Evaluation of Healing in Asphalt Concrete by Means of the Theory of Nonlinear Viscoelasticity

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The literature review demonstrates that a mechanism exists that enhances fatigue life of asphalt concrete mixtures as rest periods are introduced in fatigue testing. Results are presented and analyzed from controlled displacement, cyclic crack propagation tests in which rest periods were randomly introduced. The results demonstrate that a "healing" mechanism does indeed result in the requirement of a greater level of work to drive a crack following a rest period than was required before the rest period was introduced. The effort to identify the mechanism of chemical healing in the microcrack process zone is confounded by the concomitant occurrence of viscoelastic relaxation. Schapery's correspondence principle of nonlinear viscoelastic media was successfully used to separate viscoelastic relaxation from chemical healing. Application of the procedure of separating out the viscoelastic relaxation yields a method by which to quantify chemical healing in the microcracks of the process zone preceding the macrocrack. Chemical healing as a function of rest periods is quantified using a healing index based on pseudo-energy-density. This healing index is presented for three asphalts of varied composition.

Failure criteria associated with the fracture and fatigue of asphalt concrete layers have been developed based on mathematical models or phenomenological relationships. Perhaps the most commonly used fatigue failure criterion was presented by Epps and Monismith (*1*) in the form:

$$N_f = K_1\left(\frac{1}{\varepsilon}\right)^{K_2}$$

or

$$N_f = K_3\left(\frac{1}{\sigma}\right)^{K_4}$$

where

N_f = the total number of constant amplitude load repetitions,
K_1 to K_4 = regression constants,
ε = the initial value of the bending strain induced per load application, and
σ = the repeated stress level per load application.

This phenomenological relationship based on constant amplitude loading, which results in fatigue failure, has been used in a variety of layered elastic pavement design and/or analysis schemes.

Researchers have shown that this classic fatigue failure relationship grossly underpredicts the field fatigue life by as much as 100 times. Finn et al. (*2*) actually demonstrated that the laboratory-derived phenomenological fatigue relationships for the asphalt concrete used at the AASHTO Road Test required a shift of 13 in fatigue life to match actual fatigue cracking data derived from AASHTO field sections. This difference between laboratory and field fatigue curves may be attributed to loading differences between the laboratory and the field.

Continuous cycles of loadings at a constant strain or stress amplitude, generally applied in laboratory tests, do not realistically simulate the compound-loading conditions to which a paving material is subjected under actual traffic conditions. Major differences between the laboratory and the field loading conditions are due to:

1. Rest periods that occur in the field but not (normally) in the laboratory;
2. The sequence of the load applications of varying magnitude; and
3. Reactions or frictional forces encountered in the field between the asphalt concrete surface and the base layer.

There are two different mechanisms occurring in a partially cracked asphalt concrete pavement during rest periods. One is the relaxation of stresses in the system due to the viscoelastic nature of asphalt concrete, and the other is the chemical healing across microcrack and macrocrack faces. Both of these mechanisms enhance the fatigue life of asphalt concrete pavement.

In this paper, the correspondence principle of the theory of nonlinear viscoelasticity developed by Schapery (*3*) is applied to evaluate these mechanisms separately. The correspondence principle allowed the authors to analyze the behavior of asphalt concrete under realistic loading conditions and to differentiate between chemical healing and mechanical relaxation by separating out complicating viscoelastic hereditary effects. The effects of previous loading conditions were also studied by means of the correspondence principle in concert with damage mechanics. This study resulted in a constitutive relationship that accounts for the effect of past loading history. These results are presented elsewhere (*4*).

Terminology is defined to aid the reader's understanding and to avoid lengthy descriptions within the text. Three types

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of loading are discussed in this paper: simple loading, constant rate simple loading, and pulsed loading. Simple loading is defined as continuous, repetitive loading of a single waveform at a constant amplitude of stress or strain. When simple loading is composed of a "saw-tooth" wave, with symmetric loading and unloading segments, it is called constant rate simple loading. Pulsed loading is the same as simple loading except that a rest period is introduced after each loading application.

LITERATURE REVIEW

The significance of rest periods between load applications has been recognized by several researchers. Monismith et al. (*5*) varied rest time from 1.9 sec to 19 sec on beam samples tested by a repeated-flexure apparatus. No significant change in fatigue performance was observed. This result may partially be explained by the specific testing configurations, such as the deflection measuring point and the elastic response from the spring base. Deacon and Monismith (*6*) used pulsed loading instead of simple loading to simulate the recovery of asphalt concrete pavement because of the viscoelastic nature of the material. Raithby and Sterling (*7*) performed uniaxial tensile cyclic tests on beam samples sawed from a rolled carpet of asphalt concrete. Pulsed loading with rest periods up to three times longer than the loading cycle was applied until failure occurred. It was observed that the strain recovery during the rest periods resulted in fatigue life that was longer, by a factor of 5 or more, than the life under simple loading. Francken (*8*) developed a new expression for the cumulative cycle damage ratio in Miner's law by accounting for effects of rest periods.

McElvaney and Pell (*9*) performed rotating bending fatigue tests on a typical English base course mix and concluded that rest periods have a beneficial effect on the fatigue life depending on the damage accumulated during loading periods. The testing mode, frequency, temperature, duration of rest periods, and resulting beneficial effects of these factors were well summarized by Bonnaure et al. (*10*). Bonnaure et al. (*10*) investigated the effects of rest periods on a typical Dutch asphalt concrete by means of a three-point bending apparatus. They concluded that higher test temperatures and softer binders result in a more beneficial effect from rest periods.

At Texas A&M University, efforts (*11,12*) have been made recently to evaluate the increase in work done after rest periods from displacement-controlled cyclic testing. Al-Balbissi (*11*) studied the effects of rest periods on the fatigue life of plasticized sulfur binders used in asphaltlike mixtures. A mathematical expression for the shift between laboratory and field fatigue lives was developed. Button et al. (*12*) reported an increase in work done to open the crack after rest periods in controlled-displacement crack growth testing in asphalt concrete mixes modified with various additives. They evaluated the effectiveness of additives on fatigue performance, which was influenced not only by crack growth rate but also by healing potential.

Bazin and Saunier (*13*) reported that an ordinary dense asphalt concrete mix could recover 90 percent of its initial resistance with only 3 days of rest at 77°F, and that the healing seemed to become complete after 1 month at that temperature. They also concluded that pressure at the crack faces has a great influence on healing. Their research showed clear evidence of healing in asphalt concrete, but the duration of rest periods was too long (1 to 100 days) to mimic field loading conditions realistically.

The healing mechanism within polymeric materials has been intensely studied. Jud et al. (*14*) identified three different concepts for the time-dependent buildup of joint strength between two polymer surfaces: (a) polymer-polymer interdiffusion, (b) adhesion between rough surfaces, and (c) jointing by flow of molten material. Based on the diffusion model, Kim and Wool (*15*) proposed the following experimental relationship for amorphous polymeric materials:

$$\frac{\sigma_{fh}}{\sigma_\infty} \sim \frac{t^{0.25}}{M^{0.75}}$$

where

σ_{fh} = the fracture healing strength,
σ_∞ = the original strength,
t = the duration of the rest period, and
M = the molecular weight.

To understand the healing mechanism of asphalt concrete, the chemistry of asphalt cement must be studied with the healing models of polymers in mind. Petersen (*16*) claims that the association force (secondary bond) is the main factor controlling the physical properties of asphalt. That is, the higher the polarity, the stronger the association force, and the more viscous the fraction, even if molecular weights are relatively low. He also illuminated the effect of degree of peptization on the flow properties of asphalt as follows:

> Consider what happens when a highly polar asphaltene fraction having a strong tendency to self-associate is added to a petrolene fraction having a relatively poor solvent power for the asphaltenes. Intermolecular agglomeration will result, producing large, interacting, viscosity-building networks. Conversely, when an asphaltene fraction is added to a petrolene fraction having relatively high solvent power for the asphaltenes, molecular agglomerates are broken up or dispersed to form smaller associated species with less interassociation; thus, the viscosity-building effect of the asphaltenes is reduced.

Traxler (*17*) also suggested that the degree of dispersion of the asphalt components is inversely related to the complex (non-Newtonian) flow properties of asphalt.

Ensley et al. (*18*) and Thompson (*19*) subscribe to the view that asphalt cement consists of aggregations of micelles. These micelles consist of two or more molecules of asphaltenes and associated (if present) peptizing materials of lower molecular weight. These peptizing materials grade upward in size (from outside to inside the micelle) from naphthenes and paraffins to resins and polar compounds coating the asphaltenes (*19*). The interactions of these micelles among themselves and with aggregates largely determine cohesion and bond strengths, respectively.

MATERIALS AND TESTING METHODS

Materials

Asphalt from three sources was evaluated in this study. These sources are listed as A, B, and C throughout the text. Corbett analyses on these asphalts are presented in Table 1. Viscosities for all asphalts at 140°F were approximately 2,000 poises. A syenitic granite aggregate (crusher fines) was used with the gradation illustrated in Figure 1. Fracture within this mixture resulted in uniform crack surfaces without the irregular crack growth pattern typical of mixtures employing larger and more well-graded aggregates.

An asphalt content of 9 percent was selected as one that provided adequate specimen stability during testing yet promoted uniform crack growth. The 2-in.-wide, 3-in.-high, and 13-in.-long beam samples were fabricated using a Cox kneading compactor. Mixing and compaction temperatures were 300°F and 275°F, respectively.

The compactive effort used during fabrication was as follows:

Layer No.	*Pressure Applied (psi)*	*No. of Tamps*
1	100	5
2	100	20
	200	20
	400	40
	500	50

This compactive effort was designed to provide uniform density throughout the specimen and to avoid a density (air void) gradient within the beam (*12*). The resulting air void content of all beam specimens was in the range of 17 ± 0.5 percent without a noticeable air void gradient. This high air void content is a function of the uniformity and size (fine) of the aggregate. Although the high air void content is not representative of dense mixes, the purposes of these experiments are to develop a mechanistic method to evaluate healing and to study the relative degree of healing instead of specific levels of healing in densely graded mixtures.

TABLE 1 CORBETT ANALYSES ON THREE ASPHALT CEMENTS USED IN TESTING

Binder	Saturates (%)	Naphthenic Aromatics (%)	Polar Aromatics (%)	Asphaltenes (%)
Source A	11.22	32.49	51.14	5.15
Source B	13.95	30.02	42.37	13.66
Source C	4.92	39.12	51.67	4.29

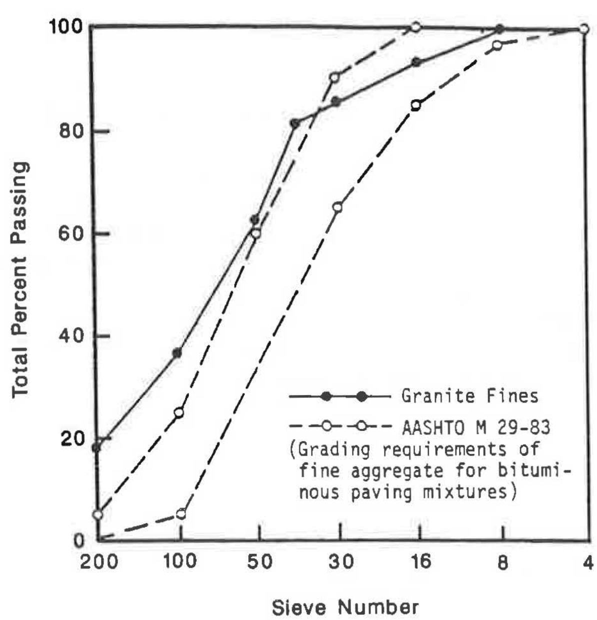


FIGURE 1 Gradation plot of granite fines and AASHTO specification.

Compacted samples were stored at 73°F for 24 hr, and their bulk-specific gravities were measured. Then, the samples were moved to a 50°F curing room and were cured between 7 and 14 days prior to testing. Selected samples were notched before testing by cutting a straight notch, 1 in. long, using a carbide-tip blade with a 45-degree tip angle. The crack tip was then sharpened using a razor blade.

Testing Method

Testing was performed in a uniaxial mode in a device fabricated for this study (Figure 2). Both ends of a beam sample were glued onto steel blocks using epoxy. Then, these blocks were bolted to two rigid aluminum platens: one was fixed, and the other was regulated to oscillate horizontally, guided by a linear track. Displacement was controlled by an MTS servo-controlled, electrohydraulic system. With this machine, the samples were subjected to a controlled horizontal movement of the base plate. This configuration eliminated bending due to the heavy weight of the asphalt concrete samples. The possibility of misalignment was minimized as the pulling direction was guided by a linear track.

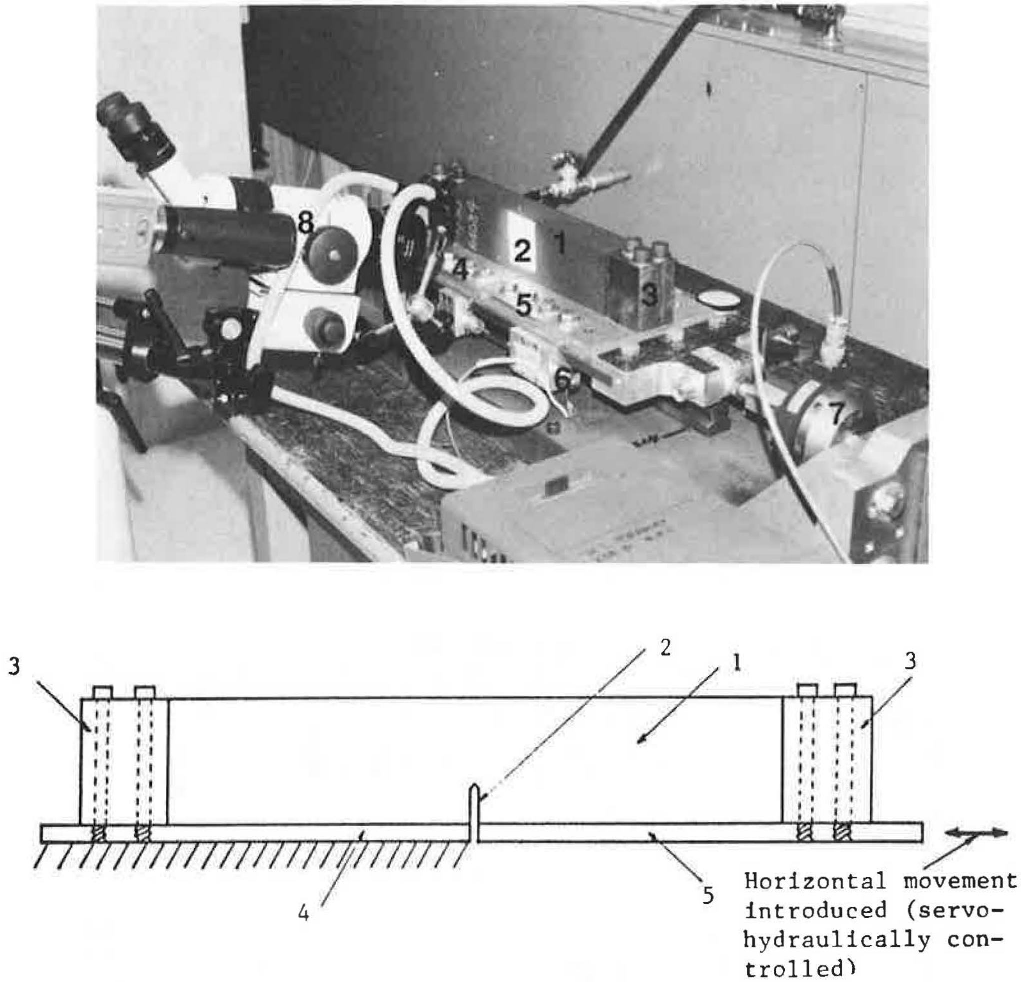
The crack length was monitored through a microscope video camera (Figure 3). Chartpak pattern film graduated at 50 lines per inch was attached beside the anticipated crack path and was used as a guide by which to monitor crack growth using the microscope. The crack information from the microscope was stored on videotape and was studied after each test.

All tests were performed in a displacement-controlled mode at 73°F. The strain was calculated from the movement of the hydraulic ram and the original sample length. This calculated strain was very close to the strain measured using two linear variable differential transformers (LVDTs) in the middle of the sample with 1-in. gage lengths.

Load and displacement data were acquired through a Hewlett-Packard acquisition unit 3497A and stored in a microcomputer. Data reduction and plotting programs were used to generate plots quickly for visual data analysis. This computerized procedure made the time-consuming calculations possible and eliminated the potential for algebraic mistakes.

THEORY OF NONLINEAR VISCOELASTICITY

Healing occurs at macrocrack faces and at microcrack faces in the stressed zone because of the flow characteristics of asphalt cement. The evaluation of chemical healing in a partially cracked asphalt concrete pavement is a difficult task because relaxation and chemical healing occur at the same time. Both of these mechanisms are time-dependent, even though their sources of time-dependency are different. Assuming that chemical healing and relaxation are the predominant mechanisms occurring during the rest period, one



1. Beam epoxied to metal end support.
2. Sharp-tipped notch (introduced in some beams).
3. Metal end support.
4. Fixed platen.
5. Moving platen.
6. L.V.D.T. (connected to M.T.S. controller)
7. Load cell.
8. Microscopic video camera.

FIGURE 2 Picture and schematic presentation of uniaxial testing apparatus.

can evaluate the magnitude of chemical healing only by accounting for the time-dependence due to the viscoelastic nature of the cracked asphalt concrete sample. In this section, the correspondence principle for nonlinear viscoelastic media (*3*) is introduced as a proper means to account for time-dependency during the relaxation process and, hence, to separate the mechanism of relaxation from the mechanism of chemical healing. Detailed theoretical development of the correspondence principle is presented elsewhere (*3,4*).

The correspondence principle allows one to reduce a viscoelastic problem to an elastic problem merely by working within the transformed domain. For a linear viscoelastic material, the applicable domain is achieved by Laplace transformation.

For some nonaging, nonlinear, viscoelastic materials, Schapery (*3*) suggested that the constitutive equations are identical to those for the nonlinear elastic case, but the stresses and displacements are not necessarily physical quantities in the viscoelastic body. Instead, they are "pseudostresses" and "pseudodisplacements" that are in the form of convolution integrals:

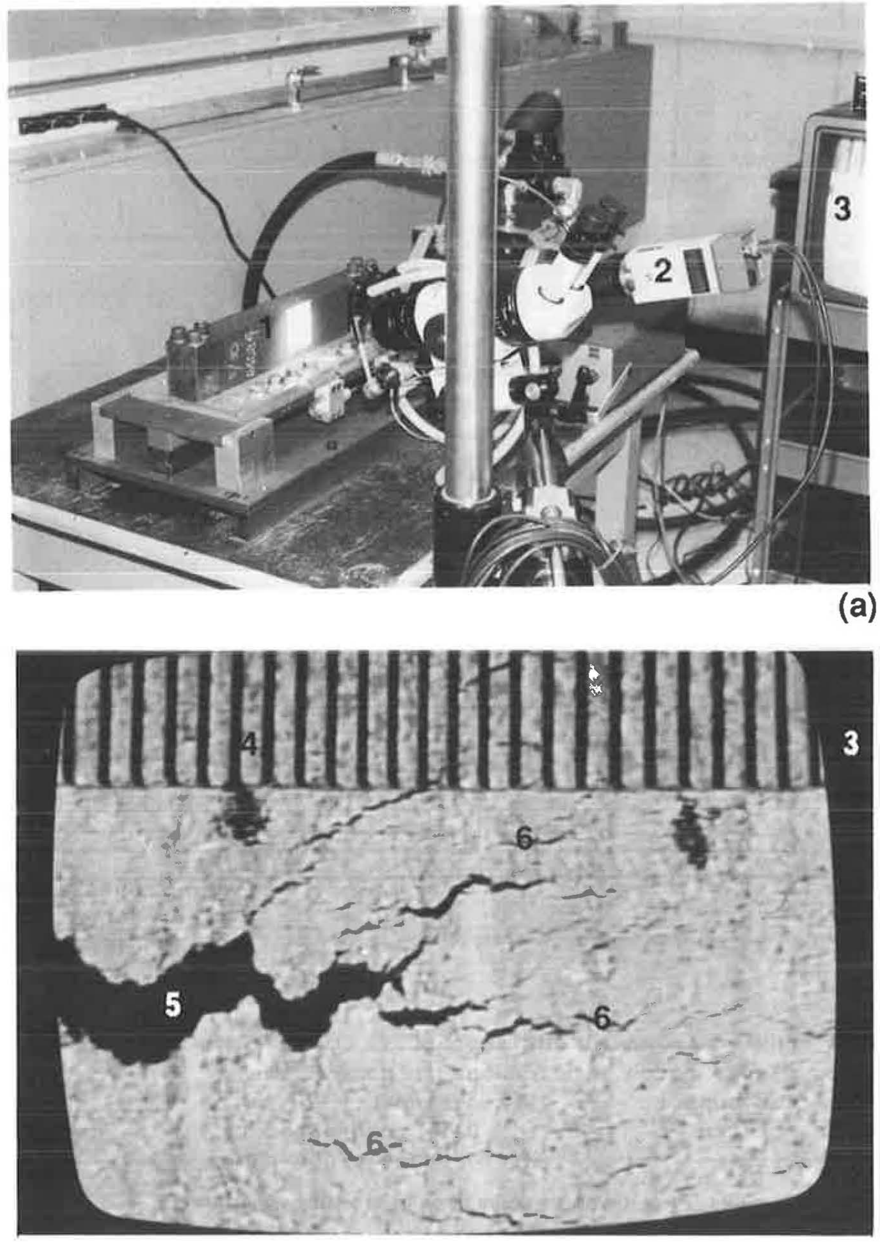
$$\sigma_{ij}^R = \frac{1}{E_R} \int_o^t D(t - \tau) \frac{\delta \sigma_{ij}}{\delta \tau} \, d\tau$$

and

$$u_i^R = \frac{1}{E_R} \int_o^t E(t - \tau) \frac{\delta u_i}{\delta \tau} \, d\tau$$

where

σ_{ij} and u_i = physical quantities;
$E(t)$ and $D(t)$ = relaxation modulus and creep compliance, respectively; and
E_R = the reference modulus that is an arbitrary constant.



1. Beam sample with a sharp-tipped notch.
2. Microscopic video camera. 3. TV monitor.
4. Chartpak pattern film (0.02 in. between lines).
5. Macrocrack. 6. Microcracks.

FIGURE 3 (a) Microscopic video camera with testing apparatus. (b) Image of cracking area pictured from TV monitor.

For crack growth problems with an increasing traction boundary, the correspondence principle gives the viscoelastic solutions as follows:

$$\sigma_{ij} = \sigma_{ij}^R$$

and

$$u_i = E_R \int_o^t D(t - \tau) \frac{\delta u_i^R}{\delta \tau} \, d\tau$$

where σ_{ij}^R and u_i^R satisfy equations of the reference elastic problem. This correspondence principle means that, using physical stresses with pseudodisplacements, one can reduce the nonlinear viscoelastic problem to the nonlinear elastic case. Then, the explicit form of the constitutive equation between stress and pseudodisplacements is dependent on the material type and the source of nonlinearity.

METHOD OF ANALYSIS

Stresses and strains used in the evaluation of healing were nominal (average) stresses and strains; that is,

$$\sigma = P/A$$

and

$$\varepsilon = u/L$$

where

P = load response,
A = cross sectional area of the beam sample regardless of the presence of a crack,
u = displacement measured from the ram movement, and
L = original length of the sample.

When a viscoelastic material is subjected to cyclic loading, a hysteresis loop is usually observed in the stress-strain diagram. According to correspondence principle theory for nonuniformly stressed bodies, such as a beam with a crack, the hysteresis loop will disappear in the nominal stress-pseudostrain plot if damage growth is negligible during the loading history. That is, the relationship between stress and pseudostrain is a single-valued function. Furthermore, even when the loading paths before and after rest periods are compared, this elasticlike behavior will be maintained, if negligible damage or healing has occurred. This is because the relaxation during the rest period is taken into account by integrating the convolution integral from the initial loading time to the present time.

When the damage is large, the stress will decrease, in displacement-controlled testing, as the number of cycles increases. The difference in the stress at the same pseudostrain level is due to the damage growth in the sample. If rest periods are introduced in the loading history and relaxation is the only phenomenon occurring during the rest period, the stress after the rest period should be equal to or less than the stress before the rest period for the same pseudostrain, based on the correspondence principle theory. If the stress after the rest period is larger than the stress before the rest period, at the same pseudostrain level, the increase in stress must logically be attributed to some chemical healing mechanism.

The concept, outlined in the preceding paragraphs, was used to evaluate the healing potential of three different asphalt cements. In this evaluation, the following three types of uniaxial tests were performed:

1. Relaxation tests;
2. Constant-strain-rate simple loading tests with rest periods (Figure 4) (the magnitudes of displacements were within the linear viscoelastic range of the material (negligible permanent damage); and
3. Constant-strain-rate simple loading tests with rest periods (Figure 4) (the magnitudes of displacements resulted in crack growth).

Beam samples with an edge crack were used only for Test Series C. All other samples were beam samples without fabricated edge (sharp-tipped) starter cracks. For both Test Series B and C, the strain rate of 0.0368 in./in./min was used.

Test Series B was designed exclusively for the verification of the applicability of the correspondence principle based on the relaxation moduli obtained from Test Series A. Because the maximum strain level for Test Series B is in the linear viscoelastic range that results in negligible damage, the stress-pseudostrain plot must be linear; and no stress drop should be observed at the same pseudostrain as the cycle number increases.

The loading history for Tests Series B and C is shown in Figure 4. The numbers of initial simple loading cycles for Tests B and C were 10 and 20, respectively. Then a set of four rest periods of 5, 10, 20, or 40 min duration was introduced in a random sequence (Figure 4). Five cycles of simple loading were applied after each rest period, and this loading pattern (rest period followed by five cycles of simple loading) was repeated until three repetitions for each rest period length were achieved.

It was experimentally found that a strain level of 6.13 by 10^{-4} in./in. was small enough for all the mixtures investigated in this research to produce linear behavior. Two strain levels, 6.74 by 10^{-3} in./in. and 9.20 by 10^{-3} in./in., were used in Test Series C and were large enough to propagate the crack in the middle of the sample.

RESULTS AND DISCUSSION

Relaxation Testing

Uniaxial tensile relaxation testing was performed for three different mixtures, and the results are plotted in Figures 5 through 7. Various strain levels were used, and the loading time to peak strain was 3 sec. The strain level dependency could not be identified for the range of strain levels evaluated because the variation among samples was substantially greater than the strain level sensitivity. Theoretically, strain in the form of a step function should be applied in relaxation testing; because of load cell range limitations, however, a 3-sec initial ramp was unavoidable.

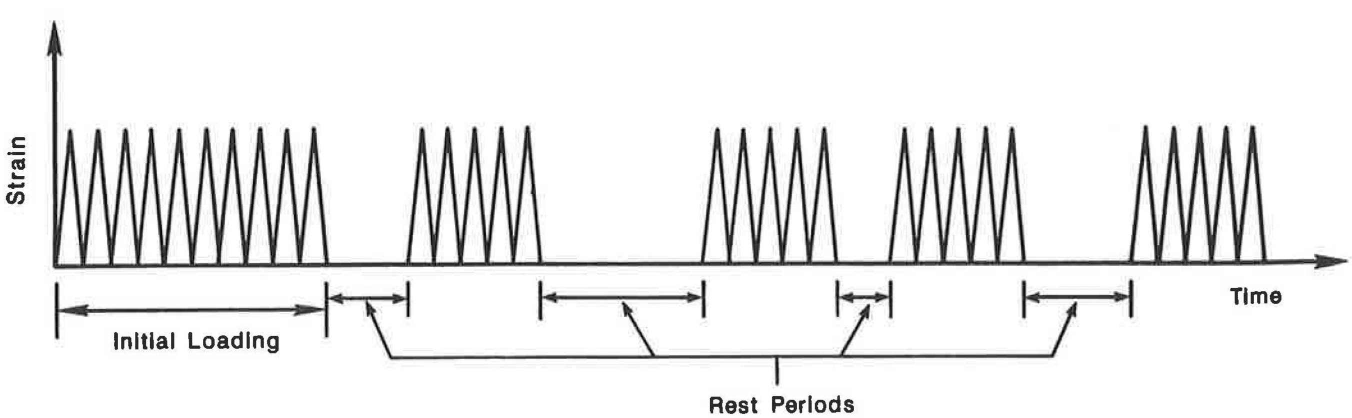


FIGURE 4 Strain history for Tests B and C.

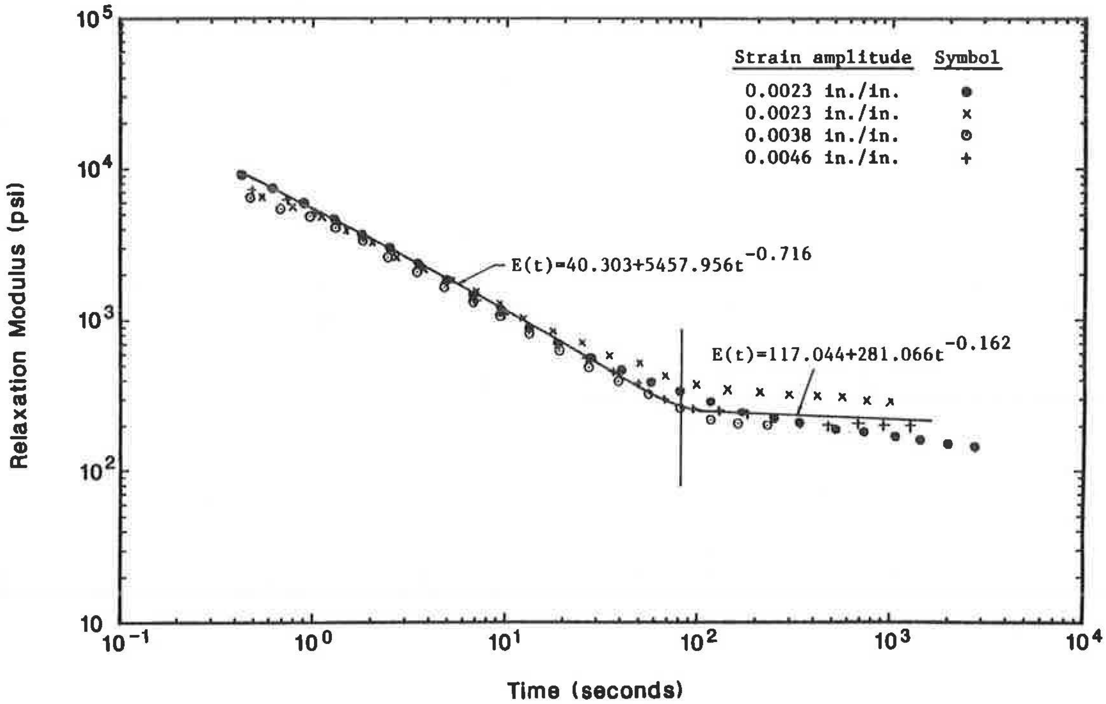


FIGURE 5 Relaxation data for the mixtures with Source A asphalt.

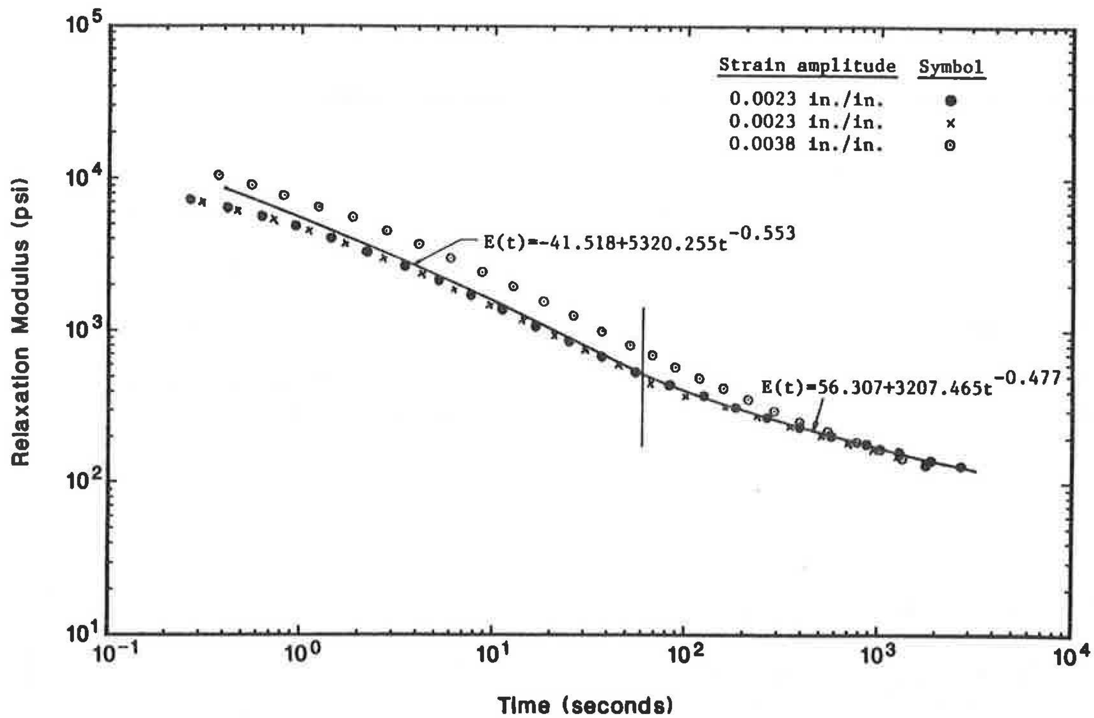


FIGURE 6 Relaxation data for the mixtures with Source B asphalt.

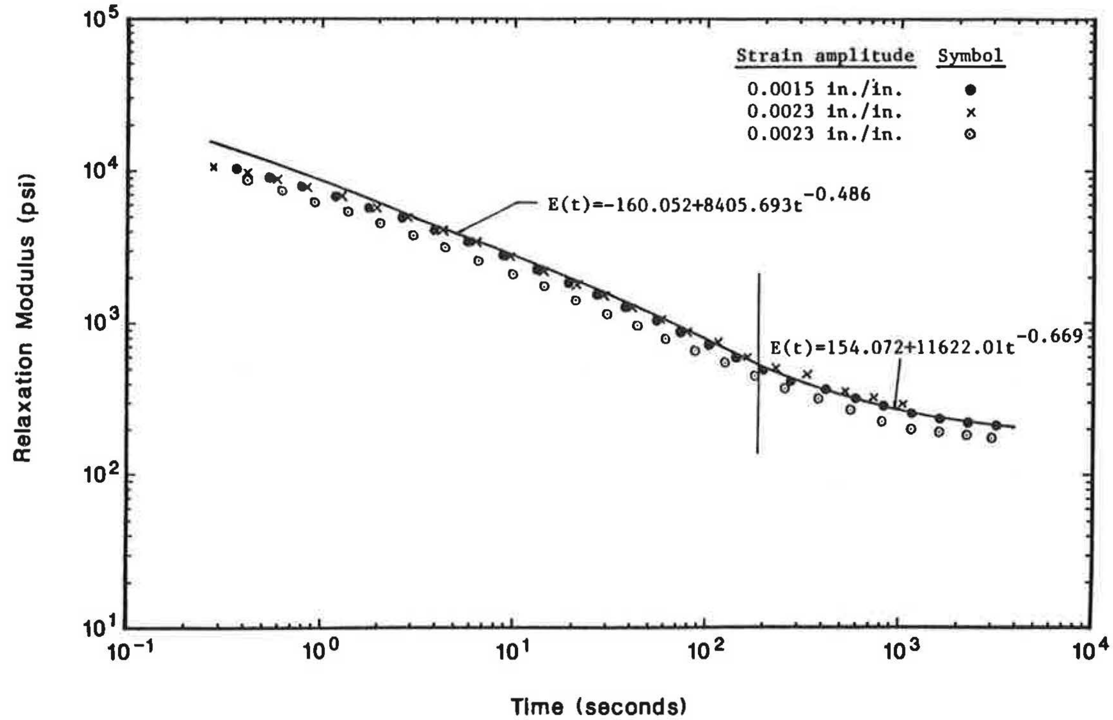


FIGURE 7 Relaxation data for the mixtures with Source C asphalt.

Usually, the relaxation data are represented in the form of a pure power law:

$$E(t) = E_1 t^{-n}$$

or by a generalized power law:

$$E(t) = E_0 + E_2 t^{-n}$$

where $E(t)$ equals the relaxation modulus and E_0, E_1, E_2, and n equal regression constants.

The best way of fitting the data in Figures 5 through 7 was to divide the whole curve into two sections and to fit each curve using a generalized power form. The regression constants in the generalized power law were obtained by a trial-and-error method. That is, assuming the value of n, a linear regression analysis was performed between $E(t)$ and t^{-n}, and the sum of squares of error was calculated. Repeating this procedure for a series of ns, the n that resulted in the smallest sum of squares of error was determined. This technique yielded the predicted curves, the regression constants of which are shown in Figures 5 through 7.

Derivation of Pseudostrains from Tests B and C

Pseudostrain for a uniaxial case is determined from

$$\varepsilon^R = \frac{1}{E_R}\int_o^t E(t-\tau)\frac{d\varepsilon}{d\tau}\,d\tau$$

For the first loading path, $d\varepsilon/dt = C$, where C is the constant strain rate. Therefore,

$$\varepsilon^R = \frac{C}{E_R}\int_o^t E(t-\tau)\,d\tau$$

Let $x = t - \tau$; then

$$\varepsilon^R = \frac{C}{E_R}\int_o^t E(x)\,dx$$

During the first unloading path, the same practice yields

$$\varepsilon^R = \frac{C}{E_R}\left[\int_o^{t_1} E(x)\,dx - \int_{t_1}^{t} E(x)\,dx\right]$$

where t_1 equals the time of peak loading.

Similarly, the pseudostrain at any time can be calculated analytically as long as the loading history and the relaxation modulus as a function of time are known, regardless of the existence of rest periods.

Constant-Strain-Rate Simple Loading Tests with Rest Periods

The results of the Test B series demonstrated the applicability of the correspondence principle to this research. Furthermore, the Test B series demonstrated that the relaxation moduli derived from the Test A series were satisfactory measurements. The stress-pseudostrain plots of the first 10 cycles and of the cycles before and after the 40-min rest period for Test B are presented in Figures 8 and 9, respectively. The asphalt cement studied in these figures was from Source C. As shown in Figure 8, the loading and unloading paths of the first 10 cycles practically fall on the same line. Also in Figure 9, the stress-pseudostrain curves before and after the 40-min rest period are practically the same. The results for the other binders and for different lengths of rest periods verified the success of this procedure.

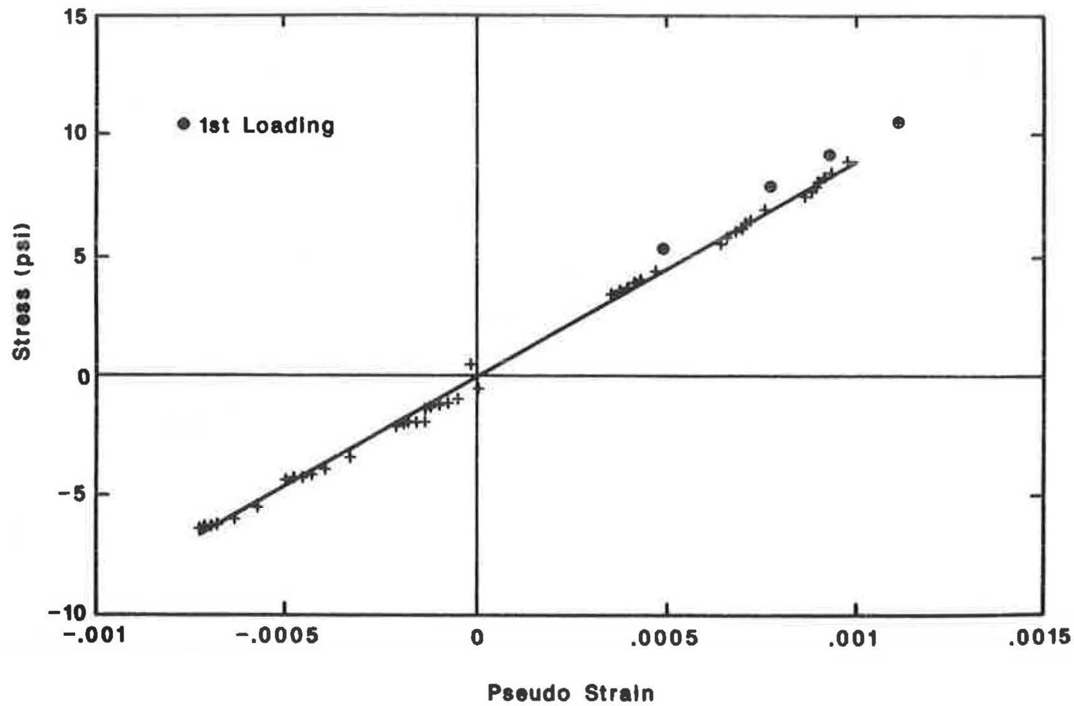


FIGURE 8 Stress versus pseudostrain of initial 10 cycles with negligible damage (Source C asphalt).

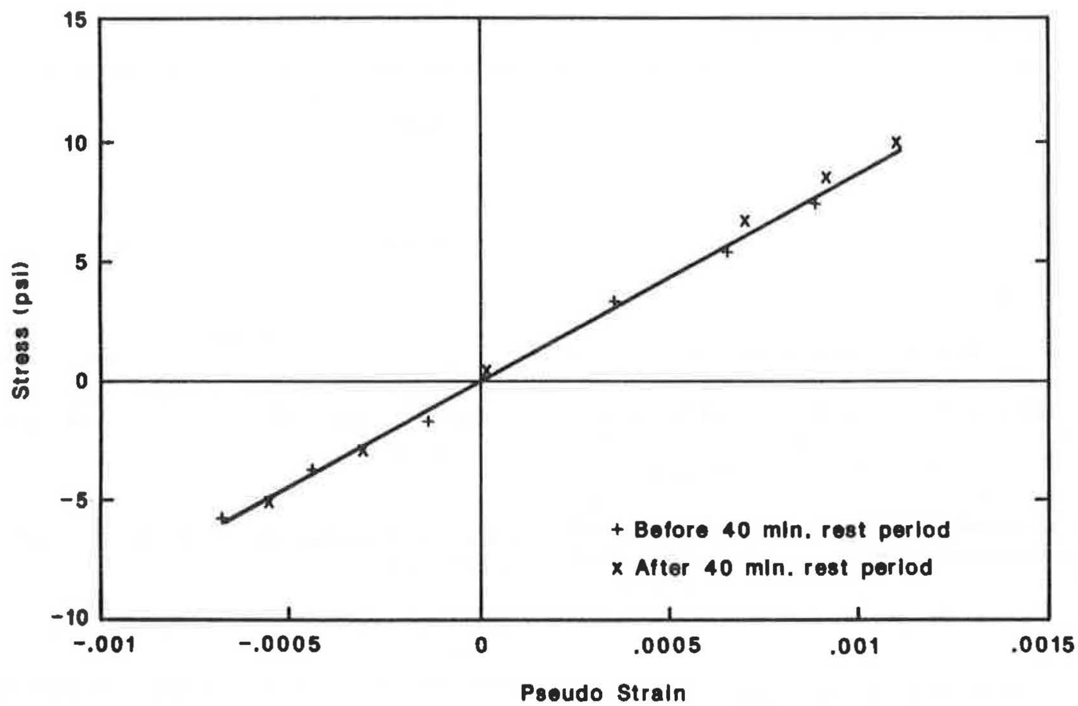


FIGURE 9 Stress versus pseudostrain before and after 40-min rest period with negligible damage (Source C asphalt).

The results of the Test C series with Source A asphalt are shown in Figures 10 and 11. In Figure 10, the loading and unloading paths of the initial 20 cycles are plotted, and the stress-pseudostrain behavior before and after the 40-min rest period is presented in Figure 11.

The first point to note in Figure 10 is that loading and unloading paths form a hysteresis loop that disappeared after the correspondence principle was applied to the Test B series results. However, under the conditions of Test C (i.e., damage accumulation through crack growth), visual dissipation of energy is due to the damage growth in the sample. Because the test was performed in a controlled strain mode with a constant strain amplitude, the stress at a selected pseudostrain level became smaller as cycling continued.

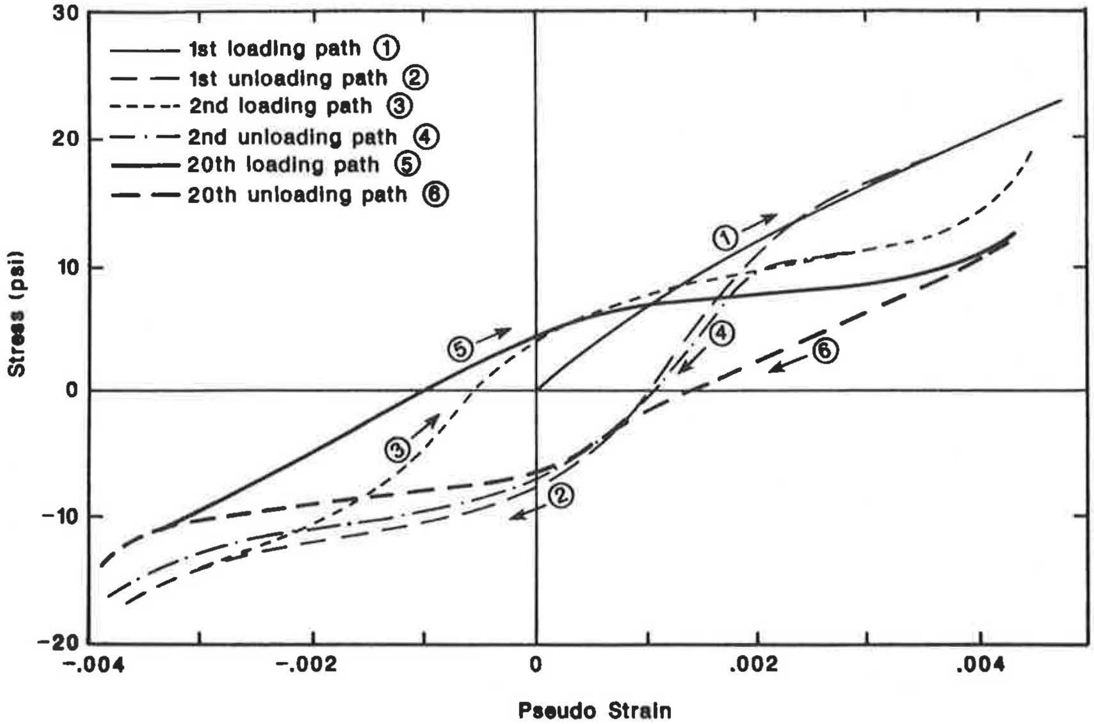


FIGURE 10 Stress versus pseudostrain of initial 20 cycles with strain amplitude of 0.0092 in./in. (Source A asphalt).

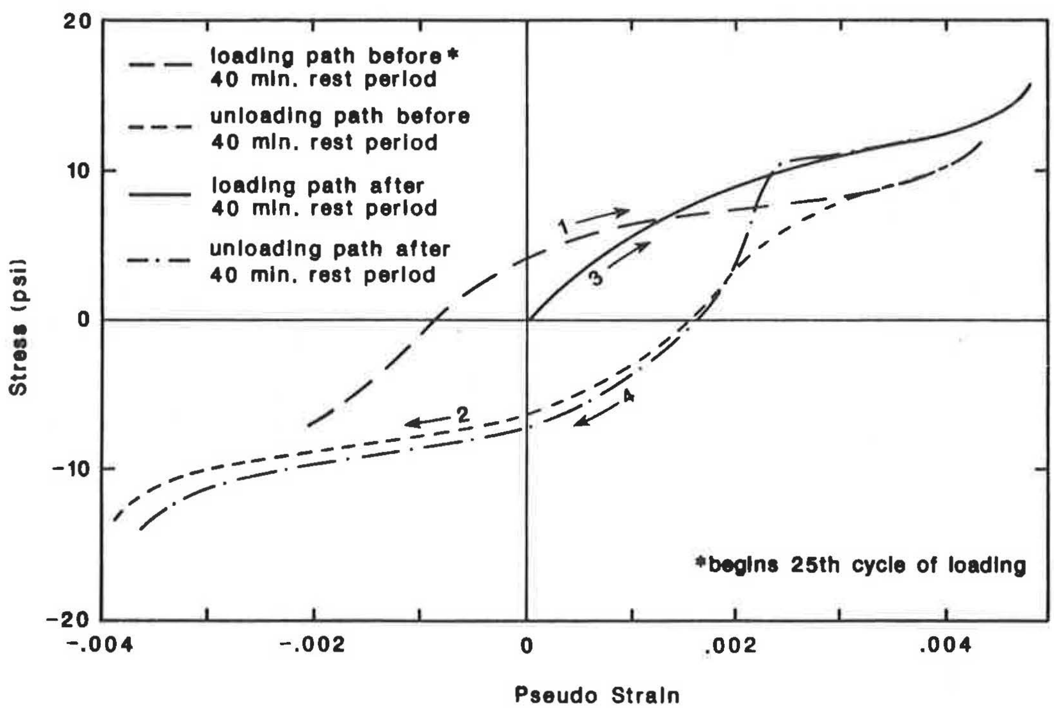


FIGURE 11 Stress versus pseudostrain before and after 40-min rest period with strain amplitude of 0.0092 in./in. (Source A asphalt).

In Figures 8 and 10, the first loading path is different from the rest of the loading paths. The reason for this is that the largest pseudostrain in the loading history, ε_L^R, for the first loading is different from that in the remaining cycles (*20,21*). That is, ε_L^R for the first loading is the current pseudostrain, whereas ε_L^R for the following cycles is a constant that is the largest pseudostrain during the first loading. The effect of this ε_L^R on a constitutive equation modeling the stress-pseudostrain relationship is presented elsewhere (*4*).

From the comparison of the recorded crack length and the stress-pseudostrain behavior, it was found that the stiffness increase during the last part of loading (Figure 10) was due to an additional growth in the crack length from the prior loading cycle. The crack was growing faster for the Source A mixture for the same maximum strain level than for the mixtures from Sources B and C.

As discussed previously, the stress-pseudostrain curve after the rest period should be positioned somewhat lower than the curve before the rest period if the relaxation is the only mechanism influencing behavior during the rest period. As shown in Figure 11, however, there was a significant increase in the stress for the same pseudostrain. This behavior was not observed in Figure 9 where the damage level was almost negligible. Therefore, it is concluded that during rest periods in a damaged asphalt concrete body, there exists a mechanism other than relaxation that provides a beneficial structural change. Assuming that cracking, regardless of the size of cracks, is the major cause of damage in these asphalt concrete samples, this advantageous structural alteration is attributed to the healing mechanism within the asphalt cement.

Because four different rest periods were randomly applied to each sample until three repetitions for each rest period were introduced, each repetition induced a different crack length and damage level. A methodology that can normalize the difference in damage level is necessary to evaluate the healing that occurs at different rest periods with different damage levels.

In this paper, pseudo-energy-density and a healing index were used to represent the healing capacity of a specific binder as a function of rest time. The pseudo-energy-density, ϕ^R, in a uniaxial case, is defined as

$$\phi^R = \int \sigma \, d\varepsilon^R$$

The pseudo-energy-densities before and after a rest period are illustrated in Figure 12. As shown, only the tension part (positive stress) is used to calculate the pseudo-energy-density. From the observation that the pseudo-energy-density after the rest period is a unique material function that can be related to the specified damage level, the healing index was used to represent the healing potential of different binders at different rest times. The healing index, H, is defined as

$$H = \frac{\phi_A^R - \phi_B^R}{\phi_A^R}$$

where ϕ_A^R equals the pseudo-energy-density after the rest period and ϕ_B^R equals the pseudo-energy-density before the rest period. The healing indices at four rest periods of three mixtures are plotted in Figure 13. This index successfully normalizes the difference in the damage level for asphalts from Sources B and C, whereas the discrepancy becomes a little larger for the Source A asphalt.

As a result, the mixture using Source A asphalt shows the lowest level of healing, whereas the mixtures with asphalts from Sources B and C demonstrate higher levels of healing. The chemical nature of the asphalts that influences these results

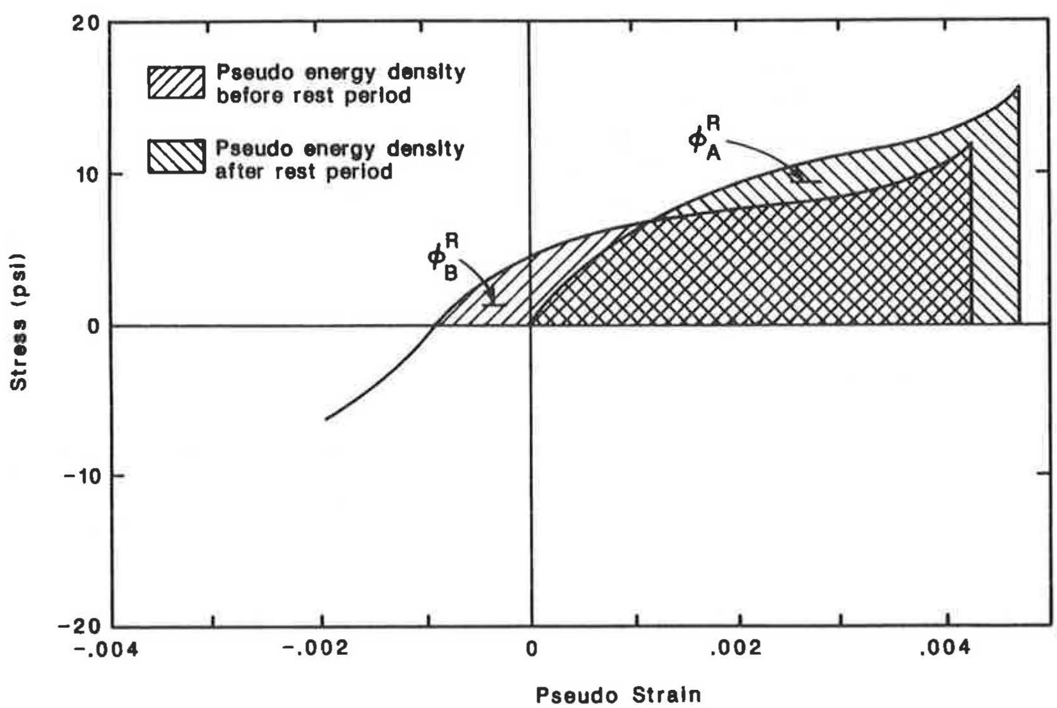


FIGURE 12 Illustration of pseudo-energy-densities before and after rest period.

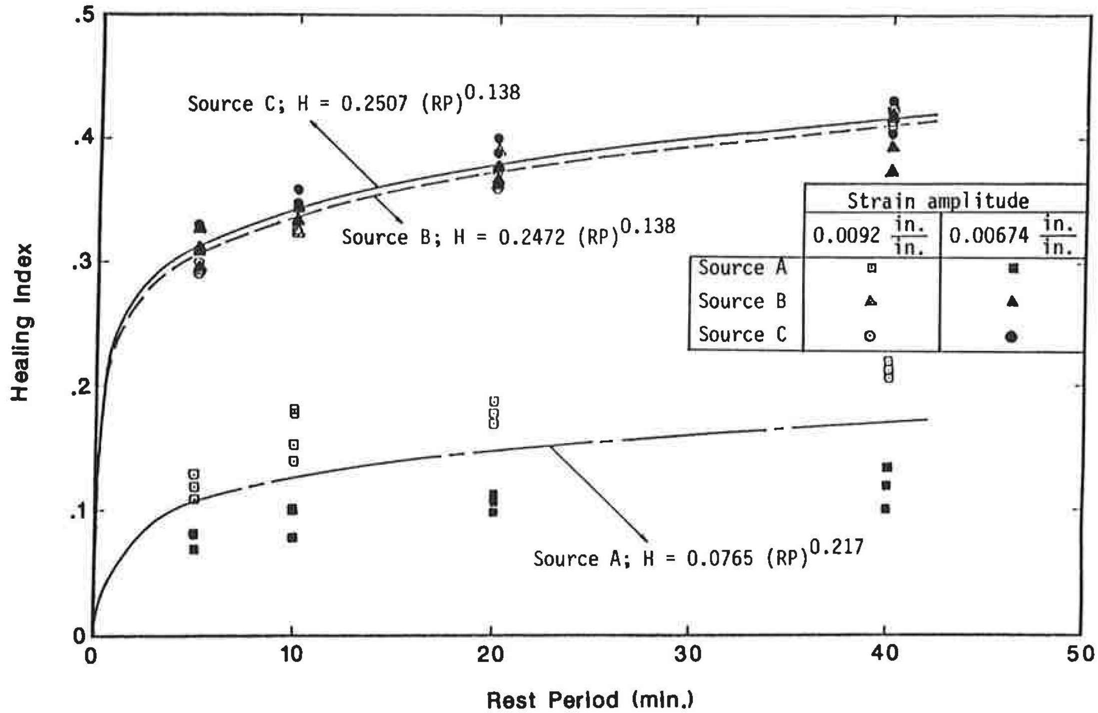


FIGURE 13 Healing potential of different binders as a function of rest period.

is being studied in parallel research as a part of this National Science Foundation project. These results will be presented in subsequent papers.

Regression analysis between the healing index and the duration of the rest period resulted in the time exponent range: 0.13–0.22. This can be compared with the time exponent of the strength ratio, 0.25, determined by Kim and Wool (*15*) for polymers.

CONCLUSIONS

The influence of rest periods on laboratory fatigue testing has been documented by a large number of authors around the world. The overwhelming consensus is that the rest periods enhance fatigue life because of healing and relaxation mechanisms. Understanding such mechanisms will be an overpoweringly important contribution to an understanding of fatigue performance and may allow the selection of asphalts with greater healing potential.

The work of polymer researchers has provided insight into a polymer healing phenomenon that may be applicable to asphalt. The procedure introduced in this paper offers a methodology by which the chemical healing can be quantified by separating out the concomitantly occurring viscoelastic effect of relaxation. The process demonstrates that a quantifiable chemical healing does indeed occur in asphalt concrete. The amount of this healing varies among the asphalt cements tested.

Continuing research is required to identify the mechanism that controls the chemical healing and to determine if and how the amount of chemical healing can be enhanced through binder modification.

The fatigue resistance of an asphalt cement should be evaluated on the basis of fatigue tests that account for the influence of rest periods. However, the fracture healing potential is only one factor contributing to overall fatigue resistance. Demonstration of a high level of healing does not by itself demonstrate an adequate fatigue life.

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