Fatigue Behavior of Styrene-Butadiene-Styrene Modified Asphaltic Mixtures Exposed to Low-Temperature Cyclic Aging

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Polymer modifiers are being considered to improve the high-temperature stiffness and low-temperature flexibility and hence the long-term performance of asphaltic mixtures. In this regard, styrene-butadiene-styrene (SBS) copolymer has received much attention. In the current research, the fatigue crack propagation resistance of an SBS-modified AC-5 mixture exposed to different durations of low-temperature thermal cycling is investigated. Beams were prepared using a constant 8 percent AC-5 asphalt by weight and 6 percent SBS as a percentage of the total binder. Aggregate gradation according to Ohio Department of Transportation Item 403 was used. Mixing and compaction were performed according to ASTM D 1559–89. A cyclic thermal aging program was performed in an environmental chamber between 21.1°C and −12°C for four different periods. The effect of thermal cycling on the fatigue resistance of the modified mixtures as determined by the modified crack layer (MCL) model was studied. A relationship between the number of thermal cycles and the specific energy of damage γ', a material parameter characteristic of the mixture's resistance to crack propagation, was established. The current investigation revealed that SBS modifier helps in maintaining a constant fatigue resistance of the mixture over a moderate number of low-temperature thermal cycles. A decrease in the fatigue resistance was observed at a higher number of thermal cycles. In addition, a dramatic improvement in the fatigue resistance of the SBS-modified AC-5 concrete mixture is seen when compared with that of the unmodified AC-5 over all durations of thermal cycling tested. The fatigue performance of the mixture as predicted from the MCL model through the specific energy of damage γ' was consistent with predictions from the conventional resilient modulus and indirect tensile tests.

The durability of asphalt pavements is greatly influenced by environmental changes during the year, especially between summer and winter and between day and night, when the daily average temperature change can be considerable. In summer, high temperatures can soften the asphalt binder and consequently reduce the stiffness of the paving mixture. At the other extreme, low temperatures in winter can stiffen the asphalt binder and reduce the flexibility of the paving mixture. As a result, thermal cracking of the pavement surface may develop, which adversely affects the performance of the paving mixture. Thus, high-temperature stiffness and low-temperature flexibility are important properties that increase the lifetime of asphalt pavements.

Various elastomer and plastomer modifiers have been sought in an attempt to address this problem. Polymer modifiers vary in function and effectiveness. Elastomers, which are at least to some extent derived from a diene chemical structure, will toughen asphalt and improve temperature viscoelastic properties. Plastomers, which come from nondiene chemicals, improve the high-temperature viscoelastic properties of softer asphalts, which have good intrinsic low-temperature properties (*1*). The properties of asphalt mixtures can be improved by selecting modifiers in the proper molecular weight range and mixing the modifiers with asphalt mixtures in an appropriate manner. In addition, these modifiers must have solubility parameters close to those of the asphalt mixtures. One of the critical factors that should be considered for better rubber-modified asphalt is the air void percentage in the total mix. The performance of a rubber-modified asphalt mixture will be improved as this percentage is reduced (*2,3*). In general, the air void percentage depends on the load capacity of the transportation facility being designed. Lower air void percentages can be obtained by increasing both the modifier and the asphalt binder content until the required value is reached (*2*).

Investigation into the effect of asphalt additives on pavement performance (*4*) has revealed that, in general, all additives improved in temperature susceptibility. Under stress control fatigue, using the phenomenological approach, which is based on the Wohler concept (*5*), these workers concluded that SBS was one of the top additives among five tested (polyethylene, Elvax, SBS, latex, and carbon black) at 0°F and 68°F. This has also been confirmed using the modified crack layer (MCL) model (*6*). However, when the mixtures containing additives were aged at 140°F for 7 days, their fatigue lifetime decreased considerably in comparison with their unaged counterparts (*4*). Under controlled displacement fatigue, using the Paris equation (*7,8*), Little et al. (*4*) also concluded that the SBS additive was considerably superior among those additives tested at 33°F. At 77°F crack branching was observed, which tends to redistribute the stress, retarding main crack growth.

The phenomenon of aging of asphalt cement has been acknowledged for a long time, and extensive research has been conducted on the effect of long-term aging on asphalt cement. However, little research has examined asphalt mixtures, and so far, no standard test methods exist (*9*). In general, studies of aging of pavements are performed by three main methods: extended heating, pressure oxidation, and ultraviolet (UV) light treatment. Aging by extended heating (*10–13*) involves an oven aging program by which pavement samples are heated to a specific temperature for a specific period. Then standard tests such as the resilient modulus test, indirect tensile tests (strain to break), and the dynamic modulus RST are performed to evaluate the effect of the laboratory aging. Pressure oxidation aging, studied by several workers (*13–15*), involves exposing heated samples of pavement to air or oxygen under pressure for a fixed time period. At the conclusion of the experiments, standard tests such as creep, resilient modulus, and fatigue are used

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to evaluate the effect of pressure oxidation aging on pavement. Aging by UV treatment (*10,16,17*) involves subjecting samples of pavement to UV radiation for a specific period and then performing standard tests similar to those for the extended heating and oxidative aging. Combined aging with UV and forced draft oven heating has been suggested by Tia et al. (*18*), who note that the effect of UV aging occurs at the surface although it does affect a significant depth of the pavement.

From the literature, all aging methods that have so far been used mainly involve heating the pavement to harden it through volatilization and oxidation. The main drawback of these methods is softening of the pavement samples during aging, which can lead to a loss in mechanical stability. This view is supported by Kim (*15*), who suggested that maintaining the integrity of a sample subjected to these aging methods presents a problem. Bell (*9*) stated that in some aging programs specimen confinement may be necessary to prevent collapse, and concludes that none of the aging methods used so far are clearly superior and the possibility exists for new methods.

Apparently, very little work has been done on aging using thermal cycling, which is of critical importance since it simulates the actual environmental aging cycles to which asphalt mixtures are normally exposed. Thermal cycling is known to cause transverse cracking in asphalt pavements, which considerably shortens their lifetime, particularly at low temperatures. Transverse cracking is caused by stresses from shrinkage that become greater than the tensile strength of the material (*19*). Thus, it appears that environmental aging of the pavements by low-temperature thermal cycling can test the hypothesis that polymer modifiers improve the performance of asphalt-modified pavements.

The current study evaluates styrene-butadiene-styrene (SBS) modified AC-5 mixtures. This evaluation involved aging by thermal cycling in a low-temperature regime. The performance of the modified asphalt concrete mixture was evaluated on the basis of its resistance to fatigue propagation using the MCL model. A comparison was made between the fatigue performance of the mixture with the conventional properties such as the indirect tensile strength and resilience modulus.

EXPERIMENTAL

Materials

AC-5 asphalt cement used in this study had the following physical properties: (*a*) penetration at 25°C (77°F) was 204 using ASTM D-5, (*b*) viscosity at 135°C (275°F) was 201 cSt using ASTM-2170, (*c*) viscosity at 60°C (140°F) was 461 poise using ASTM-2171, and (*d*) flash cleveland open cup using ASTM-92 was 313°C (595°F). Crushed limestone aggregate and quartzitic sand were selected for the preparation of test specimens. Ohio Department of Transportation (ODOT) Item 403 gradation was used (*20*).

Kraton D4463 (SBS), which belongs to the general group of thermoplastic elastomers, was chosen as the modifier. It was supplied in pellet form by Shell Chemical Company and requires mixing at temperatures between 160 and 193°C (320 to 380°F).

Beam Preparation

The AC-5 asphalt cement was heated alone to 149°C (300°F). The asphalt blend was prepared with 6 percent SBS by weight of the asphalt. The blend was maintained hot to a goal temperature ranging between 160 and 177°C (320 to 350°F) for at least 2 hr. It was then thoroughly mixed by means of low-shear mechanical mixer for at least 15 min to obtain a more homogenous blend. Finally, the blend was kept at a constant temperature of 163°C (325°F) until ready for use.

The required percentages of aggregate were mixed in one batch to produce asphalt concrete beams with a target unit weight of 2386 kg/m^3 (149 lb/ft^3). The aggregate mixes and the asphalt cement were heated to a temperature of about 177°C (350°F), along with the compaction mold and the mixing tools. The aggregate was then blended with the required amount of asphalt cement (8 percent of the total weight of mix) as quickly and thoroughly as possible to yield a mixture having a uniform distribution of asphalt cement. The heated mold was then filled with the heated asphalt cement–aggregate mixture. This percentage of asphalt cement corresponds to the optimum asphalt cement content as determined by the Marshall method of mix design (ASTM D 1559–89). Static compaction was then performed by applying a uniform pressure of 13.79 MPa (2000 psi) through a 0.051- × 0.38-m (2 in. × 15 in.) plate using a hydraulic press for 5 min. The overall dimensions of each beam were 0.38 m long × 0.051 m wide × 0.089 m high (15 in. × 2 in. × 3.5 in). The compacted beam was allowed to cool in the mold for a few hours before its removal. Curing was achieved by maintaining the beams at 60°C (140°F) for 1 day. All beams were then kept in a room with a controlled temperature of 21.1°C for 7 days before testing.

Thermal Aging

Beams were thermally cycled between 21.1°C and −12°C (70 to 10.4°F) in an environmental chamber. The temperature-time profile used in this study is shown on Figure 1. This profile was established initially by embedding a thermocouple in the middle of a beam. The rate of heating and cooling of the asphalt mixture was established as shown in Figure 1. A temperature plateau was maintained at the upper 21.1°C and lower −12°C temperature levels. The length of each cycle was taken as 1 day. Four durations of thermal cycling were used. These were 7, 14, 21, and 28 cycles. At least three specimens were tested at each duration period of thermal cycling used in the corresponding fatigue study. Three specimens were also fatigued without thermal cycling for comparison. Similar tests were

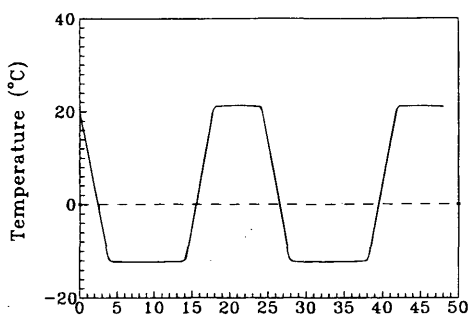

FIGURE 1 Schematic diagram of temperature-time profile for low-temperature thermal cycling program.

conducted on Marshall-sized cylindrical specimens to study the effect of thermal cycling on resilient modulus and indirect tensile failure of the SBS-modified mixture.

Fatigue Crack Propagation Tests

Four point bending fatigue crack propagation tests were performed under stress control using a repeated pneumatic flexure testing machine fitted with a 4.45-kN (1,000-lb) load cell. Tests were conducted at a constant temperature of about 21.1°C (70°F) using an invert haversine load. The load application period was 0.2 sec followed by a 2-sec rest period between repeated loads. The support span was equal to 0.26 m (10.2 in.) and the distance between the midspan loading points was 0.086 m (3.4 in.). An initial straight notch 6.4 mm (0.25 in.) deep was inserted at the middle of the specimens with a 4-mm (0.15 in.) saw that had a round tip [radius 2.4 mm (0.094 in.)]. A maximum load of 290 N (65 lb) was used with continuous cycle load applications from zero to the maximum load. A hysteresis loop (load versus deflection) was recorded at 6.4-mm (0.25 in.) intervals of crack growth using the X-Y plotter. Software was developed to digitize graphical data and to calculate pertinent areas within the load-deflection curves obtained during fatigue testing. Three specimens were fatigue-tested at four different durations of thermal cycling and three before thermal cycling, for a total of 15 beams.

RESULTS AND DISCUSSION

Fatigue Behavior

For stress-controlled fatigue, the MCL model, previously discussed in detail (*21,22*), can be expressed as

$$\left(\frac{J^*}{a}\right) = \gamma' - \beta'\left[\frac{\dot{W}_i}{a\left(\dfrac{da}{dN}\right)}\right] \tag{1}$$

where

J^* = energy release rate (i.e., $J^* = (\partial P/\partial a)/B$, where P is the potential energy and B is the specimen width);
a = crack length;
$\dot{W}_i$ = change in work;
da/dN = cyclic crack speed;
γ' = material parameter, characteristic of the mixture's resistance to FCP; and
β' = coefficient of energy dissipation.

The effect of thermal cycling on the fatigue resistance of the SBS-modified AC-5 mixture is examined in view of the MCL model. The crack length (a) versus the number of cycles (N) for typical specimens of the SBS modified AC-5 mixture, which were subjected to four different durations of thermal cycling, together with a typical specimen without thermal cycling are shown in Figure 2. It appears that samples subjected to 0 to 14 thermal cycles are close, with points clustering together. However, there exists a difference between their behavior when the first derivative of each curve was calculated to obtain the crack speed. Applying the crack length versus the number of cycles, the behavior of samples subjected to 21

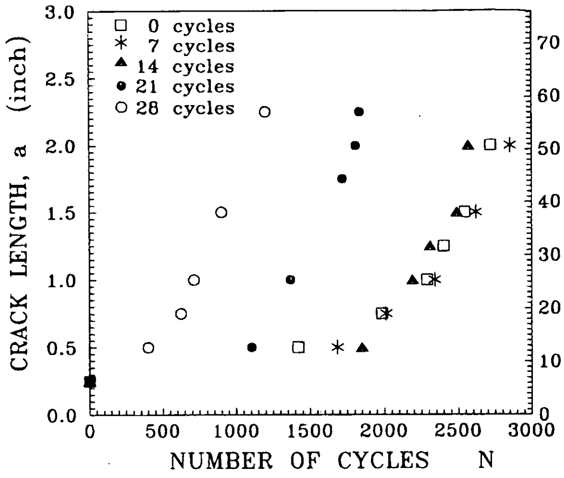

FIGURE 2 Crack length versus number of cycles for SBS-modified AC-5 asphalt concrete mixture subjected to low-temperature thermal cycling.

and 28 thermal cycles shows a marked decrease in their fatigue lifetime at a faster crack propagation rate. The crack speed was calculated, to be employed in the MCL model, at intervals of crack length from the slope of each curve in Figure 2.

The energy release rate J^*, evaluated on the basis of the potential energy principle as previously reported (*23–26*), is plotted against the crack length in Figure 3. As with the lifetime curves, the effect of thermal cycling is not seen clearly until 21 and 28 cycles. The lower values of J^*, at each crack length, with increased thermal cycling are expected. However, it is interesting to note how SBS maintains its improved properties up to a certain duration of cycling, after which the improved resistance starts to drop off. Again, the value of J^* at each crack length will be employed in the present analysis to extract γ' and β' for each mixture from Equation 1.

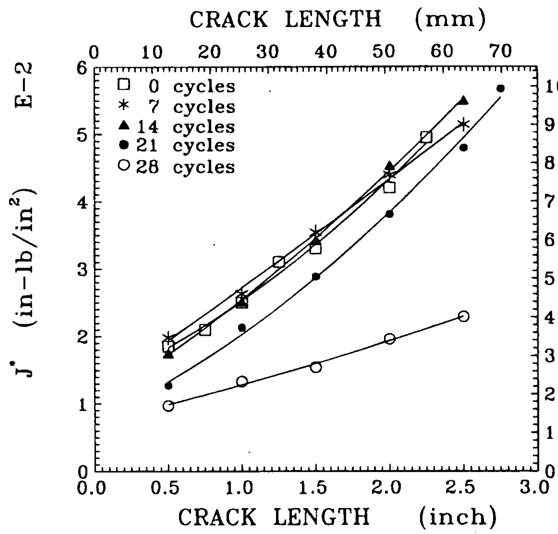

FIGURE 3 Energy release rate versus crack length for SBS modified AC-5 asphalt concrete mixture subjected to low-temperature thermal cycling.

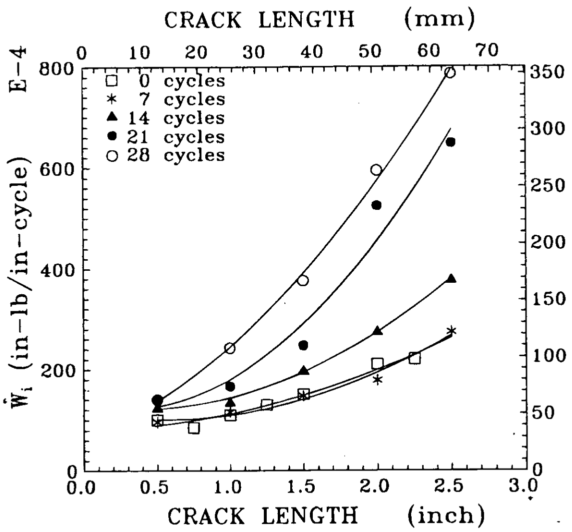

FIGURE 4 Change in work, $\dot{W}_i$, versus crack length for SBS-modified AC-5 asphalt concrete mixture subjected to low-temperature thermal cycling.

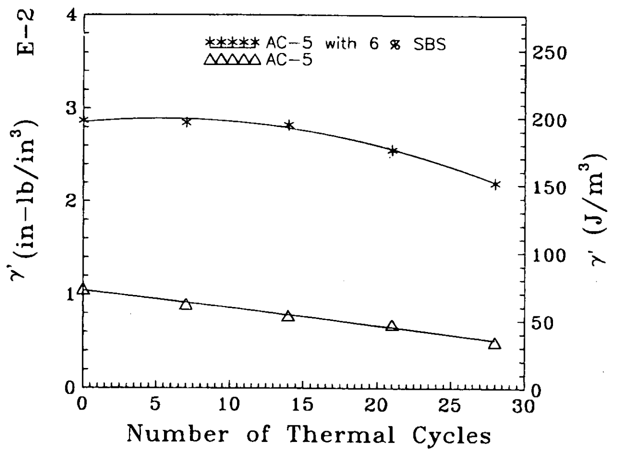

FIGURE 6 Effect of number of low-temperature thermal cycles on specific energy of damage γ' for SBS-modified AC-5 asphalt concrete mixture and unmodified AC-5.

The change in work, $\dot{W}_i$ (where $\dot{W}_i$ is the area of hysteresis loop at any crack length minus the area of hysteresis loop before crack initiation divided by the specimen thickness), versus the crack length for typical beams tested at various durations of thermal cycling (as well as beams without thermal cycling) is shown in Figure 4. The value of $\dot{W}_i$ increases with increasing number of thermal cycles. Thus, increased thermal cycling leads to the use of more work on damage formation and history-dependent dissipative processes within the active zone of the SBS-modified mixture during fatigue loading.

The previous results from a typical specimen from each duration period of thermal cycling are now plotted, on the basis of Equation 1, in order to extract γ' and β'. It is evident from Figure 5 that the experimental points for all of the mixtures make a good straight line, where γ' is the intercept and β' is the slope. The effect of thermal cycling on γ' is shown in Figure 6 for SBS-modified and unmodified AC-5 mixtures. It can be seen that γ' remains approximately constant from 0 to 14 cycles; then it decreases slightly with the increase in the number of thermal cycles for the SBS-modified mixture. This decrease in the value of γ' is indicative of reduced resistance to crack propagation. As can be seen, the addition of the SBS to the mixture greatly enhances the overall fatigue resistance over the entire duration of thermal cycling tested. In addition, the trend of a slight decrease in resistance with increased number of thermal cycles is also seen in the unmodified AC-5 mixture.

On the other hand, the coefficient of energy dissipation, β', remains constant with the increasing number of thermal cycles for the SBS-modified AC-5 concrete mixture, as seen in Figure 7. The value of β' for the unmodified AC-5 mixture was found to be higher over the entire range of thermal cycling tested. Thus, from the MCL model, a decrease in γ' with an increase in β' at all durations of ther-

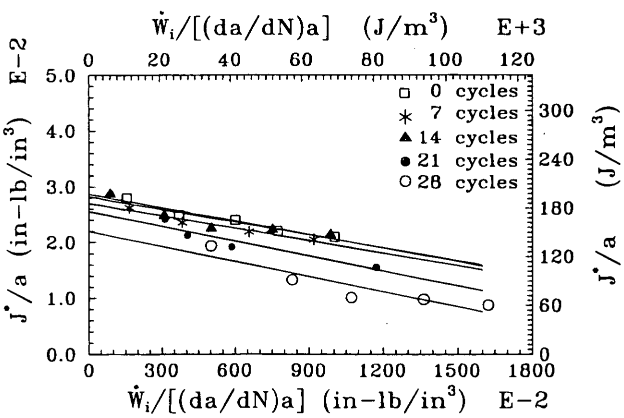

FIGURE 5 Fatigue crack propagation behavior of SBS-modified AC-5 asphalt concrete mixture subjected to various durations of low-temperature thermal cycling plotted in form of MCL model to obtain γ' and β'.

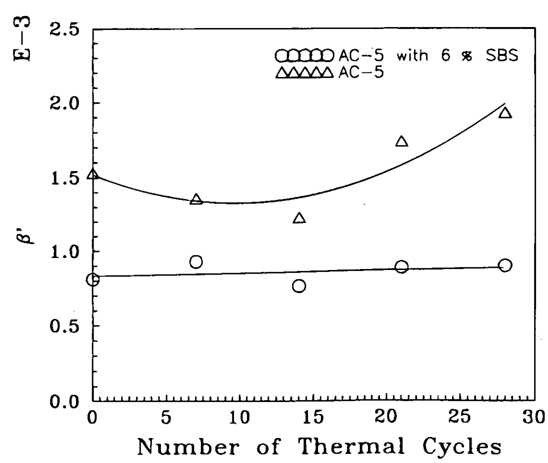

FIGURE 7 Effect of number of low-temperature thermal cycles on coefficient of energy dissipation β' for SBS-modified AC-5 asphalt concrete mixture and unmodified AC-5.

mal cycling tested indicates the fatigue resistance superiority of the SBS-modified AC-5 concrete mixture at all durations of thermal cycling tested.

The fatigue behavior of the SBS-modified mixture as assessed by the MCL model will be compared with conventional mechanical property evaluation based on the resilient modulus and indirect tensile behavior.

Resilient Modulus and Indirect Tensile Behavior

The resilient modulus tests were conducted in accord with ASTM D4123. The following equation is used to calculate the resilient modulus (M_r).

$$M_r = \frac{F(\nu + 0.2734)}{tD} \tag{2}$$

where

F = load,
ν = Poison's ratio (assumed 0.4),
t = specimen thickness, and
D = total horizontal deformations.

The average values of M_r based on three tests measured at different durations of thermal cycling for the SBS-modified AC-5 mixture and the unmodified AC-5 mixture are plotted in Figure 8. It is evident that the relationship between M_r and the number of thermal cycles is the same for the unmodified and SBS-modified AC-5 concrete mixtures up to 14 cycles after which there is a noticeable increase in the M_r of the SBS-modified mixture. The data in Figure 8 indicate that the modified mixture became less flexible as the number of thermal cycles increased, particularly after 14 thermal cycles. The unmodified AC-5 mixture exhibited a more constant increase in resilient modulus with an increase in the number of thermal cycles.

The indirect tensile behavior of specimens exposed to various numbers of thermal cycles was established in accordance with research by Kennedy and Hudson (*27*). The average compressive

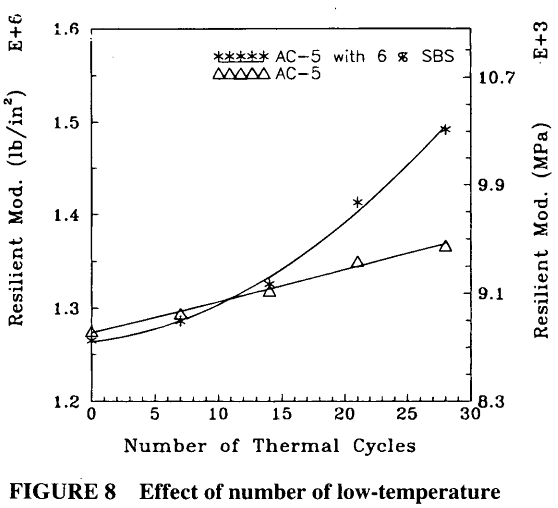

FIGURE 8 Effect of number of low-temperature thermal cycles on resilient modulus for SBS-modified AC-5 asphalt concrete mixture and unmodified AC-5.

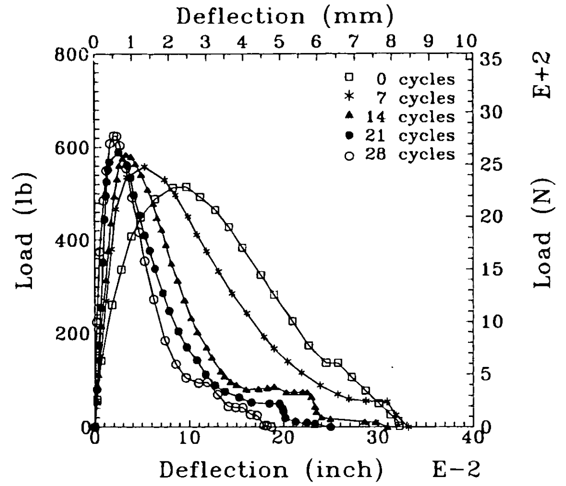

FIGURE 9 Compressive load versus horizontal deformation for indirect tensile test conducted on SBS-modified AC-5 asphalt concrete mixture subjected to various durations of low-temperature thermal cycling.

load versus the vertical displacement for Marshall-sized cylindrical specimens at different numbers of thermal cycles is shown in Figure 9. The maximum load increased slightly as the number of thermal cycles increased, whereas the deformation at failure as well as the deformation at maximum load were nearly constant from 0 to 7 cycles and then decreased considerably. It is also obvious from Figure 9 that the work needed to cause tensile failure, the area under the load-deformation curve, is considerably decreased with the increase in the number of thermal cycles after 7 cycles. Lower strain at failure and lower amount of work needed to cause tensile failure are associated with decreased resistance to fatigue crack propagation.

Thus, in view of the conventional resilient modulus and indirect tensile test, the resistance of the SBS-modified mixture to crack propagation is slightly decreased at increased durations of thermal cycling. This is in substantial agreement with the MCL analysis as reflected in the specific energy of damage, γ'.

CONCLUDING REMARKS

The effect of low-temperature thermal cycling on the fatigue fracture behavior of SBS-modified AC-5 asphalt mixture was studied. Relationships between parameters controlling the fatigue fracture process, namely, the specific energy of damage γ' and the dissipative coefficient β' of the SBS mixture, and the number of thermal cycles, were established. The current study reveals that the value of γ' remains almost constant over a moderate number of thermal cycles. This can be attributed to the flexibility of the mixture induced by the SBS modifier. The value of γ' decreases at higher duration periods. The decrease in the specific energy of damage was found to accompany a nearly constant value of the dissipative coefficient β' over all durations tested. It is also noted that γ' is considerably higher and β' lower than for the unmodified AC-5 over all durations tested, indicating superior fatigue resistance to crack propagation of the SBS-modified AC-5 mixture. Exposure of the SBS-modified asphalt mixture specimens to a high number of thermal cycles tends to stiffen the mixture and, in turn, reduce its fatigue resistance. However, it is still much improved over the unmodified AC-5 mixture, which also exhibits a similar reduction in resistance. The fatigue crack propagation resistance of the SBS-modified mixture predicted from the MCL model through the specific energy of damage γ' is consistent with the prediction made based on conventional resilient modulus and indirect tensile tests.

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