Healing in Asphalt Concrete Pavements: Is it Real?

Y. R. KIM, S. L. WHITMOYER, AND D. N. LITTLE

Microcrack healing of asphalt concrete during rest periods is among the many variables influencing the lab-to-field fatigue shift factor. Experimental approaches to evaluating this mechanism, both in the laboratory and in the field are presented. Three techniques introduced in this paper include the nonlinear viscoelastic correspondence principle, the impact-resonance test method for the laboratory characterization, and the stress-wave testing method for in situ characterization of asphalt concrete pavements. When analyzing the change in stress-strain behavior of asphalt concrete during rest periods, one must consider both the relaxation and healing of microcracks. A nonlinear viscoelastic correspondence principle based on the pseudo-strain concept was successfully applied to both controlled-stress and controlled-strain uniaxial testing under varying test conditions. The principle enabled determination of the healing potential of asphaltic mixtures. The impact-resonance test method appeared to be an excellent means of evaluating the change in elastic properties of asphalt concrete resulting from damage growth or healing. Finally, 24-hr stress-wave testing of a pavement section demonstrated a decrease in the elastic modulus as temperature increased, and an increase in the elastic modulus after the rest period, possibly due to microcrack healing in asphalt concrete layers.

In mechanistic pavement design procedures, the progression of distresses is first modeled in the laboratory using simplified test methods and theoretical approaches, such as the mechanics of materials. The laboratory models are then calibrated by observed field-performance data. A number of researchers have shown that the power relationship between number of cycles to failure and tensile strain obtained from laboratory fatigue-test data grossly underpredicts field fatigue life. The discrepancy prompted development of the so-called "lab-to-field shift factor." The most widely used shift factor, presented by Finn et al. (*1*), resulted from evaluating AASHTO Road Test data.

The difference between fatigue lives predicted from the laboratory model and those observed from the in-service pavements can be attributed to the following factors, among others:

1. Difference in loading conditions, including rest periods, multi-level loading, sequence of multi-level loading;
2. Reactions or frictional forces between the asphalt layer and the base layer;
3. Residual stresses caused by the plasticity of the pavement layers;
4. Dilatancy stresses from the expansion of paving materials under load, which builds up large confining pressures under passing wheel loads; and
5. Complicated environmental conditions in the field.

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Although it is quite difficult, if not impossible, to develop a shift factor based on sound mechanical theory that accounts for the effects of all the factors listed above, it is extremely important to determine how much of the shift factor is under the control of the designer. Being able to understand and evaluate the mechanisms governing the fatigue damage growth, one can improve materials and pavement design to extend the fatigue service life of pavements.

Of the numerous factors influencing fatigue life of asphalt pavement, this paper focuses on the microcrack healing of asphalt concrete layers during rest periods. Although the significance of rest periods on the fatigue performance of asphaltic mixtures has been recognized since the 1960s, only during the last 10 years has healing during rest periods been studied as a mechanism whereby asphalt concrete regains its strength. (*2,3*).

When an asphalt concrete pavement is subjected to repetitive applications of multi-level vehicular loads and various durations of rest periods, three major mechanisms take place: fatigue, which can be regarded as damage-accumulation during loading; time-dependent behavior related to the viscoelastic nature of asphalt concrete; and chemical healing across microcrack and macrocrack faces during rest periods. The difficulty of evaluating these mechanisms arises from the fact that they occur simultaneously in an asphalt concrete pavement; that is, during rest periods, relaxation and chemical healing take place together.

This paper presents three different approaches to evaluating the chemical healing of asphalt concrete: the elastic-viscoelastic correspondence principle, the impact-resonance testing method for the laboratory characterization, and the stress-wave testing for the field evaluation. Both laboratory and field data are presented with the following questions in mind:

- Is healing in asphalt concrete a real phenomenon both in the laboratory and the field?
- If so, how can we measure it in the laboratory and in the field?

EVALUATION OF HEALING VIA THE CORRESPONDENCE PRINCIPLE

The so-called elastic-viscoelastic correspondence principle (CP) is an excellent means of evaluating and modeling the hysteretic behavior of viscoelastic media. This principle simply states that one can reduce a viscoelastic (time-dependent) problem to an elastic (time-independent) problem merely by working in an appropriately transformed domain and substituting elastic moduli.

The nonlinear viscoelastic CP was developed by Schapery in 1984 (*4*). He suggested that the constitutive equations for certain nonlinear viscoelastic media are identical to those for the nonlinear elastic case, but stresses and strains are not necessarily physical quantities in the viscoelastic body. Instead, they are "pseudo" parameters in the form of a convolution integral. For the uniaxial case with growing damage, pseudo strain in the following form is recommended:

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

where

ϵ, ϵ^R = uniaxial strain and pseudo strain,
E_R = reference modulus which is an arbitrary constant, and
$E(t)$ = uniaxial relaxation modulus.

This principle's application to the hysteretic stress-strain behavior of asphalt concrete is illustrated using actual data. Repetitive uniaxial testing is performed under two completely different sets of testing conditions in order to demonstrate the applicability of the pseudo strain concept. The details of the testing conditions include the following:

Test 1	*Test 2*
Controlled-stress test	Controlled-strain test
Compressive loading	Tensile loading
Haversine wave form	Saw-tooth wave form
0.2 sec/cycle	1 sec/cycle
Short rest periods (1, 4, 8, 16 sec)	Long rest periods (5, 10, 20, 40 min)
Densely graded asphalt concrete (AC)	Sand-asphalt

A broad range of testing conditions are applied to cover most test conditions encountered in the characterization of asphalt concrete. All details in the materials, sample preparation methods, and testing and analysis methods are not presented here, however, because of space limitation; but they can be found elsewhere (Test 1, see Reference *5;* Test 2, see Reference *6*).

When cyclic loading is applied to asphaltic mixtures, hysteresis loops are usually observed from the stress-strain curves with changing dissipated energy (i.e., area inside the stress-strain curve) as cycling continues. Based on the control mode (controlled-stress versus controlled-strain), two different trends can be observed in the stress-strain behavior, as are illustrated in Figure 1. It is noted here that the stress and strain levels in Figure 1 are low enough not to induce any significant damage in the specimens. Relaxation moduli are determined from both the mixtures, and pseudo strains are calculated using Equation 1. The data presented in Figure 1 are replotted in Figure 2 using the pseudo strain instead of the physical strain on the abscissa. The figures indicate that regardless of the control mode, the hysteretic behavior from cyclic loading disappears when the pseudo strain is used, except for the first cycle, during which some minor adjustments occur in the specimen and test setup. It is also noted that the stress-pseudo strain behavior is linear.

The same approach is employed to investigate the ability of the CP to account for the relaxation effect during rest periods. Figure 3 presents the hysteresis loops observed in the controlled-strain and controlled-stress testing before and after rest periods. Again, the stress and strain levels are kept low so as not to induce any damage. A significant increase in the dissipated energy is observed after the rest period, irrespective of the control mode. Pseudo strains are calculated and plotted against the stress values in Figure 4. The use of pseudo strain successfully eliminates the effect of relaxation and results in a linear, elastic-like behavior between the stress and pseudo strain.

On the basis of the observations made from Figures 2 and 4, it can be concluded that, as long as the damage induced by the cyclic

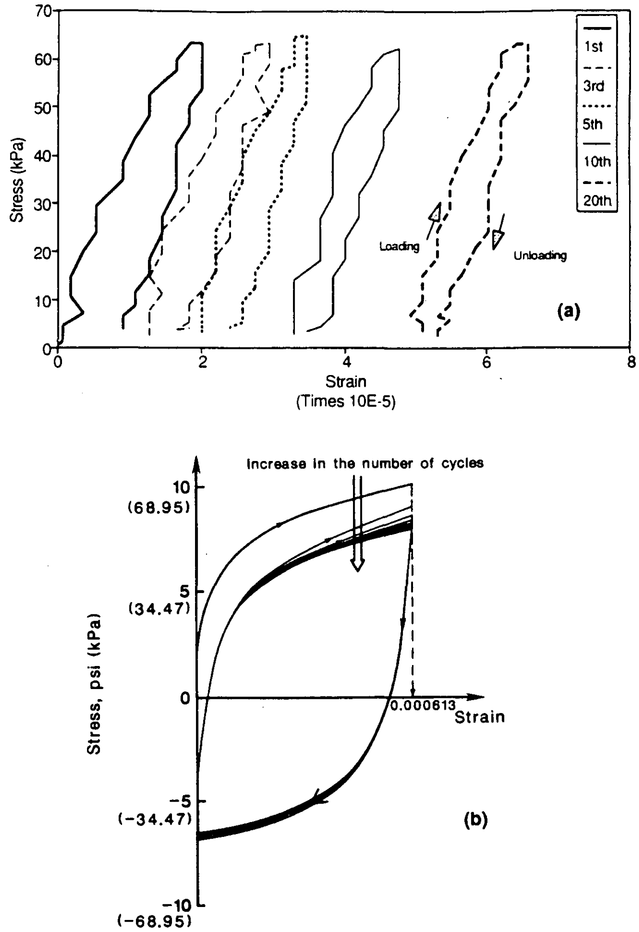

FIGURE 1 Hysteretic stress-strain behavior with negligible damage: (*a*) controlled-stress test; (*b*) controlled-strain test.

loading is negligible, the pseudo strain can be utilized to eliminate the time-dependence of asphaltic mixtures from the hysteretic behavior, irrespective of mode of control, loading type (tension versus compression), loading rate, wave form, or length of rest period. It is this use of pseudo strain that makes it possible to evaluate the healing mechanism during rest periods separately from the relaxation.

To evaluate fracture healing, the load amplitude is increased to a level at which significant damage growth can be expected during cyclic loading. Again a significant increase in the dissipated energy is observed by comparing the stress-strain diagrams before and after the rest periods that could be resulting from either relaxation or healing, or both. As mentioned previously, one cannot determine how much increase in the dissipated energy is related to healing merely by looking at stress-strain diagrams. Therefore, pseudo strains are calculated for both the controlled-stress and controlled-strain tests and plotted against the stresses in Figure 5. Different stress-pseudo strain behavior is observed in Figure 5 compared with that in Figure 4, where negligible damage occurred. Because the beneficial effect of the relaxation phenomenon now has been accounted for by using pseudo strain, changes in the stress-pseudo strain curves during the rest periods, as are observed in Figure 5, must result from the fracture healing of microcracks.

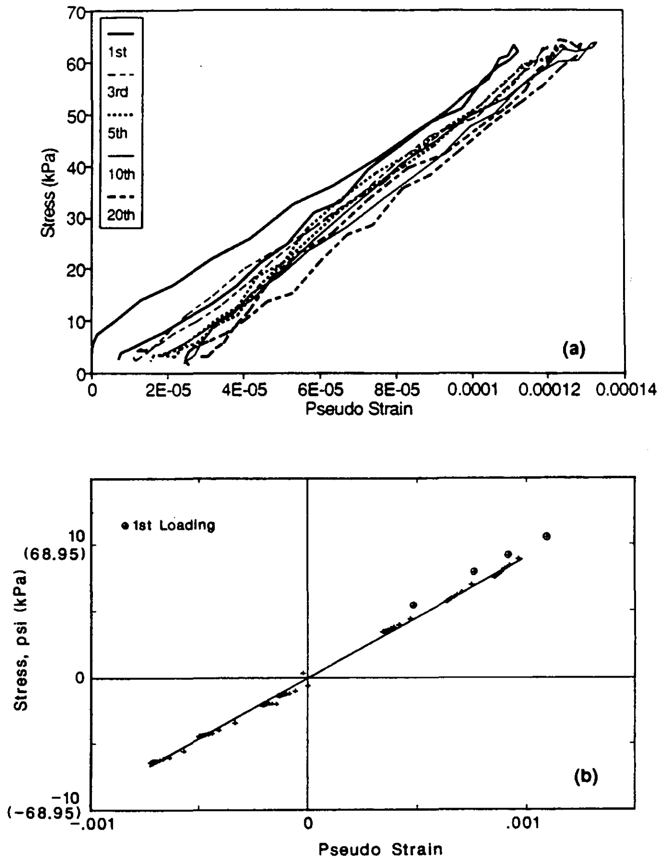

FIGURE 2 Application of CP to the data in Figure 1: (*a*) controlled-stress test; (*b*) controlled-strain test.

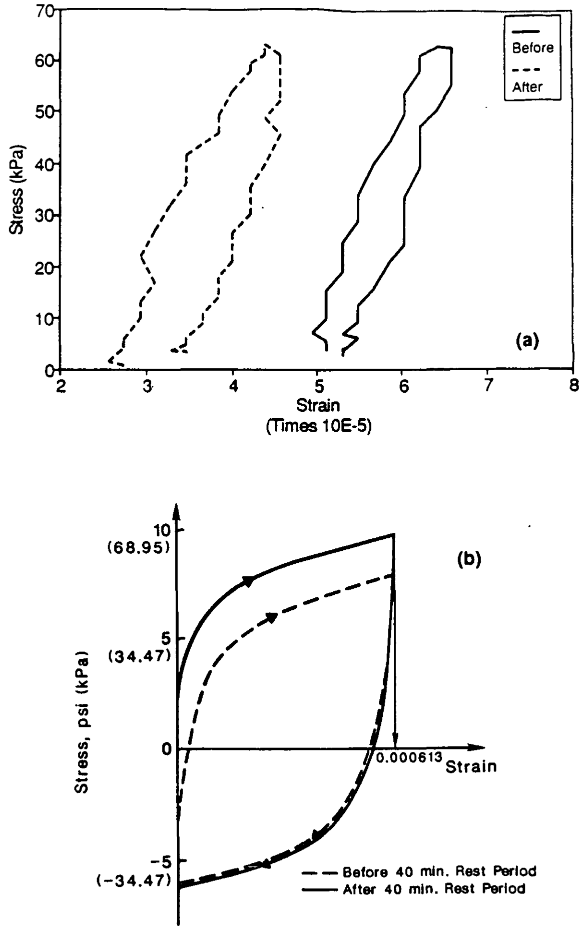

FIGURE 3 Effect of rest periods on stress-strain behavior (with negligible damage): (*a*) controlled-stress test; (*b*) controlled-strain test.

One can determine different mixtures' propensity for microcrack healing by measuring the difference in areas under the stress-pseudo strain curves before and after a rest period and normalizing it by the stress-pseudo strain area before the rest period. This method has been used successfully in differentiating the healing potentials of various binders (*3*).

LABORATORY EVALUATION OF HEALING VIA VIBRATIONAL TESTS

The impact-resonance method described in ASTM C 215 has been shown to produce very repetitive, consistent results for Portland cement concrete and for asphalt concrete (*7*). Low equipment costs and the small amount of time required to set up, conduct, and analyze results from the impact-resonance method are additional reasons to use this method as a standard.

In this study three modes of testing—longitudinal, transverse, and torsional—are performed on 10.2 cm (4 in.) by 20.3 cm (8 in.) cylindrical specimens. Test configurations, slightly modified from ASTM C 215, are illustrated in Figure 6. The impact was produced by a steel ball with a 0.64 cm (0.25 in.) diameter. A piezoelectric accelerometer with an operating frequency range of 100 to 10,000 Hz and a resonant frequency of 100,000 Hz is used, and the vibrational signal is sampled and processed by the Fast Fourier Transform (FFT) to determine the resonant frequency of the material under a specific testing mode. Elastic modulus is determined from both the longitudinal and transverse testing, and shear modulus is determined from the torsional testing. Detailed information on the impact resonance testing and analysis methods can be found elsewhere (*7*).

A set of specimens (H1, H2, and H3) are fabricated from the same mixture used in the uniaxial controlled-stress testing. Repetitive haversine tensile loads with an amplitude of 3114 newtons (700 lb) are applied to induce damage growth within the specimens. The tensile load consists of a 0.1-sec loading period followed by a 0.4-sec rest period. In order to determine whether the increase in moduli of the damaged specimens after exposure to heat was caused by healing or some type of aging phenomenon, the number of loading cycles is varied among the specimens. No tensile loads are applied to Specimen H1. Specimens H2 and H3 are subjected to 4,000 and 6,000 cycles of loading, respectively. The maximum axial strain resulting from the application of the tensile loadings is 0.57 percent for H2 and 0.59 percent for H3. After application of repetitive loads, the ends of the specimens are cut off with a circular stone saw in order to remove steel attachments and to conduct the impact-resonance tests.

Because a stone saw requires the application of water in the cutting process, the specimens are towel dried and permitted to air

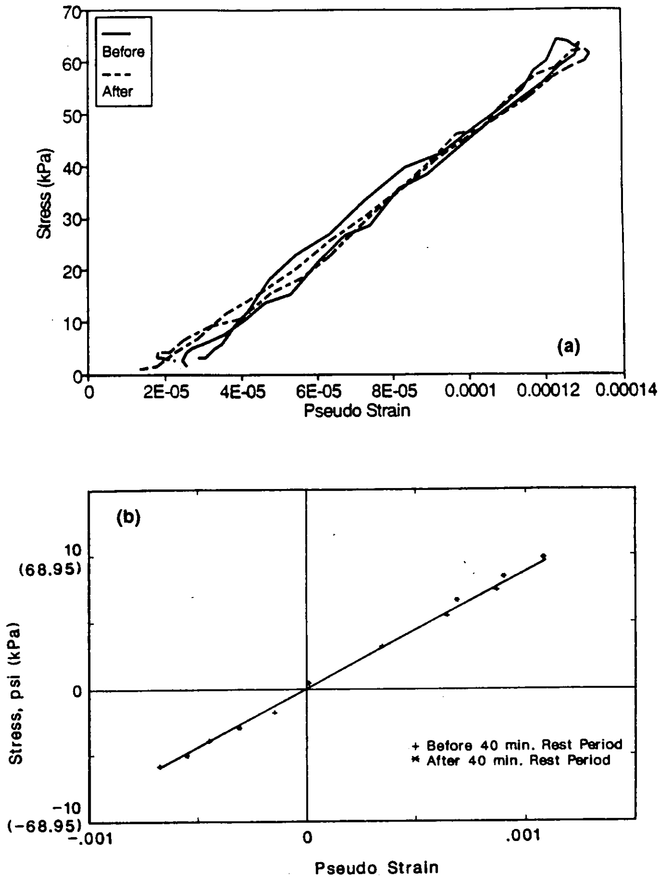

FIGURE 4 Application of CP to the data in Figure 3: (*a*) controlled-stress test; (*b*) controlled-strain test.

dry (laying on their long side) at 21°C (70°F) for 1 hr. Afterwards, the length and mass of the three H-specimens are measured. Then the longitudinal and torsional resonant frequencies are obtained at 21°C (70°F) by the impact-resonance method. The preheat experimental tests are completed within 3 hr after application of the tensile loads. Specimens then are conditioned to a temperature of 49°C (120°F) for 3 hr and permitted to cool, until post-heat frequencies are obtained at 21°C (70°F). Results are compared first to determine whether any change in moduli could be detected and, second, to evaluate whether specimens with more damage yield greater magnitudes of moduli increase after exposure to heat. Poisson's ratios are calculated to determine the accuracy of the experiment.

Experimental results obtained for the elastic and shear moduli along with Poisson's ratios are presented in Table 1. Because elastic and shear moduli were obtained independently, reasonable Poisson's ratios, obtained from the elastic and shear moduli confirmed the accuracy of the experimental test results. Healing ratios, defined as the ratio between the moduli obtained before and after exposure to heat, were calculated and are presented in Figure 7 for three specimens with varying levels of damage.

A comparison of the test results yielded the following conclusions:

1. There was a detectable increase in moduli for all three specimens after exposure to the high temperature.

2. The increase in moduli after 3 hr of exposure to 49°C (120°F) was different for each specimen. The specimen with more damage yielded a greater healing ratio, possibly indicating the presence of a reversible process at the microcracks.

Test results demonstrate that the impact-resonance test is able to determine varying magnitudes of structural regain of asphaltic mixtures after rest periods at higher temperatures.

FIELD EVALUATION OF HEALING VIA WAVE PROPAGATION TESTS

On May 20, 1993, wave propagation tests were initiated on the closed outer lane section of US 70 East outside Clayton, North Carolina. The pavement was about a year old with a 14-cm (5.5-in.) thick asphalt layer and 28-cm (11-in.) thick aggregate base course. Thermocouples were installed in the asphalt layer that allowed for temperature at various depths.

The test section was closed around 7:30 a.m. on May 20th and reopened to traffic at 8 a.m. the next day, constituting a 24-hr rest period. The wave propagation test was conducted immediately after closing the road and repeated hourly until the same time the next morning. Temperatures at different depths of the asphalt layer were measured at the time of wave propagation testing. The primary

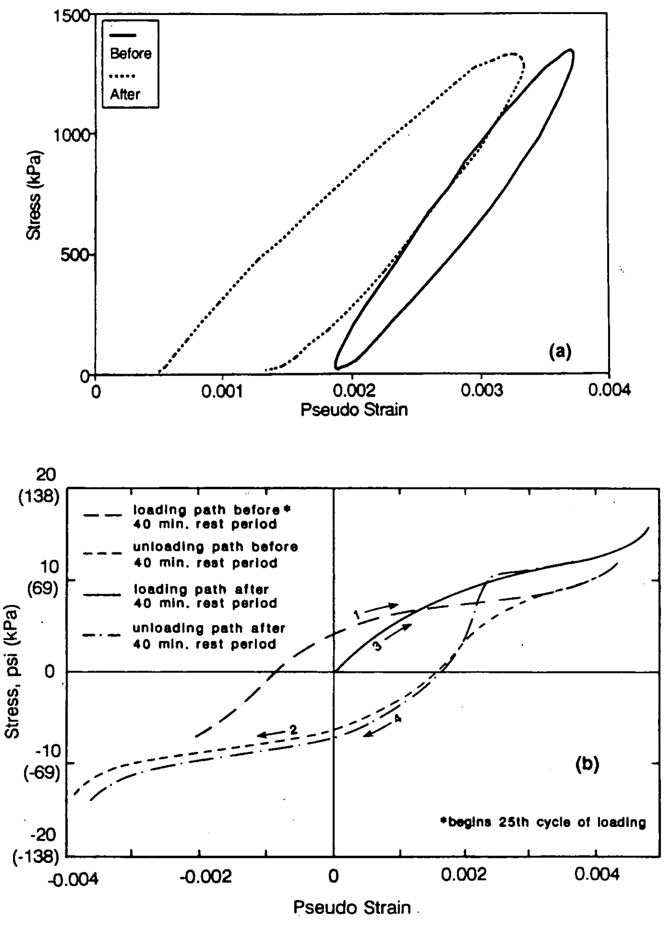

FIGURE 5 Stress-pseudo strain behavior before and after rest periods with significant damage: (*a*) controlled-stress test; (*b*) controlled-strain test.

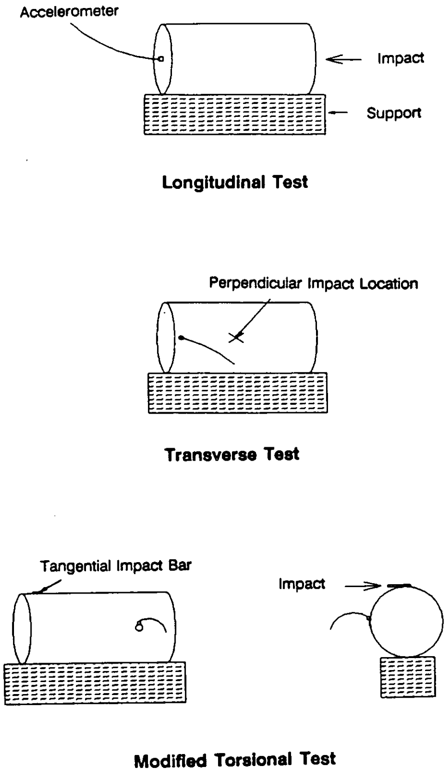

FIGURE 6 Three methods of the impact-resonance test (ASTM C 215).

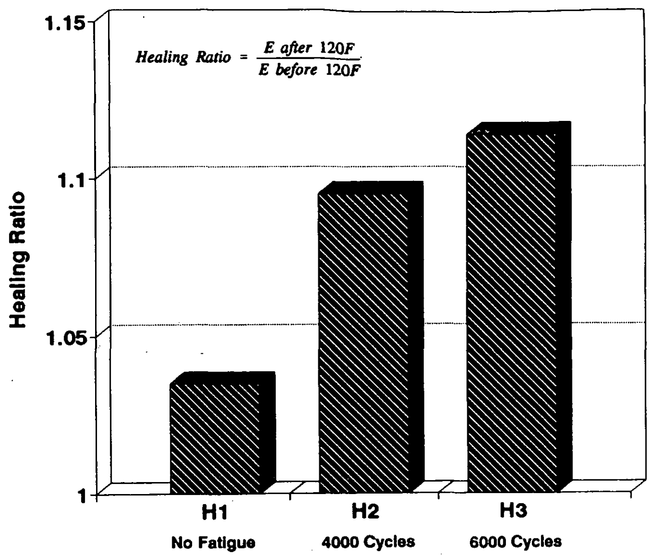

FIGURE 7 Effect of damage level on the healing ratio determined by the impact-resonance tests.

objective of the tests: to determine the change in the elastic modulus of asphalt layer as a function of temperature during a 24-hr cycle.

Stress Wave Theory

In an unbounded isotropic solid, only two types of waves (longitudinal and shear) can propagate. In an homogeneous, isotropic, linear elastic, solid half-space with a bounded surface (like the surface of a road), however, an elastic surface wave may also occur (as Lord J.W.S. Rayleigh determined in 1887). Surface waves are slightly slower than shear waves but contain vastly more energy. According to Douglas et al. (*8*), surface waves are nondispersive in the HILES half-space. However, when the half-space is a layered medium, surface waves are dispersive in nature; again, the surface wave will travel slightly slower than the shear wave, whose wavespeed is around 60 percent that of a longitudinal wave.

Given that all three of the wavespeeds are interrelated, determining one of them allows for the determination of the other two, given Poisson's ratio. In effect, the elastic modulus can be derived from the measurement of any one of the three waves by obtaining the longitudinal wavespeed from any measured wavespeed, squaring the longitudinal wavespeed, and multiplying the squared wavespeed by the density of the material through which the wave propagated.

Test Setup

Three PCB (Piezotronics, Inc.) 303A02 accelerometers were used along with a 482A05 series line power supply. The data were obtained via a Rapid Systems 4-Channel R1016 data-acquisition system attached to a 486 megabytes personal computer. At the field test section, 540 hexhead nuts were epoxied to the pavement at

TABLE 1 Impact Resonance Test Results for Evaluation of Healing Potentials as Function of Damage Level

		H1 (0 cycles)			H2 (4000 cycles)			H3 (6000 cycles)		
	Test	E[a]	G[a]	ν[b]	E	G	ν	E	G	ν
Preheating	1	19.7	7.52	0.31	18.8	7.24	0.30	19.3	7.45	0.30
	2	19.7	7.52	0.31	18.8	7.38	0.27	19.3	7.45	0.30
	3	19.7	7.52	0.31	19.0	7.45	0.28	19.3	7.45	0.30
Postheating	1	20.4	7.86	0.30	20.6	8.07	0.25	21.5	8.34	0.29
	2	20.4	7.79	0.31	20.6	8.14	0.27	21.5	8.34	0.29
	3	20.4	7.79	0.31	20.6	8.14	0.27	21.5	8.34	0.29

[a]Units are in 10^3 MPa (1 MPa = 6.89 ksi).
[b]Poisson's ratio calculated from the relationship between the elastic and shear moduli.

various locations between 7.6 cm (3 in.) and 61.0 cm (24 in.) away from the designated impact location (see Figure 8). The line of nuts extended parallel to and 1.2 m (4 ft) offset from the edge of pavement, which was the area with the most vehicular-wheel passes.

Field Testing

The initial test plan was to evaluate pavement using various accelerometer locations, in order to obtain the best possible resolution for determining the wavespeed. In order to accomplish the task, there had to be as much distance between accelerometers as possible and data had to be obtained at the highest allowable acquisition rate. On the basis of a series of experiments, we found that the most consistent data could be obtained with accelerometers placed at 7.6 cm (3 in.), 30.5 cm (12 in.), and 45.7 cm (18 in.) away from the impact. The energy of the impact dissipated so rapidly that an accelerometer 61.0 cm (24 in.) away was unable to obtain good data at test temperatures.

The experiments in this study were conducted using a 0.3 Kg (0.7 lb) steel claw hammer with a wooden handle, striking a 1.3-cm (0.5-in.) thick, 6.4-cm (2.5-in.) wide, 2.5-cm (1-in.) tall aluminum impact bar that was sitting on the surface of the road without any medium in between it and the road surface. As the temperature increased during the day, the amount of obtainable signal decreased.

Data Analysis and Results

Each signal data set was adjusted to a zero baseline, and amplitude was normalized by the maximum value. Every point in channel A (closest to the impact) was then multiplied by 100; in channel B (middle location) points were multiplied by 80, and in channel C (farthest from the impact) they were multiplied by 60. The rescaling of the amplitude allowed clearer analysis for the Short Kernel Method, which is described later. Figure 9 displays three data signals obtained from one of the tests.

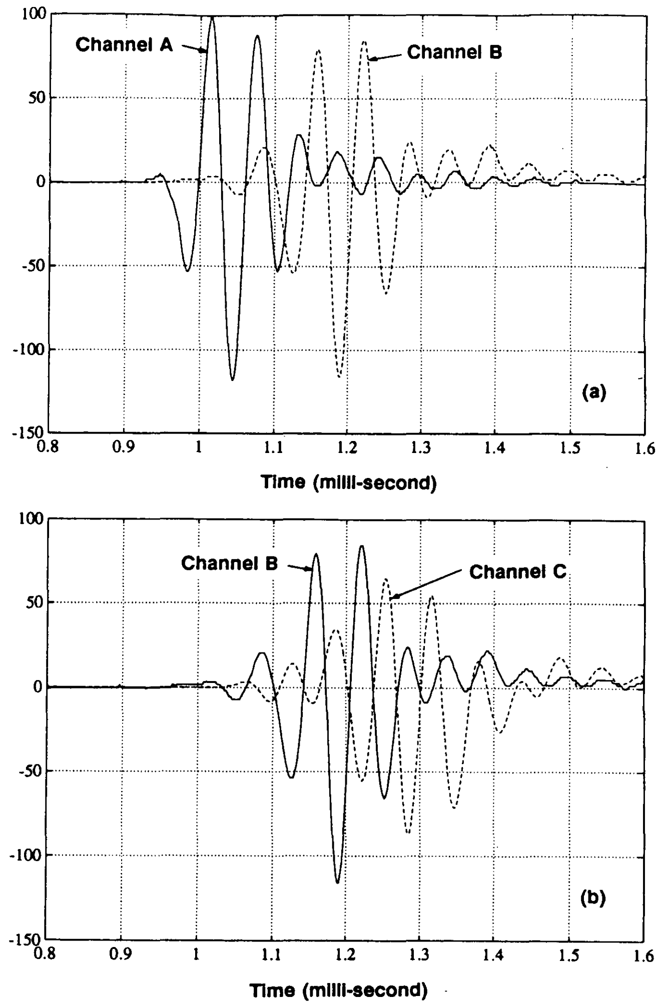

FIGURE 9 Stress wave signals from three accelerometers: (*a*) Channel A versus Channel B; (*b*) Channel B versus Channel C.

FFT Analysis

The data signals were analyzed initially via an FFT to determine the frequency range that contained the largest amount of energy. Figure 10 presents the FFT amplitude versus frequency for all three data signals. The graph demonstrates that the resulting bulk of the energy of the signal resides in frequencies around 15,000–18,000 Hz. The FFT can also be used to determine wavespeeds via the phase change of a frequency between two data signals. This analysis is in fact a simple and straightforward technique, but it does have the serious drawback of not being able to accurately define the multiple wavespeeds of the dispersion field (*8*).

In an inverted, geologically layered system, such as asphalt concrete pavements, individual frequencies can travel at several different velocities if they penetrate into layers having different elastic properties. In this study the FFT was used to determine the dominant frequencies from the wave signals only.

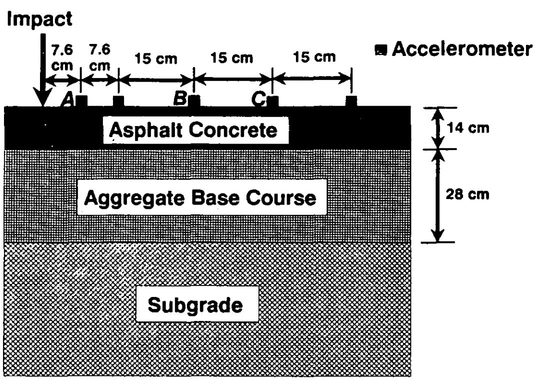

FIGURE 8 Various accelerometer locations tested in the initial testing.

Short Kernel Method

Signals are analyzed further using the Short Kernel Method (SKM) presented by Douglas et al. (*8*). The SKM is a frequency-dependent scanning operation that is based on the cross-correlation procedure. The SKM method amplifies a given frequency within the time domain of a signal to determine the time it took the wave to travel between the two gage points. Holt et al. (*9*) recently developed a

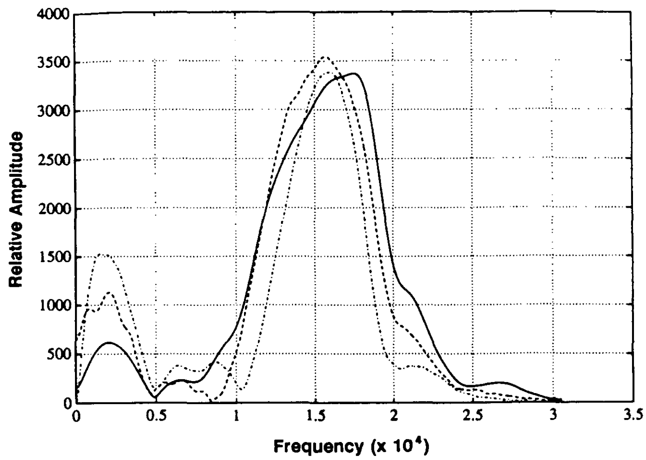

FIGURE 10 Fast Fourier Transform amplitude versus frequency for all three signals.

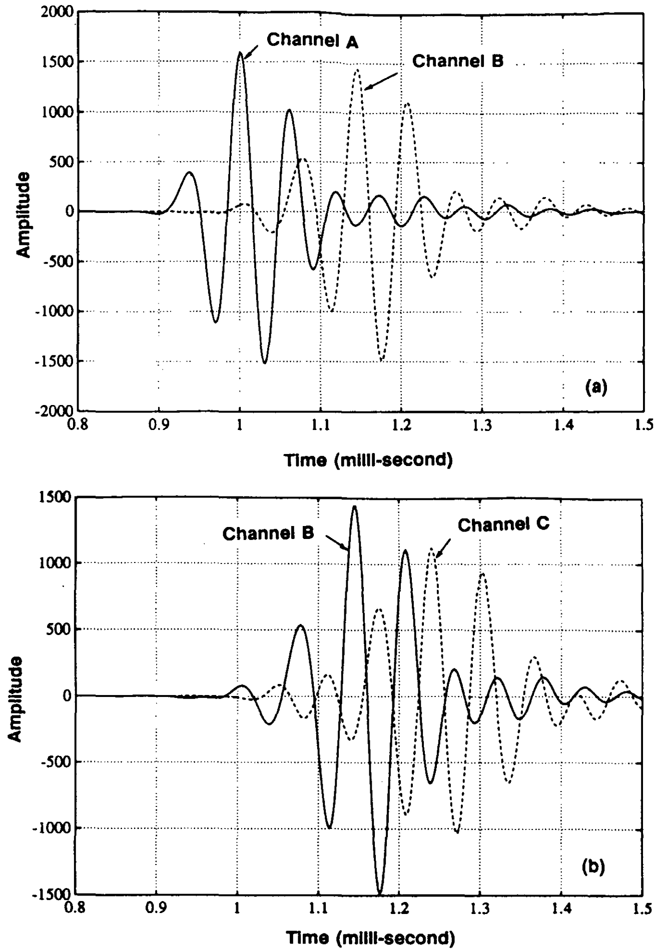

FIGURE 11 Short Kernal Method plot for all three signals: (*a*) Channel A versus Channel B; (*b*) Channel B versus Channel C.

method of determining embedments of installed timber piles that applies SKM in analyzing bending-wave signals generated by striking a pile on its side transversely to its longitudinal axis. Detailed information on the SKM is found elsewhere (*8,9*).

Because the data signal from channel A contained the largest amount of energy, a one-cycle kernel of the maximum frequency from channel A was used for the SKM analysis. The SKM results for the given data signals are shown in Figure 11. The time distance is measured between the corresponding peaks of the two transformed signals.

The wavespeed are obtained, and elastic moduli are calculated. The results are plotted with respect to their corresponding measured mid-depth temperatures in Figure 12. The density of the road is obtained by measuring the density of some field cores removed from the pavement. Poisson's ratios used in the calculation were obtained from the Poisson's ratio versus the temperature relationship, which was determined in the laboratory using the impact-resonance test method. Maximum surface and mid-depth temperatures during the test period were 43°C (110°F) and 39°C (102°F), respectively. Adequate data was difficult to obtain above 32°C (90°F) because of significant damping in the asphaltic layer that was also observed from laboratory vibrational testing (*7*).

As illustrated in Figure 12, the elastic modulus of the asphalt concrete layer decreased as the pavement temperature increased. Also, the elastic modulus after the 24-hr rest period was greater than it was before the rest period for the same mid-depth pavement temperature. The stress-wave testing method measures the stiffness of asphalt concrete in a glassy (purely elastic) region, because of the impact nature of loading, so the modulus change is not affected by time-dependent relaxation. Therefore, this increase in the elastic modulus could be a result of microcrack healing in the asphalt concrete layer.

Although the field data presented in this paper are somewhat limited, on the basis of experience with stress-wave testing at North Carolina State University, this technique has strong potential as a means of nondestructively determining the properties of asphaltic surface layers as a function of various factors, such as binder viscosity, aggregate gradation, air voids, temperature, type of modifiers. In addition, the simple and inexpensive nature of the stress-wave testing technique as well as the inability of deflection-based testing methods in determining the properties of thin surface layers make the stress-wave testing method more attractive.

CONCLUSIONS

Three different experimental approaches to evaluating microcrack healing of asphalt concrete during rest periods are presented in this paper: the elastic-viscoelastic correspondence principle to eliminate the effect of relaxation, the use of the impact-resonance testing methods in the laboratory, and the application of stress-wave testing to actual in-service pavements in order to determine change in elastic properties resulting from healing.

The nonlinear viscoelastic correspondence principle, applying the pseudo strain concept, was used successfully to eliminate time-dependence under various testing conditions, including control mode, loading type, wave form, loading rate, rest duration, and type of mixture. The principle proves to be an excellent method of modeling damage growth and healing in asphalt concrete under complex cyclic loading.

The impact-resonance method, a modified version of ASTM C 215, is also used successfully as a laboratory tool to evaluate modulus increase after rest periods at higher temperatures, that could result from microcrack healing of asphalt concrete. The

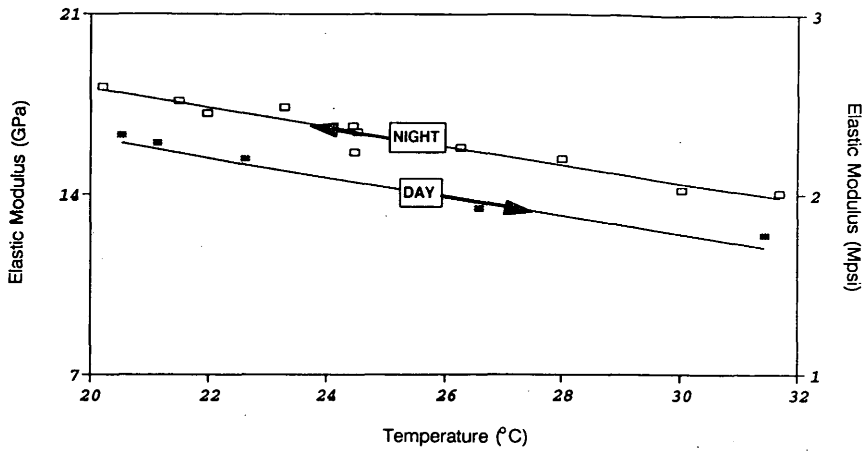

FIGURE 12 Elastic modulus versus pavement temperature from stress wave testing of a pavement in service.

testing method provides consistency of test results with simple and inexpensive equipment, making it an excellent and sensitive means for determining changes in material properties from damage growth or healing.

Stress-wave testing was performed hourly on an in situ pavement section for 24 hr. Elastic modulus of asphalt concrete decreased as pavement temperature increased. Also, an increase in elastic modulus was observed at a selected pavement temperature after a 24-hr rest period. This modulus increase is thought to result from microcrack healing in asphalt concrete pavements.

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