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Fatigue Performance Evaluation of Rubberized Porous European Mixture by Simplified Viscoelastic Continuum Damage Model

Zhaoxing Xie, [Junan Shen](#), Mathew Earnest, Bo Li, and Mike Jackson

The study investigated the fatigue performance of rubberized porous European mix (PEM) and control PEM and the influence introducing methods of crumb rubber modifier (CRM) on the fatigue performance of PEM. Four PEM mixtures were used: rubberized PEM in dry process, rubberized PEM in wet process, rubberized PEM with terminal blend binder, and control styrene–butadiene–styrene (SBS) modified PEM. Dynamic modulus and direct tension fatigue tests were performed with an asphalt mixture performance tester system. The fatigue test data were analyzed by the simplified viscoelastic continuum damage theory. There were four main results. First, the rutting resistance of the rubberized PEM in the dry process was similar to that of the wet process but slightly lower than that of the rubberized PEM with the terminal blend binder and SBS modified PEM. Second, the fatigue cracking resistance of the rubberized PEM in the dry process was similar to that of the wet process but significantly lower than those of the rubberized PEM with the terminal blend binder and SBS modified PEM. Third, the use of smaller size CRM and transpolyoctenamer (TOR) in the dry process may have made the properties of the dry process PEM close to those of the wet process. However, the 10% CRM or 4.5% TOR used in the study could not make rubberized PEMs produce longer fatigue life like the control SBS modified PEM. Fourth, the introduction of SBS into rubberized PEM by the terminal blend method may have significantly improved the fatigue performance of PEM.

Crumb rubber modifier (CRM), made from scrap tires, has been used in asphalt mixture to improve the mechanical properties of the mixture and protect the environment as well as save resources (1–4). Creating CRM modified asphalt binders and mixtures (rubberized binders and mixtures) includes three general processes: dry process, wet process on-site, and wet process at the terminal (4). In the typical dry process, larger size (4 to 18 mesh) and higher dosage (1% to 3% by mass of the total aggregate) of CRM is mixed directly with aggregate in the drum to produce rubberized mixes. In the typical wet process on-site, 15% to 20% (by mass of asphalt binder) and finer (30 or 40 mesh) CRM is mixed with asphalt at high temperature (170°C to 205°C) to form asphalt rubber, which is then mixed

with aggregate in a drum to produce rubberized mixes. For the wet process at the terminal, smaller CRM particles and polymers [i.e., styrene–butadiene–styrene (SBS)] are used to produce the terminal blend rubberized binders, which can be shipped to the mixture production plant and stored in the plant’s binder storage tanks, like SBS modified asphalt binder (4).

Considerable lab and field research has indicated that rubberized mixtures in the wet process on-site or at the terminal exhibit similar or better performance properties compared with control asphalt mixtures (5–12). However, rubberized asphalt mixtures in the typical dry process have inconsistent pavement performance and service life varies from 2 to 20 years (13, 14). These findings indicate that the typical dry process may have worse performance over the wet process. There are several possible reasons for the poor performance in the typical dry process, such as less asphalt-CRM reaction, larger CRM particle size, higher CRM content, and poor quality control in the construction (13).

A new dry process has been used in Georgia since 2007: smaller size (30 or 40 mesh) and lower content of CRM (about 10% mass of asphalt binder), and a cross-link agent [transpolyoctenamer (TOR) polymer] has been used to produce rubberized mixtures [i.e., porous European mix (PEM)] (15, 16). In the traditional dry process, CRM is typically considered as a substitute for the fine aggregate, not the binder modifier. In the new dry process, CRM is expected to work as an asphalt binder modifier, like SBS polymer.

To investigate the field performance of rubberized PEM in the new dry process, test sections of rubberized PEM in the dry process and control SBS modified PEM were paved in Georgia. The field research showed that the rubberized PEM and control PEM pavements exhibited good conditions after three or five years in service (15, 16). However, whether the long-term performance (i.e., fatigue life) of rubberized PEM in the dry process is similar to the control PEM is still unclear. In addition, it is also unclear how the introduction methods of CRM (wet process and dry process) affect the fatigue performance of PEM. Thus, it is important to investigate and compare the fatigue performance of rubberized PEMs in the different processes with control PEM.

Fatigue tests generally can be classified into two main types: phenomenological and mechanistic. The phenomenological approach, such as the flexural beam fatigue test, is empirical in nature, which could introduce large errors when used in material performance prediction. Mechanistic approaches, such as the simplified viscoelastic continuum damage (S-VECD) approach, include more rigorous theoretical considerations (11, 12, 17, 18). In addition, the

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S-VECD model can effectively predict the fatigue life of asphalt mixtures under different test temperature and loading conditions (17–24). Furthermore, it is difficult to conduct the flexural beam fatigue test on PEM mixture because PEM has higher air voids and the beam size is small. However, the S-VECD direct tension fatigue test can be performed on relatively larger cylindrical specimens than classical beam fatigue tests. This capability may make the S-VECD direct tension fatigue test on PEM sample more successful. Thus, the S-VECD approach was employed to explore the fatigue performance of PEM.

OBJECTIVES AND SCOPE

The objectives of this study were (a) to investigate and compare the fatigue performance of rubberized PEMs in the different processes and control SBS modified PEM by the S-VECD approach and (b) to explore the influence of the methods of the introduction of CRM into PEM on the fatigue performance characteristics.

In this study, three rubberized PEMs in the different processes and one control SBS modified PEM were used. The optimum asphalt contents (OAC) of four PEM mixtures were designed according to Specification 114 of the Georgia Department of Transportation (DOT) (Georgia DOT 114). Dynamic modulus and direct tension fatigue tests were conducted on four PEM mixtures with an asphalt mixture performance tester (AMPT) system. The fatigue test data were analyzed by the S-VECD theory.

S-VECD THEORETICAL BACKGROUND

The S-VECD model is based on the elastic–viscoelastic correspondence principle, the work potential theory, and the temperature–time superposition principle (21–24). The elastic–viscoelastic correspondence principle is used to model the viscoelastic behavior of a material by replacing physical strain with pseudostrain (Equation 1). The time–temperature superposition principle combines the effects on asphalt mixture response by shifting modulus values at different temperatures to a certain reference temperature. Work potential theory is then applied to model damage growth and healing (17).

$$\epsilon^R = \frac{1}{E^R} \int_0^t E(t - \tau) \frac{d\epsilon}{d\tau} d\tau \quad (1)$$

where

ϵ^R = pseudostrain;

ϵ = actual strain;

E^R = reference modulus, which is an arbitrary constant;

$E(t)$ = relaxation modulus;

t = elapsed time from specimen fabrication and time of interest;
and

τ = time when loading began.

The S-VECD model constructs the constitutive relationship that describes damage growth in a specimen. In this model, a damage parameter (S) is defined as all structural changes that result in reduced stiffness as 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 (Equation 2) (17).

$$C = \frac{\sigma}{\epsilon^R * I} \quad (2)$$

where σ is stress.

The three fundamental functions for the continuum damage theory, based on Schapery's work potential theory, are the following:

1. The pseudostrain energy density function,

$$W^R = f(\epsilon^R, S) = \frac{1}{2} \sigma \epsilon^R = \frac{1}{2} (\epsilon^R)^2 C \quad (3)$$

2. The stress–pseudostrain relationship,

$$\sigma = \frac{\partial W^R}{\partial \epsilon^R} = C(S) \epsilon^R \quad (4)$$

3. The damage evolution law,

$$\frac{dS}{dt} = \left(-\frac{\partial W^R}{\partial S} \right)^\alpha \quad (5)$$

where

W^R = pseudostrain energy density,

S = damage parameter (internal state variable), and

α = damage evolution rate.

To describe the change in C as damage (S) accumulates in the specimen, the three fundamental functions can be used to construct a damage characteristic curve (Equation 6), or C - S curve (12, 17). The C - S curve represents a unique response of the material, regardless of loading level, frequency, or mode. The curve can be fitted to an analytical form by the power law function (Equation 7) (17, 22, 23):

$$S_{N+1} = S_N + \left[-\frac{\text{DMR}}{2} (C_N - C_{N-1}) (\epsilon^R)^2 \right]^{\alpha/1+\alpha} \Delta \xi^{1/1+\alpha} (K_1)^{1/1+\alpha} \quad (6)$$

$$C = 1 - C_{11} S^{C_{12}} \quad (7)$$

where

S_N = damage at step N ,

DMR = dynamic modular ratio (Equation 8),

$\Delta \xi$ = reduced time interval,

K_1 = developed functional parameter to account for the analysis of cyclical data,

$\alpha = 1 + 1/m$,

m = maximum absolute value of log-log slope of relaxation modulus, and

C_{11} , C_{12} = material constants.

$$\text{DMR} = \frac{|E^*|_{\text{fingerprint}}}{|E^*|_{\text{LVE}}} \quad (8)$$

where LVE is linear viscoelastic.

MATERIALS AND SPECIMEN FABRICATION

To achieve the objectives of the study, four PEM mixtures were used with different asphalt binders: rubberized PEM in the dry process (dry process PEM), rubberized PEM in the wet process on-site (wet process PEM), rubberized PEM with the terminal blend binder (terminal blend PEM), and control SBS modified PEM (SBS PEM). For the wet process PEM, rubberized binder was first produced by mixing 30 mesh CRM (at 10% of the weight of virgin binder) with a virgin binder of PG 67-22 at 170°C and 900 rpm for 45 min, then mixed with aggregates to produce rubberized mixes in the laboratory. The dry process PEM 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. The terminal blend PEM and SBS PEM were produced by mixing the aggregate with the terminal blend binder and SBS modified binder, respectively. Rubberized binders in the wet process, terminal blend binder, and SBS modified binder met PG 76-22.

Crushed granite aggregate was utilized in all the PEM mixtures. Mineral fiber at 0.4% by the weight of the total mixture was added to the PEM to avoid excessive drain-down. Hydrated lime at 1.0% by the weight of the total aggregate was used for antistripping purposes. Gradation of PEM, shown in Figure 1, was designed in accordance with Georgia mix design procedure (Section 828). Georgia DOT 114 was used to select the OAC of the PEM mixtures. Table 1 presents the OAC and volumetric properties of the four PEM mixtures. The bulk specific gravity of the PEM sample was determined by dimensional analysis, as described in Georgia DOT 114.

The PEM mixtures for the dynamic modulus and direct tension fatigue tests were mixed and compacted in the following steps: first, aggregates containing 4% moisture were mixed well with hydrated lime and then dried in the oven overnight at 100°C; second, aggregates coated by lime were preheated in the 165.5°C $\pm$ 3°C oven for 5 h and then mixed with the fiber and asphalt binders to gain loose asphalt mixtures. To simulate short-aging, the loose mixtures were aged in a forced-draft oven for 2 h $\pm$ 5 min at the compaction temperature (160°C). The loose mixtures were stirred every 60 $\pm$ 5 min to maintain uniform conditioning. After the aging, the mixtures were compacted by a Superpave[®] gyratory compactor (SGC) to 100 mm $\times$ 170 mm (diameter $\times$ height) sizes. The SGC-compacted samples were then cored or cut to 100 mm $\times$ 150 mm (diameter $\times$ height) sizes for the dynamic modulus test and 100 mm $\times$ 130 mm (diameter $\times$ height) dimensions for the direct tension fatigue test. All the PEM specimens

FIGURE 1 Aggregate gradations of PEM.

TABLE 1 PEM Mixture Volumetric Properties

Mix Type	OAC (%)	G_{mm}	G_{mb}	AV (%)	VMA (%)	VFA (%)
Dry process	6.0	2.406	1.955	18.7	29.3	36.1
Wet process	6.5	2.402	1.962	18.3	29.5	37.8
Terminal blend	6.0	2.420	1.942	19.8	29.8	33.6
SBS	6.0	2.427	1.948	19.7	29.6	33.3

NOTE: G_{mm} = maximal specific gravity; G_{mb} = bulk specific gravity, which was determined by dimensional analysis, as described in Georgia DOT 114; AV = air voids; VMA = voids in mineral aggregate; VFA = voids filled with asphalt.

used in this study had target air voids of 19.0% $\pm$ 1%. In the direct tension fatigue tests, the samples were glued to two end platens with a steel epoxy and a special gluing jig was used to eliminate eccentricity.

TEST METHODS

Complex Modulus (E^*) Test

Asphalt mixture is a typical LVE material, which exhibits time- and temperature-dependent behavior. Constitutive relationships for LVE materials are typically expressed in the following convolution integral form (Equations 9 and 10) (17, 24). $E(t)$ in Equation 9 and creep compliance [$D(t)$] in Equation 10 are fundamental parameters of LVE materials, which represent their stiffness over time. E^* can be used to calculate $E(t)$ and $D(t)$ by Equations 11 and 12, respectively, with the exact inter-conversion method (17). The Prony coefficients (E_i 's) in Equation 11 can be determined with the storage modulus (E) and collocation method (12, 17, 24).

$$\delta = \int_0^t E(t - \tau) \frac{d\varepsilon}{d\tau} d\tau \quad (9)$$

$$\varepsilon = \int_0^t D(t - \tau) \frac{d\delta}{d\tau} d\tau \quad (10)$$

$$E(t) = E_\infty + \sum_{i=1}^N E_i e^{-t/\rho_i} \quad (11)$$

$$D(t) = D_0 + \sum_{i=1}^N D_i (1 - e^{-t/K_i}) \quad (12)$$

where

E_∞ = elastic modulus,

E_i = Prony coefficients,

ρ_i = relaxation time,

D_0, D_i = material constants, and

K_i = retardation time of i th Voigt element.

The E^* of PEM was measured in load-controlled, axial compression mode with the AMPT system. Load levels were fixed to obtain strain amplitudes below 115 microstrains to ensure that specimen response was within a linear viscoelastic limit. Three replicate specimens at a target air void level were tested at three temperatures

(4°C, 20°C, and 45°C) and four loading frequencies (0.01, 0.1, 1, and 10 Hz) according to the AASHTO 13 TP79-12 requirement. Before E^* testing, the specimens were conditioned in an environmental chamber to reach the test temperature stipulated in AASHTO 13 TP79-12. The conditioning times for the E^* test at 4°C, 20°C, and 45°C were 18, 3, and 3 h, respectively.

S-VECD Direct Tension Fatigue Test

The S-VECD test, sometimes called the uniaxial constant cross-head (CX) or pull-pull fatigue test, was performed to characterize fatigue performance. The machine actuator's displacement was programmed to reach a constant peak at each loading cycle. Because of machine compliance, the on-specimen strain measurements follow a power curve until failure, so the specimen does not experience a true controlled-strain or controlled-stress loading mode, but rather a mixed mode. A true on-sample controlled strain or stress test that uses cylindrical specimens is difficult to run and can damage equipment if improperly performed (24).

It was found that the effect of viscoplastic strain during the CX test is evident when the test temperature is higher, and the effect of viscoplasticity is negligible when the test temperature is lower than a specific one (25). The softer the binder is, the lower the proper test temperature is. Sabouri and Kim (25) suggested that a proper testing temperature for the CX test can be determined based on the PG of the binder used (Equation 13). The proper test temperature for the PG 67-22 and PG 76-22 used in this study would be lower than 19°C according to Equation 13. However, a much lower test temperature may cause brittle behavior of the samples. Thus, a proper test temperature should be a suitable temperature for the material's viscoelastic damage characterization, so that the material is not as brittle as at low temperature and meanwhile the effect of viscoplasticity is negligible (24). Based on these considerations, 17°C was selected as the CX test temperature in this study.

$$T(^{\circ}\text{C}) \leq \frac{\text{high temperature binder PG} + \text{low temperature binder PG}}{2} - 3 \leq 19^{\circ}\text{C} \quad (13)$$

where T is the CX test temperature.

Before the CX test, a small strain (50 to 75 on-specimen micro-strain) was applied to determine the fingerprint dynamic modulus ($|E^*|_{\text{fingerprint}}$) and DMR was calculated via Equation 8. A DMR value in the range of 0.9 to 1.1 guarantees that the linear viscoelastic properties obtained from the dynamic modulus tests can be used effectively in S-VECD analysis (18). A target peak-to-peak on-specimen strain without adaptive strain control was then input to obtain the target actuator peak-to-peak strain or displacement that would be used to control the entire fatigue test. The number of cycles at failure (N_f) was defined as the cycle at which the phase angle decreases sharply, since this drop is a result of macro crack localization (24).

The CX tests in this study were performed at 17°C at a frequency of 10 Hz with an AMPT. Four to six replicate specimens at a target air void were measured at three to four 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 as described in the following sections, with the fatigue analysis software developed by Underwood et al. (21–23).

Fatigue Failure Criteria in Fatigue Life Prediction

In the CX test, fatigue failure was defined as the cycle where the phase angle shows sharp drop. However, there is no sudden decrease of phase angle in fatigue life prediction with the S-VECD model (24). Thus, a fatigue failure criteria for the prediction needed to be developed. Sabouri and Kim (25) developed the G^R failure criterion for the S-VECD model. The criterion 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 independent of the mode of loading, strain amplitude, and temperature. Thus, the G^R method can reliably predict the fatigue life of a mixture with the S-VECD model, which is equivalent to the drop-in phase angle in experimental observations (25).

RESULTS AND DISCUSSION

Viscoelastic Material Properties

The absolute value of the complex modulus, $|E^*|$, is defined as the dynamic modulus. 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. A sigmoidal model (Equation 14) was used to describe the master curves. A nonlinear analysis was performed with an available optimization routine (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.

$$\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{[\beta + \gamma(\log f_r)]}} \quad (14)$$

where

f_r = loading frequency at the reference temperature,

δ = minimum value of dynamic modulus,

$\delta + \alpha$ = maximum value of dynamic modulus, and

β, γ = parameters describing the shape of the sigmoidal function.

Figure 2 shows the $|E^*|$ master curves for the four PEM mixtures in log-log and semi-log scales. The log-log scale is better for viewing and comparing the low loading frequency portion of the curve, while the semi-log scale is better for the high loading frequency portion of the curve. Figure 2a indicates that the $|E^*|$ master curve of the dry process PEM almost collapses with the other three PEMs in most of the reduced frequency portion, and is slightly below the others only in the lower reduced frequency portion (equal to the higher temperature). Figure 2b shows that the $|E^*|$ master curve of the dry process PEM is close to those of the other three PEMs in most of the reduced frequency portion, and is a little below that of the terminal blend PEM and slightly above those of the wet process and SBS PEM only in the highest reduced frequency portion (equal to the low temperature).

Once the $|E^*|$ master curve was obtained, $E(t)$ and $D(t)$ could be calculated with Equations 11 and 12, respectively. The $E(t)$ and $D(t)$ master curves were constructed by horizontally shifting the curves at various temperatures to the curves at a reference temperature of 21°C, following the time–temperature superposition principle. The $E(t)$ and $D(t)$ master curves can reveal the linear viscoelastic characteristics of the asphalt mixture. Higher $E(t)$ and lower $D(t)$ represent

FIGURE 2 Dynamic modulus master curves: (a) log-log scale and (b) semi-log scale (ksi = kips per square inch).

better resistance to rutting. The $E(t)$ and $D(t)$ master curves for PEM are shown in Figure 3.

As Figure 3a shows, the $E(t)$ of rubberized PEMs in the dry process and wet process are similar, and slightly lower than those of terminal blend and SBS PEMs at longer loading times. Figure 3b represents that the $D(t)$ of the rubberized PEMs in the dry process and the wet process are also similar, and slightly higher than those of the terminal blend and SBS PEMs at longer loading times. These findings suggest that the resistance to rutting of the dry process PEM is similar to that of the wet process, and slightly lower than that of the terminal blend and SBS PEMs.

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 a better resistance to damage. Figure 4 shows the C - S curves for the four PEM mixtures. In the figure, the C - S characteristic curve of the dry process PEM is very close to that of the wet process, indicating that the resistance to damage of the dry process and the wet process PEMs would be similar. In addition, the C - S characteristic curves of the terminal blend and SBS PEM

also collapse almost on the same line, suggesting that terminal blend and SBS PEM would have similar resistance to damage. However, for a given C , the dry process and wet process PEMs have significantly lower damage (S) than the terminal blend and SBS PEMs, indicating that dry process and wet process PEMs have significantly poorer resistance to damage and higher damage sensitivity, compared with terminal blend and SBS PEMs.

Characteristic Relationship Between G^R and N_f

To predict the fatigue life of PEM mixtures by the S-VECD model, the characteristic relationships between the rate of pseudostrain energy release (G^R) and N_f were developed for the four PEM mixtures in Figure 5. The faster the damage accumulates (i.e., releasing higher amounts of energy during fewer numbers of cycles), the quicker the material should fail (25, 26). In other words, for a given G^R , less N_f may indicate quicker failure and poorer resistance to fatigue. Figure 6 shows that the G^R - N_f characteristic lines for rubberized PEM in the dry process and the wet process collapse almost on the same line, indicating that the dry process and wet process PEMs would have similar fatigue performance. Similarly, the G^R - N_f characteristic lines for the terminal blend and SBS PEM mixtures are very

FIGURE 3 Viscoelastic properties: (a) relaxation modulus and (b) creep compliance.

FIGURE 4 Damage characteristic curves.

FIGURE 5 Characteristic relationship between G^R and N_f .

FIGURE 6 Fatigue life for controlled strain test at (a) 5°C and (b) 10°C.
(continued)

FIGURE 6 (continued) Fatigue life for controlled strain test at (c) 20°C.

close, suggesting that terminal blend and SBS PEMs also might have similar fatigue cracking resistance.

However, it is evident that the G^R - N_f characteristic lines for the dry process and wet process PEMs are significantly below those for the terminal blend and SBS PEMs, indicating that the dry process and wet process PEMs would have significantly poor fatigue performance. In addition, it can be also seen from Figure 6 that the G^R and N_f characteristic relationship for each PEM is highly correlated.

Fatigue Life Prediction

Once the characteristic relationships have been obtained, they can be applied to predict the fatigue life of asphalt mixture for any loading level and test temperature. Figures 6 and 7 show the simulated fatigue life for on-sample strain control and stress control at different temperatures, respectively. From the figures, the difference of fatigue life between the dry process and the wet process PEMs is negligible at lower temperatures (i.e., 5°C and 10°C), regardless of the

temperature or loading conditions and the increase in temperature slightly increased the fatigue life difference between the dry process and the wet process PEMs. This indicates that the use of smaller size CRM and TOR in the dry process may improve the asphalt-CRM reaction, which would make the properties of the dry process PEM close to those of the wet process PEM.

However, the dry process and wet process PEMs have significantly lower fatigue life compared with the terminal blend and SBS PEMs, regardless of the temperature or loading conditions. This finding suggests that 10% CRM or 4.5% TOR could not make rubberized PEM produce a longer fatigue life, as that of SBS PEM. In addition, the introduction of SBS into rubberized PEM by the terminal blend approach may significantly improve the fatigue performance of PEM.

Endurance Limit

The endurance limit of asphalt mixture is defined as the allowable tensile strain below which fatigue cracking does not occur.

FIGURE 7 Fatigue life for controlled stress test at (a) 5°C.
(continued on next page)

FIGURE 7 (continued) Fatigue life for controlled stress test at (b) 10°C and (c) 20°C.

The endurance limit represents the balance point between damage and healing of microcracks. When strains are below the endurance limit value, the damage will be completely healed during the rest period between load applications. The S-VECD model can predict the endurance limit of asphalt mixture using the CX test results. Figure 8 shows the endurance limits for the

four PEM mixtures. It can be seen that the endurance limits of the dry process PEM are the lowest, followed by the wet process PEM and the terminal PEM, and the SBS modified PEM has the highest endurance limits. The endurance limits of the dry process PEM are 9.5% to 38.3% lower than those of the other three PEMs.

FIGURE 8 Endurance limit values at different temperatures.

SUMMARY AND CONCLUSIONS

This paper presented an evaluation of the fatigue performance of rubberized PEM in three processes and SBS modified PEM, and the influence of introducing methods of CRM on the fatigue performance of PEM with the S-VECD model. The following conclusions can be drawn:

1. The dry process and wet process PEMs used in this study have similar $|E^*|$, $E(t)$, $D(t)$, and fatigue life, suggesting that the use of smaller size CRM and TOR in the dry process may make the properties of the dry process PEM close to those of the wet process.
2. The fatigue test results indicate that the dry process and wet process PEMs have significantly lower resistance to fatigue cracking than the terminal blend and SBS PEMs, indicating 10% CRM or 4.5% TOR could not make rubberized PEM produce a longer fatigue life, such as in the terminal blend PEM and SBS PEM. The introduction of SBS into rubberized PEM by the terminal blend method may significantly improve the fatigue performance of PEM.
3. The endurance limits of rubberized PEM in the dry process were the lowest, followed by the wet process PEM and the terminal PEM. The SBS modified PEM had the highest endurance limits.

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