Cracking Characterization of Asphalt Mixtures with Fiber Reinforcement Using Cyclic Fatigue and Direct Tension Strength Tests

Nelson Gibson
Federal Highway Administration
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101
Phone (202) 493-3073
Fax (202) 493-3161
nelson.gibson@dot.gov

Xinjun Li
SES Group and Associates, Inc.
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101
Phone (202)-493-3089
Fax (202)-493-3161
xinjun.li@dot.gov

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ABSTRACT

This study characterized the cracking resistance of two independent sets of mixtures from the FHWA full-scale accelerated loading facility and a Pennsylvania DOT trial section. Both sets had the same selection of three types of comparative materials; an unmodified control mixture, a mixture with SBS modified binder and the same control mixture modified with synthetic fiber reinforcement. Two methods of cracking characterization that can be conducted using the Asphalt Mixture Performance Tester were evaluated; simplified viscoelastic continuum damage cyclic fatigue and direct tension monotonic strength. Dynamic modulus results show the fiber modification has less of an effect than polymer modification. Cyclic fatigue test results predict both SBS and fiber modified mixes perform better than the control mixes in both sets of materials. Furthermore, the cyclic fatigue tests also indicated that the SBS modified mix performs better than fiber under smaller fatigue strains, but then the fiber reinforced mix performs better at higher strains. Recent performance data from the FHWA full-scale accelerated loading facility agrees with the laboratory observation. The pattern where the fiber mixtures exhibited a strain-dependent performance benefit was also observed using the same continuum damage models, but with data from a different testing methodology by means of monotonic direct tension tests. In consideration of all of the test data it appears that the performance benefits of fiber modification for crack resistance can be subtle in terms of what is observed in the laboratory, but there are likely benefits at relatively higher strains.

Key Words: Fiber Reinforcement, Asphalt Mixtures, Cracking, Fatigue Test, Accelerated Pavement Testing

INTRODUCTION

Various modifiers have been used to improve the performance of asphalt pavements. One of the earliest applications of fibers in asphalt mixtures was reported in 1969 by Puzinauskas (1) with natural asbestos fibers that were found to demonstrate effectiveness in improving the low temperature cracking properties of an asphalt mixture. Research efforts by Button and Hunter (2) concluded that the addition of fibers produced a more flexible mixture and thus increased the resistance to cracking manifested by greater elongation at failure without a significant decrease in tensile strength. This corresponds to an increase in the energy required to the fail the material. The authors stated the field performance was questionable because of different early-age performance observed in two different climatic regions of Texas. In another study conducted by Maurer and Malasheskie (3), a fiber reinforced asphalt concrete overlay was found to able to retard reflective cracking, but sections with paving fabrics and a special fiberized membrane also performed better than a control mix. None of the treatments were considered cost effective because the treated sections' crack resistance was expected to diminish and still required crack sealing such that the construction costs could not be offset. A 10-year field study by the Oregon Department of Transportation (4) evaluated combinations of ground tire rubber and chemical antistrip agents, ethylene vinyl acetate modified binder, hydrated lime, and polyester and polypropylene fibers. Both types of fiber-reinforced test sections performed better or much better than the control sections in terms of resistance to transverse and block cracking as did one of the tire rubber sections. However, the same performance was seen for both the control mixture and the fiber mixture in terms of rutting, fatigue cracking and raveling. McDaniel and Shah (5) reported on an Indiana Department of Transportation field study that considered seven different polymer modifiers and polyester fiber reinforcement in base, intermediate and surface mixes placed in an overlay on an interstate concrete pavement. The fiber section was one of the better performing sections along with some of the other modifiers in their resistance to longitudinal and transverse cracking after 11 years of service. Another interstate highway field study conducted by Prowell (6) for the Virginia Department of Transportation during the transition from Marshall mix designs to Superpave mix designs was motivated to address rutting performance rather than cracking issues. Two test sections with polypropylene and polyester fibers appeared to perform as well as the styrene-butadiene-styrene, air blown binder and styrene-butadiene rubber modified sections. Higher binder content was required for the fiber sections which resulted in lower VMA and both the fiber sections were below the minimum density requirements. No rutting or cracking was reported in any sections after 45 months of monitoring.

A Federal Highway Administration (FHWA) research project investigated a synthetic fiber reinforced asphalt mixture in the laboratory and using full-scale accelerated pavement testing (7). A polyester fiber reinforced mix was placed in one of 12 test lanes in the FHWA's accelerated loading facility (ALF). Results showed that the fatigue cracking of the fiber reinforced section was measurably better than those of the polymer modified sections even though a less-resistant unmodified asphalt binder was used in the mix. The laboratory fatigue results did not match the full scale performance using an earlier variation of an axial fatigue (push-pull) methodology that was not conducted in an AMPT where the analysis used slightly different analytical mathematics along with a conventional 50% modulus reduction failure criteria.

A study by Kaloush et al. (8) evaluated the material properties of conventional (control) and fiber-reinforced asphalt mixtures using advanced material characterization tests including triaxial shear strength, dynamic modulus, repeated load permanent deformation, fatigue, crack propagation, and indirect tensile strength tests. The conclusions were the synthetic fibers improved performance in several ways against anticipated major pavement distresses including permanent deformation, fatigue cracking and thermal cracking relative to a control mixture.

RESEARCH OBJECTIVE

The objective of this study was to assess how asphalt mixtures with distributed fiber reinforcement behave in cracking tests that can be conducted in the Asphalt Mixture Performance Tester (AMPT) and determine whether performance benefits could be observed relative to a control mixture and a polymer modified binder mixture.

MATERIALS AND SAMPLE PREPARATION

Two independent material sets were studied where each set consisted of the same three types of mixtures; a control, one with polymer modified binder, and the control mixture with added fiber reinforcement. The first set of material includes three plant production loose mixes collected when the FHWA's ALF test lanes were reconstructed. More detailed information regarding the materials, construction and performance of these sections is reported by Gibson et al. (7). The mixtures were dense graded, 12.5mm nominal maximum aggregate size (NMAS), all with identical aggregates and gradation but with variation in asphalt binder and presence of fiber. Lane 2 was a control mix with unmodified PG70-22 asphalt binder. Lane 4 was a typical polymer modified asphalt with 3% linearly grafted SBS. Lane 7 is the same as Lane 2 but with 0.2% polyester fiber (10mm long) by weight of aggregate. The fiber type and dosage rate were determined as part of a coincident, separately designated study to evaluate the use of recycled carpet fibers. The second set of materials also includes three plant production loose mixes (9.5mm NMAS) that were received from the Pennsylvania Department of Transportation (PennDOT) as part of a trial section built on SR45 in Lewisburg, Union County. One of the three PennDOT mixtures is a control with PG64-22 unmodified binder while the second mix used a PG76-22 polymer-modified binder and the third is the PG64-22 mixture with 0.05% fiber by weight of aggregate that is a combination of aramid and polyolefin (20 mm long). The fiber type and dosage rate was recommended by the material supplier. The mix design volumetric properties are provided in TABLE 1.

TABLE 1 Volumetric properties of the mix designs

Mix ID	ALF Lane 2	ALF Lane 4	ALF Lane 7	Penn Contr.	Penn SBS	Penn Fiber
Modification	Control	SBS LG	Fiber	Control	SBS	Fiber
Binder Performance Grade PG	70-22	70-28	70-22	64-22	76-22	64-22
Total Binder Content, % by mass	5.3	5.3	5.3	6.2	6.2	6.2
Effective Binder Content, % by mass	5	4.9	5	5.8	5.8	5.8
Dust, % Passing the 75-µm Sieve	6.3	6.3	6.3	4.4	4.4	4.4
Dust to Effective Binder Content	1.26	1.29	1.26	0.76	0.76	0.76
Design Air Voids, %	5.0	4.2	4.8	4.0	4.0	4.0
VMA at Design Air Voids, %	17.5	16.9	18.1	17.3	17.3	17.2
VFA at Design Air Voids, %	71.2	75.2	65.9	76.8	76.8	76.7

Loose mix was re-heated to 135˚C (about 2 hours) and then compacted in a gyratory compactor to make 150mm diameter by 187mm~190mm tall samples. The specimens were compacted to a target height and corresponding target density and not to a fixed number of gyrations in a Superpave gyratory compactor, which is fairly insensitive to temperature effects on the binder. Compacting at the same temperature also avoided any confounding effects of additional aging that could be caused by different compaction temperatures for mixtures with polymer modified or unmodified binder. The gyratory samples were cut and cored to produce dynamic modulus and fatigue testing specimens. The dynamic modulus testing specimens were 100mm in diameter and 150mm in height, while the fatigue testing specimens are the same diameter but only 130mm high. The 130mm height provides more consistent failure in the middle of the specimen (9). The target air void content for all specimens was 7±0.5%.

Later in the research study, a different geometry and test methodology was deliberately chosen to investigate whether the same pattern of predicted fatigue strain sensitivity could be determined from the same viscoelastic continuum damage analytical techniques determined in the cyclic tests, but having the material coefficients determined from monotonic test data. If this pattern could be confirmed in two materials and two different test types, then it would indicate the phenomenon is likely an engineering characteristic of fiber versus SBS mixes relative to control materials. Small-scale specimens were used for this test because the AMPT does not have sufficient actuator force capacity to monotonically fail full size samples in direct tension tests. Smaller specimens that were 38mm diameter and 110mm tall were accommodated. See FIGURE 1 and Kutay et al. (10), Li and Gibson (11) and Park and Kim (12) for more background on the small-scale geometry methodology in the AMPT.

(a)

(b)

FIGURE 1 Performance specimens; (a) cyclic fatigue specimen 130mm tall x 100 mm diameter and (b) monotonic tensile specimen 100mm tall x 38mm diameter

TESTING PROCEDURE

Dynamic modulus was measured in an AMPT following AASHTO TP79 between 4.4 and 54.4°C at frequencies between 20 and 0.1Hz on three replicates. Cyclic, axial fatigue testing also in an AMPT followed AASHTO TP 107 Determining the Damage Characteristics Curve of

Asphalt Mixtures from Direct Tension Cyclic Fatigue Tests also referred to as simplified viscoelastic continuum damage (S-VECD) direct tension cyclic fatigue test protocol that was developed by the North Carolina State University (9). The protocol is a cyclic “pull-return to zero-repeat” test in actuator control. Four actuator displacements were selected and tested at 19^{o}C and 10 Hz for simplicity since this temperature and rate is one of the standard condition for dynamic modulus tests. At least one replicate specimen was tested at one input condition.

The monotonic, direct tension strength tests were conducted at 10^{o}C so that viscoplasticity effects would be minimized which could interfere with the viscoelastic continuum damage calculations. This avoided the need to use strain decomposition to remove viscoplastic strains from the total strain that would have to be determined with a separate model and additional experiments. Three nominal strain rates controlled by the actuator from platen-to-platen (110mm gauge length) were 0.0152, 0.0076, and 0.0015 ε/sec corresponding to actuator displacement rates of 100, 50 and 10 mm/min. These strain rates are based on rates used in research conducted during NCHRP Project 9-19 Tasks F&G (13), which were chosen to bracket strain rates observed from instrumented pavements.

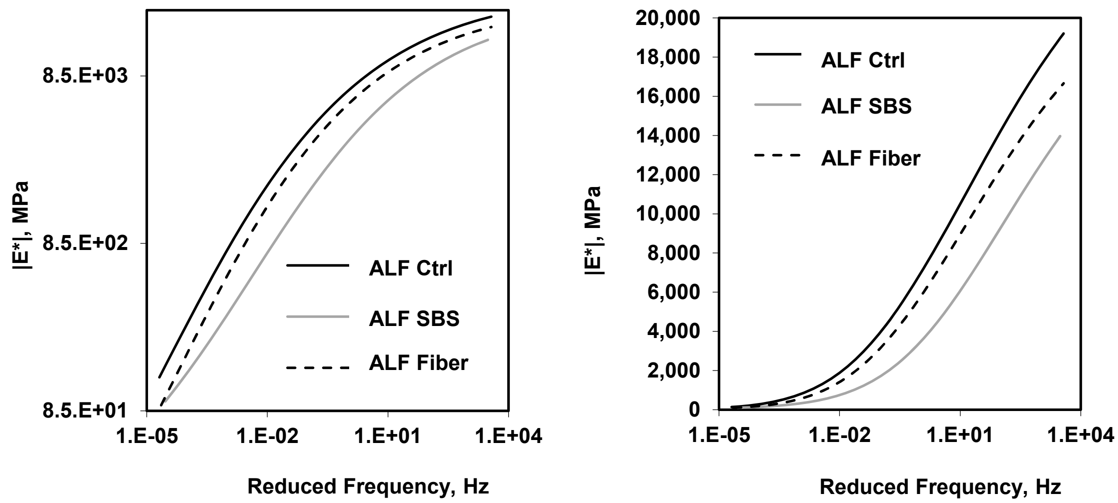
EXPERIMENTAL RESULTS AND DATA ANALYSIS

Dynamic Modulus

Dynamic modulus is measured to determine the viscoelastic relaxation modulus that is used in the cyclic and monotonic continuum damage analyses and by itself can also provide some insight into the similarities and differences between the mixes in this study. The dynamic modulus data are shown in FIGURE 2 and FIGURE 3 in both log-log and semi-log space. The extent of the dynamic modulus curves are not extrapolated beyond the limits of reduced frequency that correspond to actual data points collected. Only the PennDOT Fiber mix was found to have slightly more modulus variability above 15% coefficient of variation (COV) at the highest test temperature of 54.4°C, while all other data showed COV between 2% and 8%.

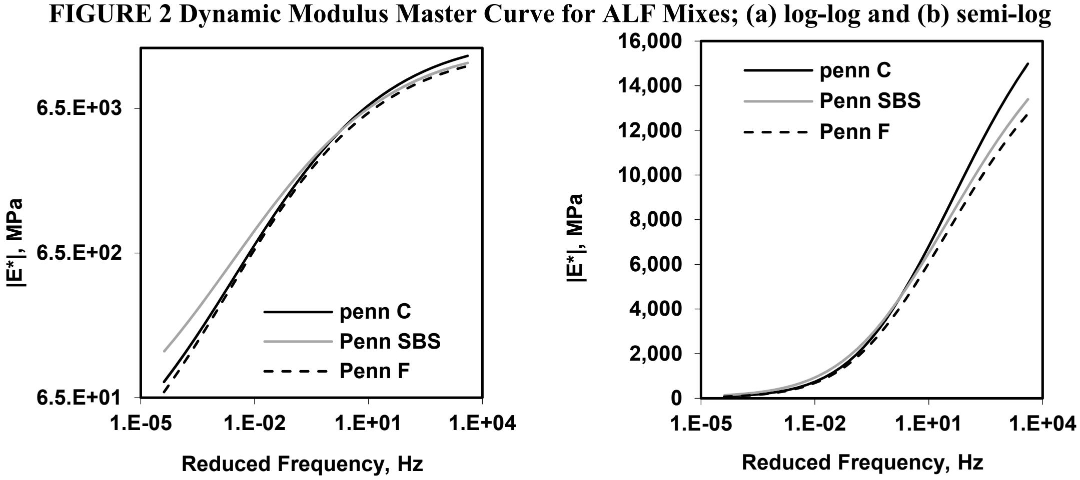
The PG76-22 Penn SBS ranged from 63% stiffer than the control in the high temperature / low frequency region of the master curve to comparable stiffness in the intermediate region and then 11% softer than the control in the low temperature / high frequency region. The fiber mix was 15% softer than the control in the high temperature / low frequency region of the master curve to 7% softer in the intermediate region and then again 15% softer than the control in the low temperature / high frequency region. The ALF SBS mixture ranged from 50% softer than the control in the high temperature / low frequency region to 30% softer than the control in the low temperature / high frequency region. The ALF fiber mix was ranged from 32% softer than the control in the high temperature / low frequency region to 13% softer than the control in the low temperature / high frequency region.

The experimental results show that the fiber modification has less of an effect on modulus than polymer modified binder. Sometimes the fiber mix was softer than the control and other times stiffer which depends on mixture volumetric properties. This is sensible given the test induces very small strains and likely does not significantly mobilize tension in the fiber.



(a) (b)

FIGURE 2 Dynamic Modulus Master Curve for ALF Mixes; (a) log-log and (b) semi-log



(a) (b)

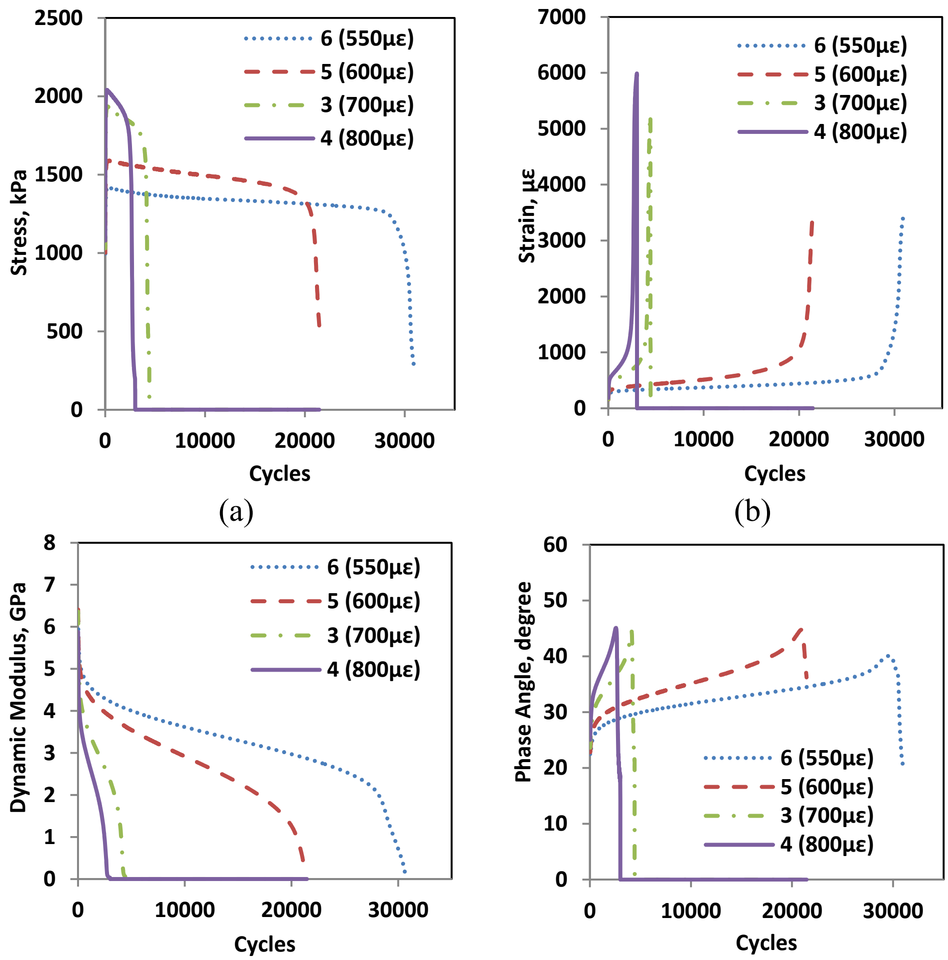
FIGURE 3 Dynamic Modulus Master Curve for PennDOT Mixes; (a) log-log and (b) semi-log

Cyclic Fatigue Testing

As shown in some previous publications (14, 15), the actual on-specimen strains in the cyclic fatigue test grow and the measured stress decreases until complete failure. FIGURE 4 illustrates typical plots of stress, strain, modulus and phase angle as a function of load cycle. As can be seen, this is neither a strain-control nor a stress-control fatigue test. However, this test protocol is used because it is a stable test for the AMPT instrument to control as significant changes occur in the system from the beginning to the end of the test.

It is necessary to account for the test control characteristics using the viscoelastic continuum damage (VECD) method. A damage characteristic curve (C vs. S) is developed, which is independent of loading mode and frequency and temperature. FIGURE 5 shows the damage characteristic curves that represent the loss in modulus or pseudostiffness (C) as a function of the internal state variable damage parameter (S) that represents the amount of micro cracking damage. It should be noted that the damage characteristic curve for each mix is obtained from regression using the fatigue data from all replicates averaged together. The phase angle pattern is important because it is used to identify a temperature-specific failure criteria. The point in the test where the phase angle reaches a maximum and then begins to decrease corresponds to damage localization rather than the conventionally assumed point of 50% loss of modulus. In general, a smaller value of pseudo stiffness at failure (C_f) indicates better performance.

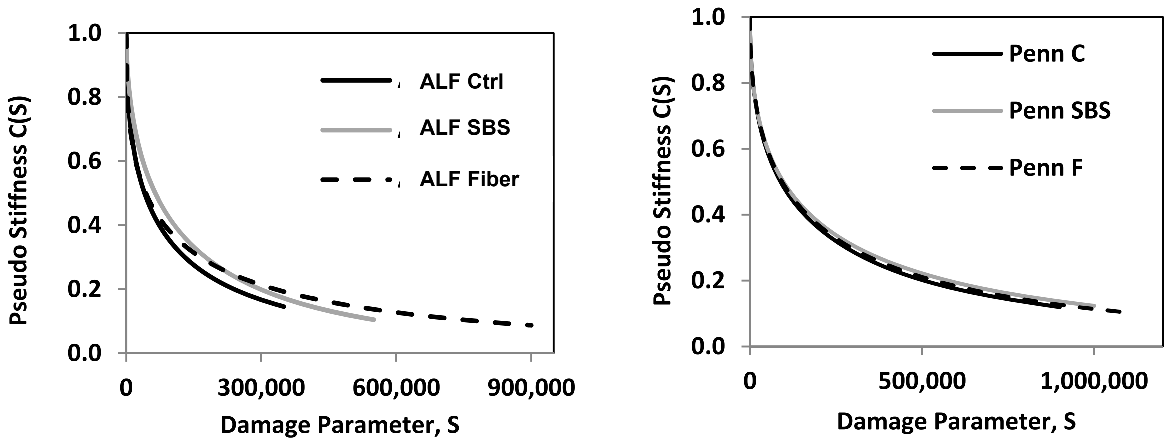
The C(S) curves alone are not intended to rank and judge performance, but still illustrate something about the different mixes. In general, higher curves can sustain more microcraking with less change in pseudostiffness and thus better performance. However, the similarities between the each set of materials' damage characteristic curves are fairly striking. This means that the differences in performance probably lies within the other material coefficients in the continuum damage analysis framework; e.g. the alpha (α) exponent related to the relaxation modulus shape and the psueostrain at failure criteria C_f.



(a) (b)

(c) (d)

FIGURE 4 Typical plots of (a) stress versus load cycles, (b) strain versus load cycles, (c) modulus versus load cycles and (d) phase angle versus load cycles; legends indicate sample ID and controlled actuator strain



(a) (b)

FIGURE 5 Cyclic S-VECD Fatigue Damage Characteristic Curves; (a) ALF mixes and (b) PennDOT mixes

Damage Normalization and Fatigue Prediction from Cyclic Tests

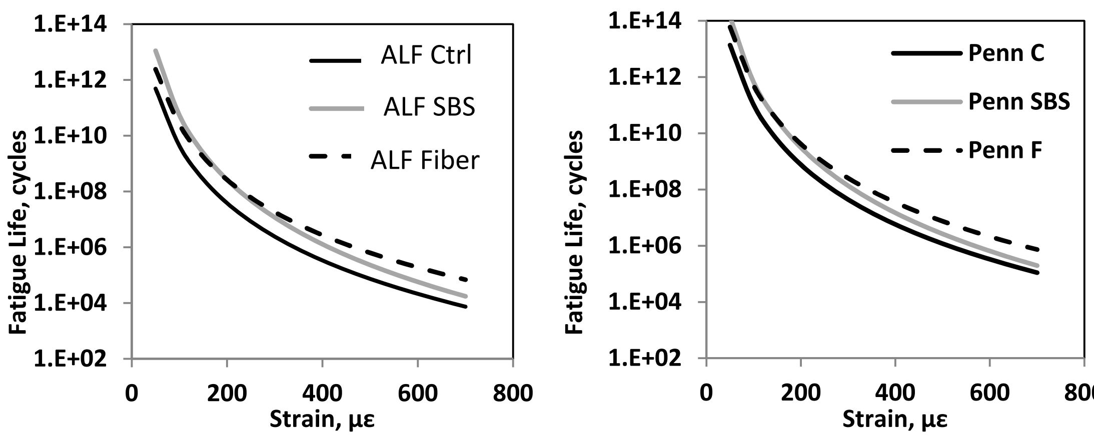
The accuracy of an analysis based upon viscoelastic continuum damage (VECD) concept is not compromised as a result of not running a true strain or stress controlled test. By using the VECD method, damage characteristic curves can be computed using any loading history. That is, the methodology can be used to predict the results of controlled strain tests once the material parameters are determined. The key inputs for the VECD analysis are the linear viscoelastic modulus and phase angle, and the damage exponent (α), which is calculated from the inverse log-log slope of the relaxation modulus ($E(t_R)$) curve, C_f and C(S). In general, larger values for the α damage exponent (smaller slopes) may indicate better performance although experience indicates that the predicted performance is more sensitive to the psuedostrain at failure criteria C_f. Once the C(S) damage characteristic curve is obtained, the VECD-based fatigue life of the mixture can be determined by simulating a fatigue test with inputs such as test temperature, frequency and strain levels. The pseudostiffness at which the maximum phase angle was reached was used for the failure criterion in the simulation. The pseudostiffness at the maximum phase angle was averaged from individual specimens reaching the maximum phase angle and the values were found to be C_f = 0.15, 0.10 and 0.085 for the three ALF mixtures (L2 Control, L4 SBS and L7 Fiber) and 0.12, 0.12 and 0.11 for the three Penn DOT mixes (Penn C, Penn SBS and Penn F), respectively. The α damage exponent for the three ALF mixtures was 3.41, 3.84, and 3.29 (L2, L4 and L7) and for the three Penn DOT mixes the parameter was 3.53, 3.46, and 3.86 (Penn C, Penn SBS and Penn F).

A total of 14 strain levels ranging from 50 to 700$\mu\varepsilon$ at the physical test temperature of 19^{o}C and 10 Hz were simulated for both the mixture sets. The results for the ALF mixtures are shown in FIGURE 6a. FIGURE 7a depicts the ratio of the predicted fatigue life of the SBS and Fiber mixes relative to the control mixes; L4 SBS/L2 Control, L7 Fiber/L2 Control for the ALF mixes. The simulation results indicate that the two modified ALF mixes perform better than the control mix. The ranking of the fatigue life is L4 (SBS) > L7 (Fiber) > L2 (Control) when the strain is smaller than 200$\mu\varepsilon$; however, the ranking is L7 (Fiber)> L4 (SBS) > L2 (Control) when the strain is higher than 200$\mu\varepsilon$. The fatigue ratio data in FIGURE 7a illustrates that the ALF SBS mix exhibits about 2 to 23 times the number of cycles to failure of the control mix while the ALF Fiber mix is about 5 to 10 times of the control mix in terms of the fatigue life.

A comparison between the ALF field performance data (7) and laboratory results illustrates that the measured ALF cracking data are consistent with the results of the laboratory fatigue test and predictions. The measured strain of the fiber mix from embedded strain gauges was between 539 and 550 με which is above the 200 με fatigue life ratio cross-over in FIGURE 7a. The SBS mixture exhibited a field-measured strain between 862 and 976 με. Furthermore, to achieve approximately 25% fatigue-cracked area, the control mixture sustained 40,250 cycles under the ALF, the SBS mixture 210,000 cycles and the Fiber mix 380,000 cycles.

Very similar laboratory results were found for the Penn DOT mixes as seen in both FIGURE 6b and FIGURE 7b. The fatigue performance of the two modified mixtures yielded predictably better performance than the control mixture. Specifically, the ranking of the fatigue life is Penn SBS > Penn Fiber > Penn control mix when the strain is smaller than 150με; the ranking is Penn Fiber > Penn SBS > Penn control mix when the strain is higher than 150με. For the Penn DOT mixes, the fatigue life of Penn SBS mix is predicted to be about 1.75 to 10 times of the control mix while that of the Penn Fiber mix is about 4 to 6 times of the control mix.

It is noteworthy that the same pattern of the fatigue ratio was observed in both sets of materials. Specifically, the fatigue life ratio drops for the SBS/Control when the strain increases whereas that from the Fiber/Control increases with the strain. This could be attributed to the assumption that the fiber plays a more significant role to make a relatively more fatigue crack resistant mixture when the material is loaded to higher deformations and strains thereby mobilizing tensile stresses and strains in the distributed fibers. This behavior could be an engineering characteristic of polymer modified and fiber reinforced asphalt mixtures.



(a) (b)

FIGURE 6 Cyclic S-VECD Predicted Fatigue Life at 19ºC and 10Hz; (a) ALF mixes and (b) PennDOT mixes

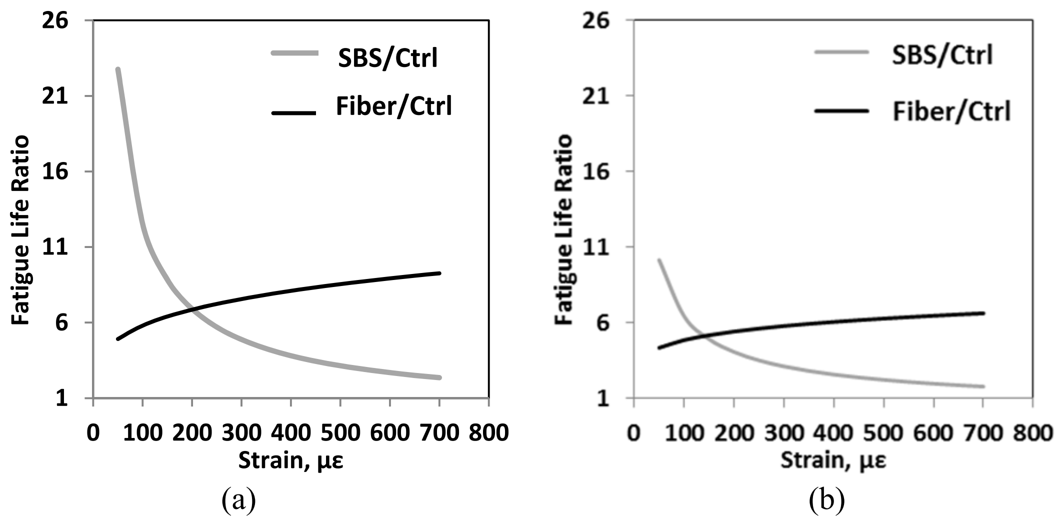


FIGURE 7 Cyclic S-VECD Predicted Fatigue Life Ratio; (a) ALF mixes and (b) PennDOT mixes

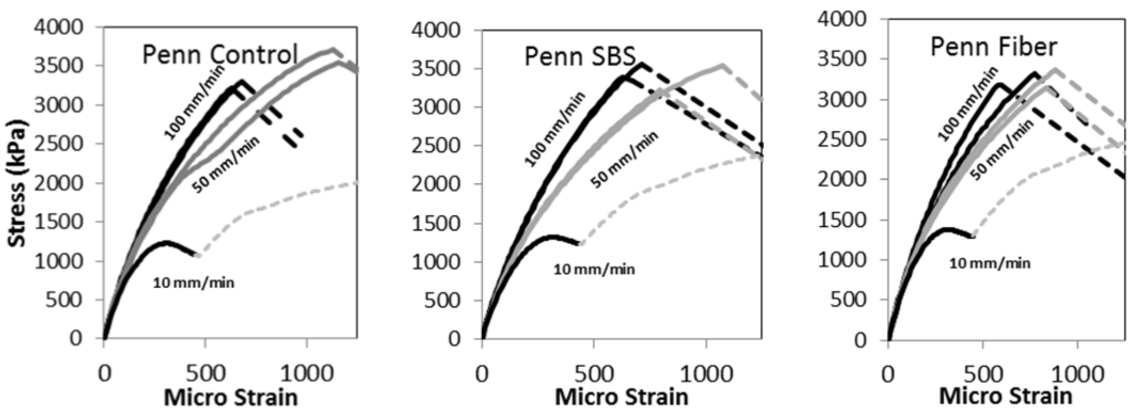
Monotonic Tests to Further Explore Fatigue Strain Response

Following the observation of this unexpected the fatigue life ratio pattern (FIGURE 7) in both sets of materials, the study sought to further validate these findings. Theoretically, the same viscoelastic continuum damage principles can be used to analyze monotonic data and define the same damage characteristic curve C(S) as was done in the cyclic tests. Several strain rates were used to define separate C(S) curves from each individual test and a "good" materials characterization occurs when the curves from different strain rates coalesce onto a common curve. Material quantities for the monotonic tests on the Pennsylvania DOT mixtures were limited and thus two replicates were tested for the higher strain rates and one replicate for the slowest strain rate. There were not sufficient quantities of materials to conduct additional monotonic tests on the ALF materials.

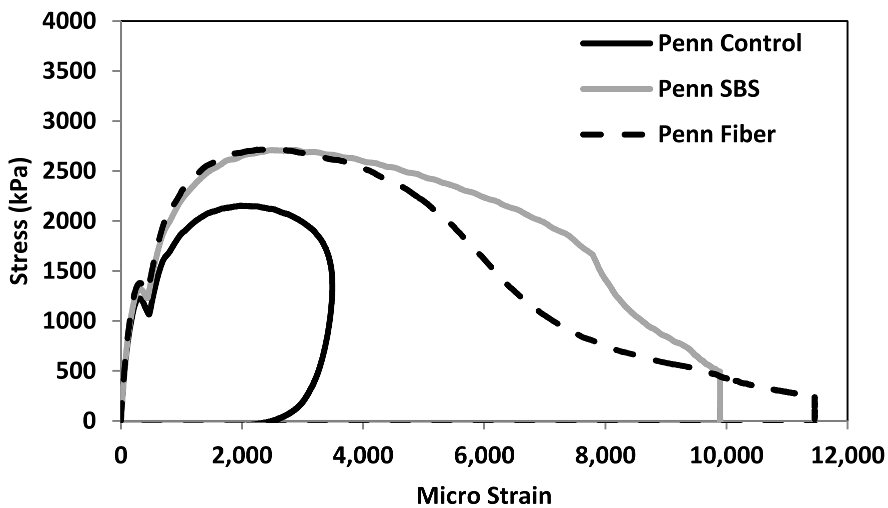
The basic stress-strain curves from the three strain rates used on the three PennDOT materials are shown in FIGURE 8a, b and c. Several observations can be made:

- The three materials have very similar strength and deformation characteristics. No one material stands out from the other. Faster rates induce steeper stress-strain curves as would be expected for a viscoelastic material.
- The exception to the above observation can be seen in FIGURE 8d where the data from the slowest strain rate is presented for all three materials. A much longer post-peak and higher peak strength is observed in the SBS and Fiber modified materials and hence the total energy to fail the materials is larger than the control mixture.
- A stress-strain anomaly was observed in the slowest strain rate for all three materials in the very beginning of the test where an abrupt increase in strain with a slight decrease in stress was observed. The anomaly was followed by a climbing stress strain curve and a usual post-peak. This created some instability in the viscoelastic continuum damage analysis and thus only the solid line portion in FIGURE 8a, b, and c was analyzed. The anomalies are not believed to be a testing flaw or random because they were repeatedly observed in all three of the lowest strain rates for each of the three materials possibly indicating an actual staged or incremental failure.

- The failures that occurred with the two fastest strain rates was more of a brittle mode abrupt failure denoted by the dashed lines after the peak in FIGURE 8a, b and c.
- All of the replicates cracked in the middle of the sample and no end failure occurred.
- The reduced size specimens were necessary because the maximum stress that can be achieved in 100mm diameter specimens with a 15 kN actuator is about 1,900 kPa which was exceeded in most monotonic tests at the relatively cold 10^{o}C temperature to avoid viscoplasticity effects.



(a) (b) (c)

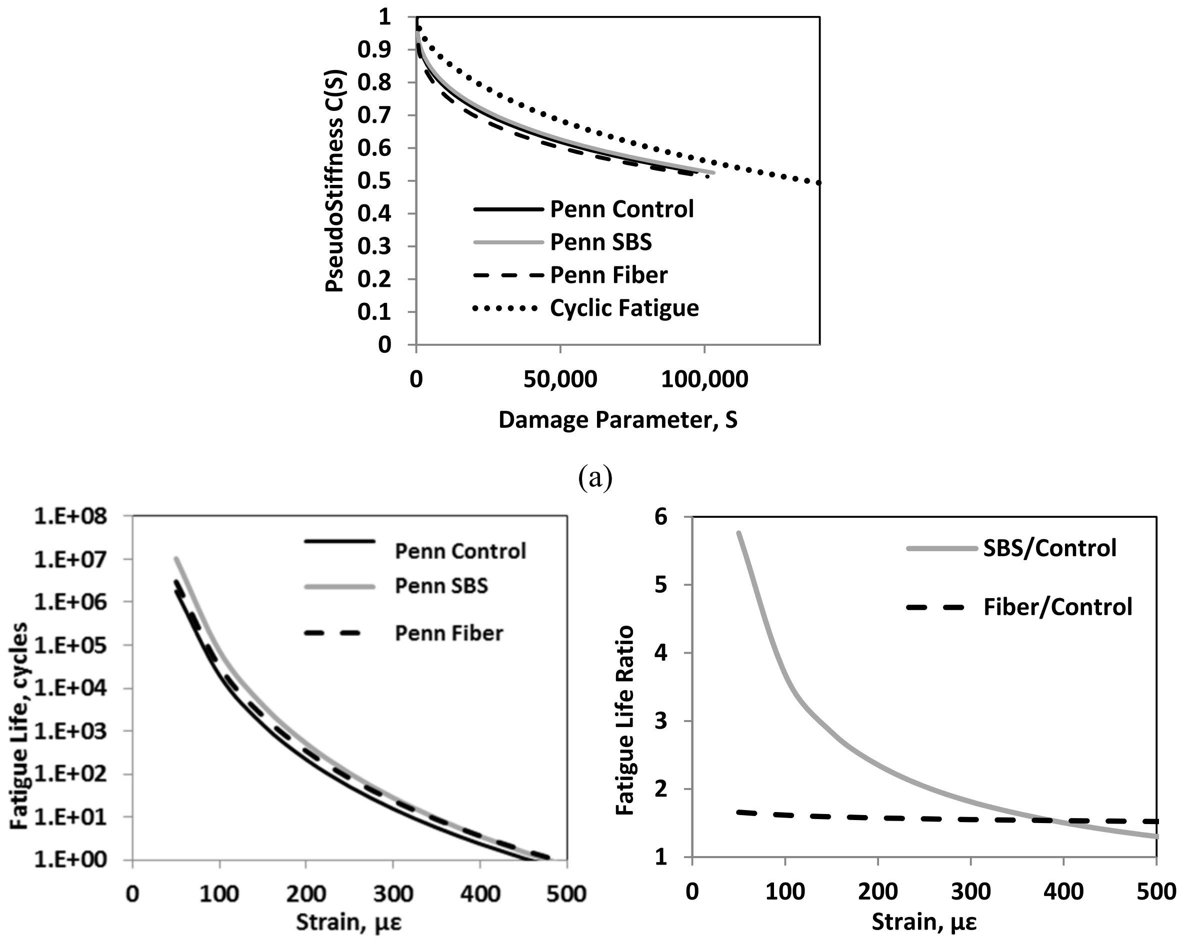


(d)

FIGURE 8 Stress and strain response of monotonic tests. All three rates (a) Control, (b) SBS, (c) Fiber and (d) entire stress-strain curves from the slowest strain rate for all three mixtures

Viscoelastic continuum damage analyses were conducted on the monotonic test data. Viscoplastic strains were assumed negligible at this cooler temperature. For completeness, additional tests for dynamic modulus and phase angle were measured on a separate set of small-scale specimens which were not reused. This was done to ensure there were no inaccuracies in using the full-size dynamic modulus and phase angle data in the small-scale monotonic continuum damage calculations. From the dynamic modulus and phase angle data, the relaxation modulus, $E(t_R)$, was calibrated using a 32- term Prony series for loss, $E''(\omega_R)$, and storage modulus E'(ω_R) in frequency space by means of a best fit log-normal distribution for the individual elastic terms, E_i, over an assumed set of relaxation times, ρ_i. Following this, the pseudostrain was calculated from the measured strains. The pseudostiffness, C, was determined from the computed pseudostrain and measured stresses. The numerical techniques outlined in AASHTO TP107 (9) were followed for the methods of computing of pseudostrain C as well as the damage internal state variable, S.

The results of the damage characteristic curve fit to the monotonic tests at 10^{o}C are shown in FIGURE 9a along with the curves from the cyclic fatigue tests at 19^{o}C. The curves are similar but not identical to that obtained from the cyclic data (FIGURE 5b) and the pseudostiffness at failure is much higher than for the warmer, cyclic fatigue tests. The predicted



(a)

(b) (c)

FIGURE 9 Viscoelastic continuum damage analyses from monotonic tests on PennDOT mixes; (a) damage characteristic curves (b) predicted fatigue lives and (c) fatigue life ratios.

fatigue lives was calculated at 10^{o}C and 10Hz for a range or strains based on the temperature-specific pseudostiffness failure criteria of 0.54, 0.48, and 0.52 for the Control, SBS and Fiber mixes. The corresponding α damage exponents were 3.26, 3.58 and 3.28. It can be seen the fatigue life at a cooler temperature of 10^{o}C is much smaller than the fatigue life earlier shown at 19^{o}C. Nonetheless, the fatigue life ratio is shown in FIGURE 9c where a similar pattern is observed as was from the cyclic fatigue tests (FIGURE 7a and b) where both the Fiber and SBS provide better fatigue cracking performance that the Control mixture and eventually at higher strains the fiber mix exhibits better performance while the SBS mixture exhibits better performance at smaller strains.

SUMMARY AND CONCLUSIONS

The objective of this study was to assess how asphalt mixtures with distributed fiber reinforcement behave in cracking tests that can be conducted in the AMPT. Loose mixtures from separate plant production runs provided two independent sets of mixtures that included unmodified, SBS modified and fiber modified mixes. Monotonic tests were conducted as a companion to cyclic fatigue tests as a means to provide an alternative methodology to verify some of the apparent cracking performance benefits observed from the fiber modification. The differences in small-strain dynamic modulus, cyclic fatigue, continuum damage characteristic curves, energy, yielding and predicted fatigue behavior were measured, calculated and compared. The following can be concluded:

1) Depending on the test, the observed improvements to mixture performance from the presence of fibers can be subtle.
   - SBS polymer modification had a larger effect on dynamic modulus than fibers.
   - Strength and deformation during monotonic, direct tension strength tests are nearly identical for the three types of mixtures except at the slowest strain rate where the post peak of polymer and fiber modified mixes exhibited a higher peak strength and longer post peak; e.g. more energy require to fail the material.
   - This subtlety seems consistent with the literature where the observed performance enhancements from fiber were sometimes observed and other times the performance was no different from control sections.
2) Overall, cracking performance benefits were observed that depended on the particular materials and strain magnitudes under consideration; there is no general rule with fibers.
   - Based on cyclic fatigue testing and viscoelastic continuum damage analysis, fatigue life ratios relative to control mixtures showed that the ALF SBS mix is about 7 to 23 times better than the control mix at strains smaller than 200 $\mu\varepsilon$. Above this level ALF Fiber mix is about 7 to 10 times better than the control mix. The fatigue life of PennDOT SBS mix was predicted to be about 1.75 to 5 times of the control mix below 150 $\mu\varepsilon$ and then above that the Penn Fiber mix is about 5 to 6 times of the PennDOT control mix.
   - A similar pattern with different magnitudes was observed in the PennDOT mixtures determined from a different test methodology. This supports but does not prove the phenomenon is an engineering characteristic of fiber versus SBS mixes relative to control materials.
3) Lastly, data from well controlled conditions under full-scale accelerated pavement testing support the fatigue performance benefits observed in the laboratory tests for all three material types.

The findings from this study might be considered in the design of additional experiments such as the crack resistance performance of combined polymer modified binder with fiber reinforcement. Field sites with thin pavement structures, overlays or surface courses where strains are relatively large might be targeted for further validation and, ideally, provide stronger cost:benefit ratio(s) that the pavement community still needs for fiber reinforced asphalt mixtures.

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