–viscoelastic correspondence principle, the work-potential theory, and the temperature-time superposition principle (Hou 2009; Underwood et al. 2006, 2010, 2012). The elastic–viscoelastic correspondence principle is used to model the viscoelastic behavior of a material by replacing physical strain with pseudostrain Eq. (1). The time–temperature superposition principle combines their effects on asphalt mixture response by shifting modulus values at different temperatures to a certain reference temperature. The work-potential theory (Schapery 1984) is then applied to model both damage growth and healing (Kim et al. 2009). In the S-VECD model, a damage parameter, $S$, is defined as all structural changes that result in reduced stiffness as the asphalt mixture undergoes loading. Stiffness reduction is defined by the pseudostiffness, which is typically normalized for specimen-to-specimen variability by the initial pseudostiffness, $I$, and denoted as $C$ in Eq. (2) (Kim et al. 2009)

$$
\varepsilon^{R} = \frac{1}{E^{R}} \int_{0}^{t} E(t-\tau) \frac{d\varepsilon}{d\tau} d\tau
$$

where $\varepsilon^{R} = \text{pseudostrain}$; $\varepsilon = \text{actual strain}$; $E^{R} = \text{reference modulus}$, which is an arbitrary constant; and $E(t) = \text{relaxation modulus}$

$$
C = \frac{\sigma}{\varepsilon^{R} \times I}
$$

The three fundamental functions for the continuum damage theory based on Schapery’s work-potential theory are as follows:

- the pseudostrain energy density function
  $$
  W^{R} = f(\varepsilon^{R}, S) = \frac{1}{2} \sigma \varepsilon^{R} = \frac{1}{2} (\varepsilon^{R})^{2} C
  $$

- the stress-pseudostrain relationship
  $$
  \sigma = \frac{\partial W^{R}}{\partial \varepsilon^{R}} = C(S) \varepsilon^{R}
  $$

- the damage evolution law
  $$
  \frac{dS}{dt} = \left(-\frac{\partial W^{R}}{\partial S}\right)^{\alpha}
  $$

where $W^{R} = \text{pseudostrain energy density}$; $\varepsilon^{R} = \text{pseudostrain}$; $S = \text{damage parameter (internal state variable)}$; and $\alpha = \text{damage evolution rate}$.

**Experimental**

**Materials and Sample Preparation**

To achieve the objectives of this study, five SMA mixtures were used with different asphalt binders: virgin asphalt of PG 67-22 (called virgin SMA), CRM modified in wet process (called wet-process SMA), CRM modified in dry process (called dry-process SMA), terminal-blend binder (both CRM and SBS modified, called terminal SMA), and SBS-modified binder (called SBS SMA). The wet-process binder was produced by mixing a 30-mesh CRM at 10% of the weight of the asphalt binder with a virgin binder of PG 67-22 at 170°C and 700 RMP for 45 min in the laboratory. The dry-process binder used the same CRM and virgin binder, which were introduced into aggregates together with a cross-link agent—TOR polymer at 4.5% of the weight of the CRM.

To avoid excessive drain-down, cellulose fiber at 0.35% by weight of the total mixture was added to all mixtures. For antistripping purposes, hydrated lime at 1.0% by the weight of the total aggregate was used in all mixtures. The gradation of 12.5-mm SMA shown in Table 1 was designed in accordance with Georgia’s mix-design procedure (Section 828), and OAC of SMA mixtures were designed according to the specification of SMA design (GDT 123). Table 2 presents the OAC of the SMA mixtures.

Dry-processed PEM is mixed in the following steps: (1) aggregates are mixed with lime and water, then heated in a 100°C oven to dry condition; (2) mineral fiber is mixed with aggregates until the fiber separates well; (3) asphalt binder is added and mixed until it coats the other ingredients; and (4) a blend of CRM and TOR is added uniformly. The mixing temperature is 140–150°C, and the mixing time is about 3 min. Mixture specimens were prepared in the following ways. The loose mixtures were aged in a forced-draft oven for 2 h ± 5 min at a compacted temperature before compaction to simulate short-aging. The aged mixtures were compacted by a Superpave gyratory compactor (Pine Test Equipment, Grove City, Pennsylvania) (SGC) to 100 × 170 mm (diameter × height) sizes. The SGC compacted samples were then cored/cut to 100 × 150 mm (diameter × height) sizes for the dynamic modulus test and 100 × 130 mm (diameter × height) dimensions for the direct-tension fatigue test. Before proceeding to these two tests, the air void is measured for each specimen. All the SMA specimens used in this study have the target air void of 5.0 ± 0.5%. In direct-tension fatigue tests, the samples were glued to two end plates using a steel epoxy, and a special gluing jig was used to eliminate eccentricity.

To verify the relationship of fatigue life between the SMA mixtures and binders used, the binder-fatigue test was performed. It is difficult to obtain the CRM-modified binder in the dry process. Thus, only four binders were used for the fatigue test: virgin asphalt, CRM modified in wet process, terminal-blend binder, and SBS-modified binder. To ensure that the asphalt binders in the binder-fatigue test have similar aging conditions with those in SMA mixtures, the previously mentioned four asphalt binders were short-term aged in the rolling thin film oven (RTFO) prior to the binder-fatigue test.

**Table 1. Aggregate Gradation of SMA**

| Sieve (in.) | Percentage passing (%) |
|------------|------------------------|
| 3/4        | 100                    |
| 1/2        | 90.7                   |
| 3/8        | 61.7                   |
| Number 4   | 27                     |
| Number 8   | 17.8                   |
| Number 200 | 10                     |

**Table 2. Optimum Asphalt Content of SMA Mixture**

| SMA mix type       | OAC (%) |
|--------------------|---------|
| Virgin             | 6.3     |
| Dry process        | 6.3     |
| Wet process        | 6.9     |
| Terminal           | 6.4     |
| SBS                | 6.3     |

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Test Method

Dynamic Modulus ($E^*$) Test for SMA Mixture

Dynamic modulus tests were conducted to measure the linear viscoelastic (LVE) behavior of SMA mixtures. Dynamic modulus tests were performed in load-controlled and axial-compression mode using AMPT. In this test, the strain amplitudes were controlled below 115 micro strains to ensure the specimen response was within a linear viscoelastic limit. Three replicate specimens at a target air void level were tested at three temperatures (4, 20, and 45°C) and four loading frequencies (0.01, 0.1, 1, and 10 Hz) according to the AASHTO 13 TP79-12 requirement. Conditioning times for the $E^*$ test at 4, 20, and 45°C were 18, 3, and 3 h, respectively.

Fatigue Test for SMA Mixture

The S-VECD direct-tension fatigue tests, sometimes called the uniaxial constant crosshead (CX) or pull-pull fatigue test, were performed to characterize fatigue performance of SMA mixtures. The CX fatigue test is not a true controlled-strain or controlled-stress loading mode but rather a mixed mode. A true on-sample controlled-strain or stress test using cylindrical specimens is difficult to run and can damage equipment if improperly performed (Hou 2009). Photographs of the AMPT device and S-VECD sample are shown in Fig. 1.

The proper test temperature is critical for the success of the S-VECD direct-tension fatigue test. Previous research indicated that higher test temperatures may result in viscoplastic strain, whereas lower test temperatures could cause brittle behavior of the samples (Hou 2009; Sabouri and Kim 2014). The CX test temperature of 17°C was selected for this study based on the previous study (Hou 2009; Sabouri and Kim 2014).

In the CX test, the number of cycles at failure ($N_f$) was defined as the cycle at which the phase angle decreases sharply, as this drop is a result of macrocrack localization (Kim et al. 2009; Hou 2009). However, the phase-angle-based failure definition cannot be used for predicting fatigue life because the phase angle is not included in the S-VECD model framework (Wang et al. 2015). Sabouri and Kim (2014) developed a $G^R$ failure criterion for predicting fatigue life by the S-VECD model. $G^R$ is the rate of change of the averaged released pseudostrain energy values throughout the CX test. In the $G^R$ method, the characteristic relationship between $G^R$ and $N_f$ is unique for a given asphalt mixture and is independent of the mode of loading, strain amplitude, and temperature (Sabouri and Kim 2014).

Based on previous research (Kim et al. 2009; Hou 2009; Norouzi et al. 2014; Sabouri and Kim 2014) the CX tests in this study were performed at 17°C at a frequency of 10 Hz with an AMPT. Three to four replicate specimens at a target air void were measured at three to four different strain amplitudes (high, medium, and low) to produce a wide range of $N_f$ (from 1,000 to 100,000). Prior to the CX test, the specimens were conditioned in an environmental chamber for 3 h to reach the test temperature. The data from the CX test were analyzed using the fatigue-analysis software developed by Underwood and Kim, the and $G^R$ failure criterion was used in the fatigue life prediction of SMA mixtures.

Fatigue Test for Asphalt Binder

The parameter $|G^*| \cdot \sin \delta$ at intermediate temperatures is generally used to evaluate fatigue performance of asphalt binders. However, this parameter is not a good indicator of the damage resistance because it is only a single point at a small strain level and does not take the traffic loading into account (Wang et al. 2015). Considering the disadvantage of $|G^*| \cdot \sin \delta$ for evaluating the fatigue performance of binders, the linear amplitude sweep (LAS) method (AASHTO TP101) was developed to estimate damage tolerance of asphalt binders.

In the standard LAS test (AASHTO TP101), the fatigue-failure criterion is defined as the peak of shear stress. However, some polymer-modified binders did not display obvious peaks of shear stress in the LAS test (Wang et al. 2015). Thus, Wang et al. (2015) developed the new failure criteria for the LAS test: the peak in stored pseudostrain energy (PSE), which is more desirable to determine fatigue failure. For the fatigue-performance prediction, Wang et al. (2015) developed $G^R$ failure criterion for asphalt binders, which is similar to that for asphalt mixtures. The S-VECD model combined with the $G^R$ failure criterion can effectively predict fatigue life. To obtain the $G^R$ versus $N_f$ relationship, three LAS tests are required at varying constant strain-amplitude rates (CSRs) (Wang et al. 2015).

In addition, the latest research showed that intermediate temperatures (i.e., 31°C for PG 76-22) used in the LAS test may result in the flow of binders rather than fracture failure, whereas lower temperatures may lead to adhesive failure between the DSR plates and asphalt specimen, which is found to confound results (Soenen et al. 2004; Safaei and Hintz 2014). Therefore, the fatigue properties of asphalt binders can be correctly evaluated only in a narrow stiffness or temperature region using a DSR. Safaei and Hintz (2014)
Results and Discussions

Dynamic Modulus \(|E^*|\)

An \(|E^*|\) master curve can be constructed at the reference temperature of 21°C based on the time-temperature correspondence principle, which uses the equivalence between frequency and temperature. The sigmoidal model in Eq. (6) was used to describe the master curves. A nonlinear analysis was performed using an available optimization routine (in Microsoft Excel) to obtain the model parameters of the master curve by minimizing the sum of squares of error between the predicted and measured dynamic modulus values

\[
\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{[\beta + \gamma \log(f_{\text{ref}})]}}
\]

where \(f_{\text{ref}}\) = loading frequency at the reference temperature; \(\delta\) = minimum value of dynamic modulus; \(\delta + \alpha\) = maximum value of dynamic modulus; and \(\beta, \gamma\) = parameter describing the shape of the sigmoidal function.

Fig. 2 shows the \(|E^*|\) master curves for the five SMA mixtures in both log-log and semilog scales. Fig. 1 indicates that the \(|E^*|\) master curve of dry-process SMA almost collapsed with that of wet process in the whole reduced frequency. In addition, \(|E^*|\) master curve of dry-process SMA is above that of virgin SMA in the whole reduced frequency, although slightly below those of terminal and SBS SMA in the lower reduced-frequency portion. This means that \(|E^*|\) of the dry-process SMA used in this study was similar to that of wet-process SMA and higher than that of virgin SMA regardless of lower or higher temperatures, although a little lower than those of terminal and SBS SMA at high temperature. Two sample \(t\)-tests (\(\alpha = 0.05\)) show there was no statistical difference between the \(|E^*|\) of the rubberized and control asphalt mixtures, regardless of temperature or load frequency.

Damage-Characteristic Curve

The damage-characteristic curve (\(C-S\)) depicts an asphalt mixture’s resistance to damage. For a given normalized pseudostiffness (\(C\)), higher damage (\(S\)) may mean better resistance to damage. Fig. 3 shows the \(C-S\) curves for five SMA mixtures. It can be seen, for a given \(C\), both terminal and SBS SMAs have similar and higher damage (\(S\)) values, followed by dry-process SMA and wet-process SMA, which have similar \(S\) values, and virgin SMA, which has the lowest \(S\) values. This indicates that the resistance to damage of dry-process SMA would be similar to wet-process SMA and higher than virgin SMA, although lower than terminal and SBS SMAs.

Characteristic Relationship between \(G^R\) and \(N_f\)

Fig. 4 presents the characteristic relationship between \(G^R\) and \(N_f\) for five SMAs. For a given rate of pseudostrain energy release (\(G^R\)), less \(N_f\) may indicate quicker failure and poorer resistance to damage. It can be found that the \(G^R\)-\(N_f\) characteristic line of dry-process SMA is close to that of wet-process SMA and slightly above that of virgin SMA, although below those of terminal and SBS SMAs. This suggests that dry-process SMA would have similar damage resistance to that of the wet-process SMA and higher than both of terminal and SBS SMAs.

Fatigue Life of SMA Mixture

After obtaining the \(C-S\) curve and \(G^R\)-\(N_f\) characteristic relationship, the fatigue life of five SMAs can be predicted by the S-VECD theory at any temperature and any loading condition. Figs. 5 and 6 show the fatigue lives of strain-controlled and stress-controlled loads, respectively, at 10, 17, and 25°C and 10 Hz loading frequency.

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\(\alpha\) Terminal
\(\delta\) Dry process
\(\beta\) Virgin
\(\gamma\) Wet process
\(\gamma\) Terminal
\(\gamma\) SBS

Fig. 3. Damage-characteristic curves

Fig. 2. \(|E^*|\) master curves: (a) log-log scale; (b) semilog scale
According to the strain-controlled simulation results (Fig. 4), the fatigue life of the dry-process SMA is similar to that of the wet-process SMA at higher strain (i.e., 700 με), although slightly higher than that of the wet-process SMA at lower strain (i.e., 300 με) or higher temperature (25°C). In addition, the dry-process SMA has slightly higher $N_f$ than the virgin SMA. Furthermore, the dry-process SMA has lower $N_f$, especially at higher strain (i.e., 700 με), compared to both terminal and SBS SMAs.

According to the stress-controlled simulation results (Fig. 5), the fatigue life of the dry-process SMA is similar to that of the wet-processed SMA and higher than the virgin SMA, although lower than both terminal and SBS SMAs, regardless of the stress levels or the test temperatures.

Overall, $N_f$ of the dry-process SMA is higher than that of virgin SMA, suggesting CRM introduced by the dry process may improve the fatigue property of SMA. $N_f$ of the dry-process SMA is similar
or slightly higher than that of the wet-process SMA, indicating the introduction methods of CRM (dry and wet process) had no significant effect on the fatigue performance of SMAs. $N_f$ of the dry-process SMA is lower compared to both terminal and SBS SMAs, meaning 10% CRM plus 4.5% TOR could be insufficient to make dry-process rubberized SMA have the same fatigue life as terminal and SBS SMAs.

**Fatigue Life of Asphalt Binder**

Four RTFO-aged binders were investigated for fatigue performance using the improved LAS test at 17°C. In this test, two types of testing were performed in succession: a frequency sweep test, which is designed to obtain information on the rheological properties and an amplitude sweep test, which is intended to measure the damage characteristics of the binders. Frequency sweep tests were conducted by employing an applied load of 0.1% strain over a range of frequencies from 0.2 to 30 Hz. Amplitude sweep tests were performed at a constant frequency of 10 Hz with linearly increasing strain amplitude from 0.1 to 30%. Three different CSRs were used for each binder in amplitude sweep tests. The fatigue life of the binders was predicted using S-VECD theory with the $G^*$ criterion by the software developed by Hintz.

Fig. 7 shows the characteristic relationship between $G^*$ and $N_f$ for four asphalt binders. Fig. 8 prescribes the predicted fatigue life for four asphalt binders. It can be seen that the $G^*$.-$N_f$ characteristic relationship and $N_f$ from the binders have similar trends with SMA mixtures: the $G^*$.-$N_f$ characteristic line and $N_f$ of virgin binder remain the lowest, followed by the CRM binder in the wet-process and terminal-blend binder, the $G^*$.-$N_f$ line, and the $N_f$ for SBS binder is highest.

The applied strain in asphalt-binder fatigue is equivalent to the strain in the mixture pavement layer multiplied by 80 (Safaei et al. 2014; Wang et al. 2015). Thus, binder strain levels of 2.4, 4.0, and 5.6% corresponded to 300, 500, and 700 microstrain in SMA mixtures. Fig. 9 shows the $N_f$ relationship between binders and SMA mixtures under the corresponding strain levels. The result demonstrates a high correlation between the binder and mixture fatigue life. In addition, it can be seen that mixture fatigue life predictions are lower when strain levels are higher, and higher when strain levels are lower, compared to the binder-fatigue life.

**Summary and Conclusions**

This paper investigated the fatigue performance of rubberized SMA in the dry process and compared its fatigue characteristics to SMAs with other typical binders. Five SMA mixtures were used with different asphalt binders. Dynamic modulus and direct-tension fatigue tests were performed on SMA mixtures using AMPT. The improved LAS tests were performed on the binders by a DSR. The fatigue test data were analyzed by S-VECD theory.

The following conclusions may be offered from the present research:

- The dynamic modulus of the rubberized SMA in dry process used in this study was similar to that of wet process and higher than that of SMA with virgin asphalt, although a little lower than those of SMAs with terminal-blend binder or SBS binder at high temperature;
- The damage resistance and fatigue life of the rubberized SMA in dry process is higher than that of SMA with virgin asphalt and similar or slightly higher than the wet process, although lower than SMAs with terminal-blend binder or SBS binder;
- The CRM introduced by the dry process may improve the dynamic modulus and fatigue performance of SMA. The influence of the introduction methods of CRM (dry and wet process) had no significant effect on the dynamic modulus and fatigue performance of SMA. Ten percent CRM plus 4.5% TOR could be insufficient to make the dry-process rubberized SMA have longer fatigue life like the SMAs with terminal-blend binder or SBS binder; and
- A high correlation between the binder and SMA mixture fatigue life was found based on the results from direct-tension fatigue tests and the improved LAS tests.
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