AN ANALYSIS OF THE MECHANISM OF MICRODAMAGE HEALING
BASED ON THE APPLICATION OF MICROMECHANICS FIRST PRINCIPLES
OF FRACTURE AND HEALING

By

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ABSTRACT

The fatigue process is viewed as the result of the competing processes of crack growth and crack healing. The crack growth or damage process is one of microcrack development and growth and ultimately coalescence of microcracks and propagation in the form of macrocracks. During the entire process, and especially during the period of microcrack growth, microdamage healing strongly influences the process. The significance of the process of healing on fatigue damage is proven through laboratory testing during which a very significant recovery of dissipated pseudo energy is demonstrated following rest periods. The significance of the healing process is also proven from field data demonstrating recovery of stiffness measured by surface wave techniques.

The mechanism of healing is discussed based on first principles of fracture and healing. These principles show that surface energy of the mixture constituents and mixture compliance must affect both fracture speed and healing speed. The impact of surface energy on the healing process was verified by comparing bitumen surface energies measured for various bitumens to the rate of healing of mixtures containing those bitumens. A micromechanics fracture and healing model linked to a finite element analysis of direct tensile, controlled-strain fatigue tests further verifies the link between surface energy and fracture and healing.
INTRODUCTION

Selection of mixture constituents (i.e., bitumen and aggregate) and mixture properties (i.e., stiffness, void content, etc.) to promote fracture fatigue resistance has been a formidable challenge to bituminous, materials and pavements engineers. The fatigue process is complex. Excellent work has been done [i.e., Monismith et al. (1985), Epps (1968), Van Dijk (1975), Van Dijk and Visser (1977), Tayebali et al. (1992), Tayebali et al., (1994) and Kim (1988)] which helps us develop a better understanding of the process and how to design asphalt mixtures to resist fatigue cracking. Lytton et al. (1993) point out the importance of the “shift factor” between laboratory and field derived fatigue data. This factor typically ranges from about 3 to about 100 and is strongly influenced by the rest period between loading cycles. Little et al. (1994), Kim (1988), and Benson and Little (1988) further explained the impact of binder and mixture components on the magnitude of healing developed during rest periods.

Williams et al. (1998) discussed the crack growth and healing process from a thermomechanical standpoint. He concluded that, during a rest period, given a minimal (nearly zero) applied stress and nearly virgin strain state, a healing process can be driven by locally available heat or other internal energy and residual viscoelastic stresses. Each of these relationships is limited by the Clausius-Duhem inequality combining the first and second laws of thermodynamics.

This study considers two opposing components of the fatigue process, fracture and healing. Both processes must be considered for an accurate accounting of the fatigue process. This study focuses on the healing component of the process and the bitumen and mixture properties which influence healing.

This study employs first principles of fracture and healing to develop a theoretical basis for the constituent factors that might influence the processes. A primary experiment was developed to evaluate the chemical components of the bitumen that should logically affect healing. These include compositional aspects (i.e., amphoteric, aromatics and waxes) and surface energy of wetting. Healing was evaluated using a “healing index” which quantifies the recovery in dissipated pseudo strain energy (DPSE) following rest periods introduced throughout the fatigue process. A secondary experiment was designed to assess the effect of selected additives and the process of aging on healing.

This major objectives of this paper are to: (1) demonstrate that the process of healing can be accounted for using a micromechanics model of fracture and healing, (2) establish a theoretically sound working hypothesis of the healing process from which the effects of bitumen and mixture properties can be assessed and (3) examine the effects of changes in these properties on microfracture healing. A fourth and secondary objective is to present field data that demonstrates the importance of healing in the fatigue process and that healing is measurable in the field.
BACKGROUND

Mechanism of Fatigue

Fatigue is the result of a crack initiation process followed by a crack propagation process. During crack initiation, microcracks grow from microscopic size until, as some research indicates, a critical size of about 7.5 mm is reached. In crack propagation, a single crack or a few larger cracks grow entirely through the pavement layer. At that point, others of the larger microcracks begin to propagate and coalesce to complete the disintegration process.

Fatigue is a two stage process: (1) microcrack growth and healing and (2) macrocrack growth and healing. There is no reason to expect that the two obey different laws, and the available evidence demonstrates that they do not, but instead are governed by the same principles. Fracture properties such as Paris' A and n values are known to depend upon more fundamental continuum properties. The chief among them are the compliance and tensile strength (mechanical properties) and the adhesive and cohesive surface energy density (chemical and thermodynamic properties).

Both microcracks and macrocracks can be propagated by tensile or shear stresses or combinations of both. Thus, in a pavement structure, microcracks form and grow in any location where sufficiently large tensile or shear stresses or a combination of both occur. Thus, in a pavement structure, microcracks can form and grow in any location where tensile or shear stresses are generated by traffic or environmental stresses. Microcrack zones can be introduced into the pavement by thermal stresses due to a drop in air temperature. These cracks may grow, reach critical size, and propagate due to either a significant decrease in temperature or to smaller repeated daily decreases in temperature.

The same pattern of microcracks may develop because of contractile stresses exacerbated by the embrittlement of the asphalt pavement through aging. Any tensile or shear stress applied to a field where microcracks exist may cause them to grow, to reach critical size, and then to propagate as macrocracks.

Paris' law states that the "crack speed", \( \frac{dc}{dN} \), depends upon the size of the J-integral or its elastic equivalent, the stress intensity factors due to tension \( (K_t) \) and shear \( (K_s) \). The distribution of \( K_t \) and \( K_s \) varies with depth and may be calculated using finite element methods. Surface initiation is more common in thick asphalt layers (>200 mm) and bottom initiation is more common in intermediate thickness layers (50-200 mm).

The number of traffic load cycles, \( N_t \), to cause a crack to penetrate through the full depth of the pavement surface layer is the sum of the number of load cycles for crack initiation, \( N_i \), and the number of load cycles required for the macrocrack to propagate to the surface, \( N_p \).

\[
N_T = N_i + N_p
\]
Both $N_f$ and $N_g$ obey a type of the Paris' law as modified to include both fracture and healing. The actual number of load cycles required in each process is calculated by following the growth of a crack. Not only does the stress-intensity factor change with crack length, but the values of the Paris' law coefficients $A$ and $n$ for both fracture and healing also vary depending upon whether the crack is momentarily growing along the surface of an aggregate (adhesive fracture) or in the mastic surrounding the aggregate (cohesive fracture), or temporarily arrested by an object blocking its path (crack arrest).

The beam fatigue tests that were performed in the Strategic Highway Research Program A-003A contract provided an excellent opportunity to observe the two phases of crack growth: initiation and propagation (Lytton et al., 1993). The tests included both "constant-strain" and "constant-stress" tests, which made the process of separating the two phases of crack growth simpler.

In the constant-strain fatigue test, no crack propagation occurred and only the damage due to the formation and growth of distributed microcracks was observed. This was observed principally with two measurements: the stiffness of the beam fatigue sample decreased and the rate of change of dissipated energy per load cycle continued to change with the increasing number of load applications.

Numerous measurements of the beam deflections and the dissipated energy per load cycle permitted the use of a finite element model of microfracture damage to be used together with a systems identification method to determine the fracture properties of the mixture being tested. The "systems identification method" used is described briefly in subsequent discussion.

In the constant stress test, crack propagation did occur after a period of crack initiation. A clear separation of the two phases was observed in the plot of the rate of change of dissipated energy per load cycle versus the number of load cycles. At the beginning of the crack propagation phase, the rate of change of dissipated energy increased rapidly above the rather steady increase in the rate of change which characterized the previous crack initiation phase.

The fracture properties that were computed from the constant-strain fatigue tests were successfully used to compute the growth of microcracks and the rate of change of dissipated energy per load cycle in the constant-stress fatigue tests during the crack initiation phase. The same fracture properties were successfully used to compute the growth of the visible crack in the crack propagation phase.

Two distinctively different parts of the crack growth process were observed consistently in the "constant stress" tests. The first part consisted of a steady growth of the rate of change of dissipated energy per load cycle, $\frac{dW}{dN}$. In this part, microcracks grew in length until some reached a critical size which was calculated to be 7.5 mm. At that point, macrocrack growth began. In the second part of the crack growth process the rate of change of dissipated energy per
load cycle accelerated as the single macrocrack demanded a much greater expenditure of energy to drive it to greater lengths. A graph of the rate of change of dissipated energy, $dW/dN$, versus the number of load cycles, $N$, is shown in Figure 1. These two parts of the crack growth process, have been known to exist qualitatively for many years, during which they were termed the “crack initiation” and “crack propagation” phases. The distinction between the two parts is refined by focusing on the rate of change of dissipated energy, $dW/dN$, as shown in that Figure 1. The Paris' law coefficients, $A$ and $n$, which predicted microcrack growth also predicted the growth of the macrocrack.

Figure 1. Illustration of the Relationship of the Parts of the Crack Growth Process as Related to the Rate of Change of Dissipated Energy Per Load Cycle, $dW/dN$. 

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DEVELOPMENT OF MICROMECHANICS FRACURE AND HEALING MODEL

Lytton et al. (1993) and Chen (1997) developed an analysis approach based on continuum damage mechanics (CDM) and micromechanics to assess microdamage and healing. The first task was to apply this micromechanics Fracture Healing Model (MFHM) and derive a finite element formulation with which the fracture properties of asphalt mixtures could be calculated. By using Griffith's (1920, 1921) model for total energy per unit area for a cracked element and the MFHM concept, they were able to develop a mechanical equation to describe damage due to the growth of multiple microcracks under loading. The Weibull distribution was then utilized to simulate microcrack growth and size distribution with each load repetition. The details of this approach are discussed in Lytton et al., 1993 and 1998.

This approach resulted in a relationship between the ratio of the reduced modulus of the asphalt sample under loading, \( E' \), to the modulus of the undamaged sample, \( E \), and the change in dissipated pseudo strain energy per load cycle, \( dW/dN \). Pseudo strain energy (PSE) was calculated using the viscoelastic correspondence principle. The importance of using PSE in fracture and healing calculations to separate out viscoelastic time-dependency is discussed by Kim et al. (1990), Kim et al. (1995), and Kim et al. (1997). According to the relationship, the ratio of reduced modulus due to damage and original modulus of the undamaged specimen, \( E'/E \), is not only a function of \( dW/dN \) but also certain material properties of the mixture including Paris-type fracture coefficients \( A \) and \( n \) and the Weibull crack length distribution parameters. These coefficients and parameters and their application are discussed in detail by Lytton et al., 1993 and 1998.

This measured value of \( dW/dN \) was used in analyzing laboratory tests that were made to determine the material properties that are related to microcracking. This use of the measured rate of change of dissipated pseudo-strain energy is explained by Lytton et al. (1998) on pages 31-38 and particularly in equations (60) through (74) of that volume.

The finite element formulation developed in this study accounts for the development of a distribution of microcracks according to Griffith's theory. These microcracks develop perpendicular to the application of the tensile load during tensile loading and their lengths grow according to a Weibull distribution. Damage is recorded as the modulus in the direction of the applied tensile load is reduced and the dissipated pseudo-strain energy changes during the process of microcrack growth. The ratio of reduced modulus, \( E' \), to the original modulus, \( E \), is related to the rate of change in dissipated pseudo strain energy, \( dW/dN \), and basic fracture properties including the Paris-type parameters \( A \) and \( n \). It is also related to and other parameters that explain microcrack distribution (\( p \), \( d \) and \( q \)) as well as the cohesive surface energy density of the mixture,
\( E' \), the normal and shearing stress state in the sample (\( \sigma \) and \( \tau \)) and the average crack length \( \bar{c} \).

The relationship is presented conceptually as:

\[
\frac{E'}{E} = F(\frac{dW}{dN}, A, n, p, d, q, \Gamma, \bar{c}, \sigma, \tau)
\]  

[1]

where \( F(\cdot) \) represents a function of all of the variables listed. The exact form of equation [1] is presented, developed and discussed by Lytton et al. (1993) in the SHRP A-357 report.

Chen (1997) developed a finite element model of a cylindrical test sample subjected to direct tensile, controlled-strain loading. Using the relationship shown conceptually in equation [1], Chen recorded the ratio of reduced stiffness and \( dW/dN \) throughout the test sequence and then used a systems identification method to determine the basic fracture properties and the Weibull distribution of crack length (including the expected value of crack length). Systems identification is a systematic non-linear search process to determine from the test measurements the material properties and crack lengths and their distribution in accordance with a least-square sum of error criterion. This is sometimes called inverse analysis or back calculation. Figure 2 illustrates a calculated distribution of average microcrack length as a function of load application. Note the increase in average microcrack length as load cycles increase and the reduction in average microcrack length following a rest period during which microcrack healing occurs.

The dramatic reduction in average microcrack length after the rest period stems from a recovery in PSE and a concomitant recovery in pseudo stiffness. These reflect microcrack healing.

![Figure 2. Change in Crack Length During Loading Cycles and Reduction of Mean Crack Length Following Rest Periods.](image)

Note: After 22 loading cycles in loading period No. 1 a two minute rest period is introduced before beginning loading cycles No. 2. The rest period produces a 50% reduction in average crack length.
Relationship Between Dissipated PSE and Loading Cycles and The Ability of the MFHM to Match the Data.

The MFHM model considers only microcrack growth as a means of damage and therefore the only reason for PSE dissipation during loading. This was verified by Lytton et al. (1998) at low (4°C) and intermediate (25°C) test temperature. At these test temperatures, plots of back-calculated dissipated PSE closely matched measured values of dissipated PSE density, Figure 3. However, at the high test temperature of 40°C, this was not the case. Here the match was poor indicating that damage occurred largely through plastic deformation and not only through microcrack growth.

In addition to the MFHM approach to assess the effects of microcrack growth and healing during fatigue testing, Lytton et al. (1998) used first principles of fracture mechanics to account for the effects of mixture variables on fracture (crack growth) and healing (crack rebonding). This approach ultimately explains the fatigue process as a balance between crack growth and healing. The form of the equation explaining the rate of crack growth, \( \frac{dc}{dN} \), (where \( dc \) is change in mean crack length and \( dN \) is change in load cycle number) is then:
Fracture Speed  

\[ \frac{dc}{dN} = \frac{K_f(\gamma_f E_f J_f)^{1/3}}{(2\Gamma_f - D_{of} E_f J_f)^{1/3}} \]

Healing Speed

\[ \frac{dc}{dN} = \frac{K_h(\gamma_h E_h H_f)^{1/3}}{(2\Gamma_h - D_{of} E_h H_f)^{1/3}} \]

In this relationship, \( K_f \) and \( K_h \) (which are functions of the time permitted for crack growth and healing) are constants; \( \alpha \) is the length of the fracture process zone before the crack surface; \( D_{of} \) and \( D_{fr} \) are components of tensile compliance; \( D_{oh} \) and \( D_{nh} \) are components of compressive compliance; \( E_R \) is a reference modulus; \( J_0 \) is the viscoelastic J-integral (the change in dissipated pseudo-strain energy per unit of crack growth area from one tensile load cycle to the next); \( H_0 \) is the viscoelastic H-integral (the change in dissipated pseudo-strain energy per unit of crack healing area from one compressive cycle to the next); \( m_t \) is the slope of the tensile compliance relationship; \( m_h \) is the slope of the compressive compliance relationship; \( \Gamma_f \) is the surface energy density of a crack surface in fracture (dewetting) and \( \Gamma_h \) is the surface energy density of a crack surface in healing (wetting).

The micromechanics model further verifies that crack growth is the mechanism of damage in the samples subjected to repeated tensile fatigue loading as values of \( \Gamma_f \) and \( \Gamma_h \) were back-calculated from the dissipated PSE data and the micromechanics fracture relationship described by equation [1]. The back calculated values for \( \Gamma_f \) and \( \Gamma_h \) (determined after a two-minute rest period) were in reasonable agreement with measured values of surface energy densities for the asphalts and aggregates used in this study at temperatures below 25°C. No such agreement exists above this temperature, indicating that above this temperature the damage mechanism is not primarily microcracking. Having measured all of the components of the total surface energy separately, it was possible to compare these back-calculated values of \( \Gamma \) with the independently measured values. The two values compared very well based on experiments at or below 25°C as is shown in Tables 5 through 10 of Lytton et al. (1998).

LABORATORY EVIDENCE OF HEALING - THE HEALING INDEX

General Discussion

The ability of an asphalt mixture to recover from damage occurring during a controlled-strain fatigue test was assessed using the concept of the healing index (HI). This index, Kim et al. (1990), is defined as the ratio of the recovered dissipated PSE following a rest period to
dissipated PSE measured prior to the rest period:

\[
Healing \ Index = HI = \frac{(\phi_h - \phi_d)}{\phi_d}
\]  

where

\[
\phi_d = \text{Dissipated pseudo strain energy (PSE) when the damaged sample is loaded}
\]

\[
\phi_h = \text{Dissipated pseudo strain energy (PSE) when the healed sample is loaded.}
\]

Controlled-strain fatigue testing was performed on 100-mm diameter by 200-mm high cylindrical samples of asphalt concrete prepared by kneading compaction with an air void content of 4.0% and with a tolerance of 0.25%. Each mixture was prepared with 5.0% bitumen. The initial load on each sample consisted of the application of 350 microstrain over a period of 0.5 seconds. The strain was held for 10 seconds and then removed over a 0.5 second period. This trapezoidal strain was used to calculate the characteristic compliance of each mixture which is an important material property used in the micromechanics model. Following the initial trapezoidal function, the controlled-strain experiment consisted of haversine loading applied of 0.1 seconds with a 0.5 second rest period between haversine load application.

The strain induced during each haversine load was converted to pseudo strain by adjusting the strain waveform for the effects of relaxation with application of the Boltzmann superposition principle. This process is explained in detail in by Williams et al. (1998). This conversion to pseudo strain eliminates the time-dependent effects. A resulting plot of pseudo strain versus pseudo stress represents the hysteresis plot of PSE that produces cracks and crack growth. Figure 4 is an example of the PSE hysteresis plot of sample M/DG/21. Notice the substantially increased level of PSE following the rest period compared to that before the rest period. This trend was consistent with all samples tested, but the degree of PSE recovery varied significantly with the different materials evaluated.

The healing index is simply a “picture” of the change (recovery) that a sample undergoes during a rest period. The HI is actually a recovery in stiffness of the mixture at the stress required to produce a target strain (350 microstrain in this series of testing). The HI is therefore not a material property like compliance or relaxation moduli. Since the HI is not a fundamental property, its values have rightly been questioned as being possibly tainted by the mechanisms of strengthening and softening germane to the behavior of asphalt mixtures. These factors include but are not limited to molecular structuring (steric hardening), hysteresis heating (or damping) and of course stress relaxation.
Influence of Molecular Structuring

Molecular structuring or steric hardening produces a reversible phenomenon that can produce large changes in the flow properties of asphalt without altering the chemical composition of the asphalt molecules. Petersen (1984) indicates that it is a slow process that may go on for days or even years, and it can be promoted by mineral aggregate surfaces. Petersen (1984) discussed the hardening rates of selected asphalts as a function of asphalt source and found the rate and degree of steric hardening to be source dependent with air blown asphalts showing a greater rate of structuring. According to the data presented by Petersen (1984), the time required to realize significant levels of molecular structuring at 25°C is between 10 and 1000 hours depending on the source of the bitumen. Molecular structuring that can be influenced by the aggregate mineral surface may occur at more rapid rates in mixtures, and it is apparent that the effects of molecular structuring are synergistic with oxidation. The authors do not feel that the effect of molecular structuring in and of itself accounts for the recovery in dissipated PSE measured in these experiments at temperatures of between 20°C and 25°C and at rest periods of only 2 minutes. Instead they feel that molecular structuring can account for only a small portion of the effect.

![Diagram](Figure 4. Data About (Before and After) the First Rest Period Collected During the Fatigue Test Presented in Transformed Pseudo Energy Values for Sample M/DG/21. (The designation indicates: M = binder AAM; DG = dense-graded mix; 21 = tested at 21°C).)

Confounding Effects of Temperature

The analysis of the effects of temperature on the mixture response due to hysteresis heating under the type of haversine loading used in this testing is discussed in detail by Williams et al. (1998). Asphalt samples must undergo a considerable number of fatigue cycles (thousands) to develop significant temperature changes which would affect the modulus of the mixture. This is likely due to the need for the asphalt, which exhibits the damping behavior in tensile tests, to heat the aggregate, which comprises approximately 95% by mass of the mixtures tested in these experiments. Once heated, the mixtures cool at a very slow rate, which must decrease with cooling as the thermal gradient between the specimen and the surrounding diminishes. Work by Di Benedetto (1996) in fatigue testing at a loading rate of 10Hz required 75,000 cycles to increase the temperature of a mixture by 1.2°C. This apparently represents a steady state condition. He also observed that the specimen required at least 1000 seconds to lose one-half the heat developed during loading. It is unlikely that global heating had an effect on specimens (in these experiments) which are tested for two hundred cycles per loading sequence. To check this, the samples were monitored during testing at TTI by placing thermocouples on the exterior of the samples. The temperature fluctuation during the experiment from the time the test was begun to the time the rest period was complete was always less than 0.05°C. It is the authors’ opinion that the application of 200 loads (damage cycle) at two cycles per second followed by a two minute rest period does not provide a significant swing in temperature increase or dissipation to affect the stiffness of the mixture. Localized crack tip heating could indicate a potential for greater molecular mobility and activity at the crack tip, however, as well as a change in the environment in which the asphalt surface interactions occur in the vicinity of the crack with respect to the molecular motion and interaction. This is discussed in greater detail by Williams et al. (1998).

Influence of Specimen Stiffness

Specimen stiffness, in a strain-controlled experiment such as those performed in this study, exerts a powerful effect on both the rate of material degradation and the potential for temperature evolution. Obviously, since only the applied strain can be controlled, stiffer mixtures will undergo much more rigorous testing in terms of the energy applied to them in a given number of cycles. This energy will be dissipated in a number of ways in asphalt specimens; chiefly through cracking damage and damping.

Damping is dependent directly on the stress amplitude. Since the strain amplitude is controlled in the haversine wave test, the damping is directly proportional to the material stiffness at the time of loading. Thus, the damping will decline with successive loading dependent on the
rate of damage. The degree of the effect that stiffness exerts on damping (and therefore the potential for temperature evolution) can only be assessed after the relaxation behavior is removed from the scenario, so as to isolate the effects.

Stiffness exerts a great influence on the damage developed in the sample in strain-controlled tests of any kind. In the absence of relaxation, it directly relates the dissipated energy to the applied strain. Since relaxation behavior is present in asphalt mixes and independent of damage, the relaxation effects must be removed from the data before assessing the rate of damage applied to the material. The transformation to dissipated PSE as was done in this study makes this analysis more complete and accurate. The approach used to calculate PSE is discussed by Williams et al. (1998).

The HI becomes a simple yet powerful index by which to evaluate PSE recovery following rest periods. The value of HI has been found to be strongly and statistically significantly affected by the source of the bitumen, additives to the bitumen, the temperature of testing, the length of the rest period and the number of rest periods introduced during the fatigue process, (Little et al., 1998).

**Consideration of Bitumen Composition**

Particular emphasis in this study was given to the effects of the chemical and physical nature of the bitumen on the healing index. Asphalt binders were selected, with the help of Dr. Jan Branthaver of Western Research Institute, according to their chemical compositional differences, Table I. This matrix in Table I serves as a guide for direct evaluation of healing rates with respect to chemical composition. Direct evaluation of the compositional effects was performed by a statistical contrast/comparison test of the mixture data and is discussed in detail later in this paper. As shown in Table 1, the selected SHRP binders vary in wax, amphoteric and aromatic quantities.
It was the opinion of the research team that strong differences in these compositional factors would have the strongest tendency to affect the healing potential of the mixtures prepared with these bitumens. The aromatic molecules form stacks of molecules due to their flat shape, and the electrons in the aromatic rings interact with one another to form pi-pi bonds. This pi-pi interaction is unique in aromatic molecules and deserves study as to its possible effect on the fatigue process and in particularly microdamage healing. The amphoteric structure is equally interesting and deserving of investigation as a chemical entity which may affect fracture and healing. An amphoteric material is one that can exhibit either an acidic or basic character. In asphalt this actually means that the asphalt molecule has both an acid and a base group (one or more of each) on the same molecule. Data have provided strong evidence that amphotericity play an important role in building the polar-polar bonds that give asphalt its unique properties. Jones (1992) explains that this interaction makes the asphalt molecules able to form “chains” of weak polar-polar interactions. These chains are the foundation of the network described in the SHRP asphalt model where the asphalt is considered to consist of two entities: interactive polar and non-polar. An example of an amphoteric asphalt molecule is one that has both an acid (i.e., carboxylic acid (COOH)) and basic unit (i.e., sulfoxide (S=O)) on the same molecule. Such a structure allows the molecule to interact at the two sites with two other molecules and continue, not terminate, the interactive or chain-building process among asphalt molecules. The contribution of amphotericity to the general interactivity among asphalt molecules would seem to make amphotericity a factor in the processes of flow and healing. Finally, the wax content of the
asphalt is important. Waxes are long, aliphatic molecules that may either be amorphous or crystalline in nature depending on the proximity of their arrangement. Interactive forces among waxy molecules include the weak Van der Waals force developed as the long chains of hydrocarbons intertwine and weakly interact.

The aromatics, amphoteric and wax contents of asphalt binders, and their interactions, should affect the flow and aging characteristics of the binders and hence the fracture and healing characteristics of the binders. An additional parameter of considerable importance is the heteroatom content. High concentrations of heteroatoms such as sulfur, oxygen and nitrogen promote polarity. The effects of the heteroatoms are indirectly accounted for when considering the aromatic and amphoteric parameters.

Consideration of Surface Energy

Asphalt concrete is a composite blend of bitumen and aggregate (of a number of size fractions). Unlike other composites, comparatively little has been done to characterize the asphalt-aggregate bond thermodynamically in terms of adhesion and cohesion. The thermodynamic change in the surface free energy is the theoretical work required to break an interface, or to form one. Knowledge of the energy required to sever and reform an interfacial bond would certainly be an important contribution in explaining the fatigue process. The more energy required to sever a bond in the surrounding media, the more work would be required to propagate the crack (other factors being equal). The effect of surface energy on the re-estabishment (healing of the crack) is equally as important although perhaps not as clearly apparent. The concept will be discussed subsequently based on data collected in these experiments.

Surface energy density (SED) is explained by Schapery (1989) to be an integral part of the fracture and healing processes. Furthermore, Lytton et al. (1998) propose an allied theory of how the rate of fracture and the rate of healing (in asphalt mixtures) can be explained by the first principles of fracture originated by Schapery and considering the effects of surface energy density. Since SED is a measurable parameter for both of the two major components of the asphalt mixture (bitumen and aggregate), and since it is related fundamentally to fracture and healing theory, the authors considered it wise to develop a theoretical understanding which links surface energy density to the fatigue process. Hopefully this will help explain differences in fatigue and healing among different bitumens and aggregates based on their different SED values (for both bitumen and aggregate). Furthermore, it should follow that SED values of the bitumens relate to differences in the aromatic, amphoteric and wax contents of these bitumens.
EXPERIMENT

The primary experiment (Table 2) is to assess the influence of bitumen composition on the healing index. The test is a controlled-strain direct tensile fatigue test discussed previously. In the secondary experiment (Table 3), the effect of additives and aging on the healing index are assessed.

Table 2. Partial Factorial of Experiment to Assess Effect of Bitumen Composition on Healing.

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Mix Type</th>
<th>Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watsonville Granite SHRP (RB)</td>
<td>Dense (DG)</td>
<td>AAB-1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9 replicates</td>
</tr>
</tbody>
</table>

Table 3. Partial Factorial Experiment to Assess the Effect of Additives and Aging.

<table>
<thead>
<tr>
<th>Aggregate and Mix Type</th>
<th>Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AAM + LDPE</td>
</tr>
<tr>
<td>Dense Graded Aggregate RB</td>
<td>3 replicates</td>
</tr>
</tbody>
</table>
EXPERIMENTAL DATA LINKING MECHANICAL FATIGUE AND HEALING TESTING OF MIXTURES WITH CHEMICAL COMPOSITIONAL MEASUREMENTS AND SURFACE ENERGY DENSITY MEASUREMENTS OF THE BITUMENS STUDIED

Surface energy testing was performed in the Chemical Engineering Department at Texas A&M University by Gerry Elphingstone (1997) using the Wilhelmy plate device. The test centers around the use of a highly sensitive balance, the Cahn C2000, married to a computer-controlled motor and data acquisition module. In the experiment, asphalt-coated plates are lowered into and pulled out of different fluids (water, glycerol and ethylene glycol). The angles of wetting and dewetting are very carefully measured during the process and the rate of advancement and extraction are very carefully controlled. The protocol measures a surface energy of wetting and a surface energy of de-wetting. The surface energy of wetting is thought to be directly related to the potential for microcrack healing, and the results of this testing are summarized in Table 4 for the five binders included in the experiment.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \Gamma )</th>
<th>( \sigma )</th>
<th>( \Gamma_{\text{LVW}} )</th>
<th>( \sigma )</th>
<th>( \Gamma_{\text{AB}} )</th>
<th>( \sigma )</th>
<th>( \Gamma' )</th>
<th>( \sigma )</th>
<th>( \Gamma'' )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAB-1</td>
<td>10.1</td>
<td>0.5</td>
<td>9.4</td>
<td>0.5</td>
<td>0.7</td>
<td>0.2</td>
<td>2.4</td>
<td>0.4</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>AAD-1</td>
<td>14.0</td>
<td>0.2</td>
<td>13.6</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.06</td>
<td>0.2</td>
<td>0.05</td>
</tr>
<tr>
<td>AAF-1</td>
<td>10.0</td>
<td>0.4</td>
<td>6.2</td>
<td>0.1</td>
<td>3.8</td>
<td>0.4</td>
<td>4.3</td>
<td>0.3</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>AAG-1</td>
<td>13.0</td>
<td>0.1</td>
<td>8.2</td>
<td>0.1</td>
<td>4.8</td>
<td>0.1</td>
<td>4.8</td>
<td>0.1</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>AAM-1</td>
<td>58.2</td>
<td>0.1</td>
<td>5.3</td>
<td>0.1</td>
<td>2.9</td>
<td>0.1</td>
<td>5.6</td>
<td>0.2</td>
<td>0.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Note:

\( \Gamma \) = Total Surface energy density (SED) (mean values)
\( \Gamma_{\text{LVW}} \) = Lifshitz-Van der Waals component of SED (mean values)
\( \Gamma_{\text{AB}} \) = Acid-base component of SED (mean values) \[\Gamma_{\text{AB}} = (\Gamma' - \Gamma'') \delta\]
\( \sigma \) = Standard deviations of preceding values
\( \Gamma' \) = Acid component of SED (mean values)
\( \Gamma'' \) = Base component of SED (mean values)

Two components of thermodynamic surface energy (\( \Gamma \)) of either wetting or de-wetting...
have been identified (Good and Van Oss, 1991): Lifshitz-Van der Waals (\(I^\text{LW}\)) and Lewis Acid-Base (\(I^\text{AB}\)). These two components can be used to explain cohesive and adhesive bonding interactions within the asphalt concrete specimen. Actually both cohesive and adhesive fracture and healing can and do occur. The cohesive fracture and healing is where the crack advances or heals in the binder or mastic region and the adhesive fracture is where the crack advances or heals at the aggregate interface. This discussion is limited to cohesive fracture, which is a significant portion. In fact we believe that most of the healing occurs in cohesive regions, between two mastic surfaces. This belief is based upon the relatively close match between the measured fracture surface energies and the calculated cohesive surface energies. Adhesive fracture can occur and a model of adhesive fracture has been proposed by Lytton et al. (1998). Surface energies of different aggregates were also measured as reported by Lytton et al. (1998), and the surface energy differences among different aggregate types were found to be great. The differences are overpowering when compared to the smaller differences among the various binders, even though the binders were selected based on their wide range of chemical property differences (e.g., amphoteric, aromatics and waxes).

Lifshitz-Van der Waals effects are the interactions of electron shells of neighboring molecules whereas the acid-base component is due to acid-base interactions among constituent molecules. The Lifshitz-Van der Waals effects are complex and related not only to weak secondary interactions such as London Van der Waal forces but also to positional and geometric hindrance effects. The acid-base effects generally dominate for asphalt-aggregate components and are important in the development of strong adhesive bonds that are resistant to the effects of water. The acid-base interaction component, in turn, consists of two components of its own: a Lewis acid parameter and a Lewis base parameter. The surface energies of the five bitumens were determined from the sum of the Lifshitz-Van der Waals component and the acid-base component.

Fracture and Healing Models Accounting for Surface Energy

The fundamental relation of cohesive fracture mechanics as stated by Schapery (1984) was derived from first principles of fracture:

\[
2\Gamma = E_R D_f(t_4) J_v
\]

where

- \(\Gamma\) = the surface energy density of a crack surface (units: FL\(^{-1}\));
- \(E_R\) = reference modulus (units: FL\(^2\)) used to make equation [4] dimensionally correct;
- \(D_f(t_4)\) = tensile creep compliance at time \(t_4\) that is required for a
crack to move through a distance which is the length of the process zone ahead of the crack tip (units: F·L²); and

\( J_n \)

the viscoelastic J-integral which is the change in dissipated PSE per unit of crack area from one tensile load cycle to the next (units: FL⁻¹);

\( F, L \)

appropriate consistent force and length units such as N and m.

It is an energy balance: the energy given up on the right-hand side of the equation is taken up by the newly created crack surfaces on the left-hand side of the equation. After expanding the first principles approach to healing speed, Schapery (1989) derived a relationship between healing speed, \( \dot{h}_r \), and several material properties including surface energy:

\[
\dot{h}_r = \frac{2\gamma_m E_R^2 D_{tc} \Gamma_n}{(1 - \nu^2) c^{1/m_c} H_v} \left[ \frac{1}{\beta} \right]^{\frac{1}{m_c}}
\]

Where:

- \( E_R \) = Reference Modulus, a constant derived of the stress transformation,
- \( \nu \) = Poisson's ratio,
- \( D_{tc} \) = Compressive creep compliance constant (D is assumed to equal zero),
- \( H_v \) = Healing Integral;
- \( \Gamma_n \) = Wetting surface energy;
- \( m_c \) = Creep compliance slope;
- \( c, \gamma_m \) = functions of \( m \) as defined in Schapery (1989), \( c \) varies between 1 and 1.5, and \( \gamma_m \) varies between 1 and 2/3 as \( m \) varies between 0 and 1; and
- \( \beta \) = size of the crack healing zone.

Lytton et al. (1998), on the other hand, used Schapery's fundamental fracture equation to postulate a direct parallel cohesive healing process as the reversal of fracture.
\[ \dot{h}_1 = \left[ \frac{(k_a) D_{1c} E_R H_v}{2 \Gamma_h} \right]^{\beta} \]  \hspace{1cm} [6]

Note this is an inverse of the relationship between healing rate and surface energy \( \Gamma_h \) and the healing integrals \( H_v \), from the relationship in equation [5]. \( k_a \) is a function of \( m \) with a value around 1/3.

Schapery’s healing model was developed for a linear, isotropic, viscoelastic material assuming interfacial forces of attraction and external or applied loading. This inclusion of surface forces is significant in that it accounts for the case where complete contact of the fractured surfaces is not initially achieved by loading, but rather the healing process is driven in significant part by the attractive forces on the fractured surface. This makes for a self-sustaining process available in some quantity to all systems, virtually regardless of the instantaneous loading regime. The surfaces in Schapery’s scheme are assumed to be “locally flat” but not necessarily so throughout the cracked regime. A key representation in Schapery’s equation of healing rate to the consideration of microcrack healing in asphalt mixtures is the direct relationship between surface energy and the rate of microfracture healing, i.e., a greater surface energy signifies a greater potential for healing, all other component remaining the same. It is also important to note that the form of equation [5] was developed by assuming that the \( D_0 \) component of the power law compliance is zero. If this were not so, then a more complex form for the healing rate equation will result.

Since the Lytton healing rate model was derived by analogy with the fracture laws, it results in a relationship where the healing speed is inversely related to the surface energy, which is seen as an inhibitor to the healing process. Viewed from a conservation of energy standpoint, the surface energy is an energy density required to close a given area of surface crack. The lower the surface energy density, the greater is the degree of healing that will proceed under otherwise equal conditions. Viewed in this manner, a higher surface energy density reduces the amount of crack surface that can be closed with the same amount of available pseudo-strain potential energy or applied loading. Lytton viewed surface energy not as acting as an attractive force between asphalt surfaces on either side of a crack face but as an impedance toward closure or reformation of the cracked surface.

**Unified Model of Fracture Healing**

Figure 5 presents the healing index for the five bitumens evaluated as a function of the
ordinal rest period (i.e., the number of sequential rest periods applied during the experiment). The healing indices in this plot are calculated as explained earlier based on PSE recovered following rest periods. As can be seen from the plot, two bitumens (AAD and AAB) respond with an appreciable immediate level of healing but with no apparent increase in healing throughout the experiment. On the other hand, bitumens AAF, AAG and AAM show a substantial increase in healing index with additional rest periods. A similar trend was noted when the healing index was plotted for the various bitumens against the length of a single rest period (Little et al., 1998), Figure 6. From this relationship it is apparent that some binders, for example AAM, continue to heal with the application of rest periods. The data in Figure 5 are averages of between six and nine samples for each point. The replicates demonstrate the repeatability of the trends. Conceptually one might imagine a fracture which partially heals during a rest period but which re-opens or re-fractures during the fatigue process. Although the fracture healing is not complete, the partial healing delays crack growth. The introduction of more rest periods at the same cracked surface seems to stimulate more of a healing response and hence a greater delay in fracture propagation leading to a greater fatigue life.

Kim et al. (1998) and Kim et al. (1997) substantiated the healing effect and the mechanism of immediate recovery of pseudo stiffness following a rest period. Figure 7 illustrates this quite vividly. In this figure, an immediate recovery is seen in the pseudo stiffness rate from B to A. Then as additional fatigue load cycles are introduced damage reoccurs at an accelerated rate A-B' until the same rate of damage (pseudo strain loss) occurs B' - D' as occurred prior to the rest period C - D. However, the resulting shift in fatigue life ($\Delta N_f$) is very meaningful in the fatigue process and the effects ($\Sigma \Delta N_f$) are additive as shown in Figure 8 which compares beam fatigue data with and without rest periods for a dense graded mixture containing bitumen AAM.

![Figure 5. Healing Index versus Ordinal Number of Rest Periods For Asphalt Bitumens Prepared With Selected Bitumens](image-url)
Figure 6. Effect of Rest Period Length and Temperature on Magnitudes of Healing for Dense Graded Mixes Containing Bitumen AAM.

Figure 7. Change in Pseudo Stiffness Before and After a Rest Period (After Kim et al., 1997).
The sampled healing index data were fitted to a general nonlinear model through nonlinear regression. A conceptual picture of the model is presented in Figure 9. The model consists of two slopes, \( h_1 \) which corresponds to short term healing which is rapidly realized in the asphalt mixtures and \( h_2 \) which is long term healing realized more slowly and throughout the test. Also included in the model is a spacing factor, \( h_0 \) (the maximum percent of healing that can be achieved by the short-term healing rate). The average healing indices calculated for each specimen per time increment were fitted to the model through a linear transformation. The resulting short and long-term slopes are as presented in Table 5.
Figure 9. Model of the HI versus Length of Rest Period in Terms of Short-Term Healing rate (\( \dot{h}_1 \)) and Long-Term Healing Rate (\( \dot{h}_2 \)).
Table 5. Constituents \( \hat{h}_1 \), \( \hat{h}_2 \), and Spacing Factor, \( h_p \), Used to Fit HI to Ordinal Number of Rest Periods Data Using Non-linear Model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bitumen</th>
<th>AAB-1</th>
<th>AAD-1</th>
<th>AAF-1</th>
<th>AAG-1</th>
<th>AAM-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{h}_1 )</td>
<td>0.02</td>
<td>0.00</td>
<td>0.15</td>
<td>0.12</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>( \hat{h}_2 )</td>
<td>0.27</td>
<td>0.17</td>
<td>0.32</td>
<td>0.46</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>( h_p )</td>
<td>0.04</td>
<td>0.03</td>
<td>0.17</td>
<td>0.05</td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

In the course of analyzing the measured healing data, it was discovered that the actual rate of healing, \( \frac{dh}{dt} \), is governed by two separate healing mechanisms, one of which is controlled by the non-polar (Lifschitz-Von der Waals) and the other is controlled by the polar (Lewis acid-base) components of the surface energy densities, \( \Gamma_{LW} \) and \( \Gamma_{AB} \), respectively. Both healing rates occur simultaneously and govern the actual healing rate according to the relation:

\[
\dot{h} = \dot{h}_2 + \frac{\dot{h}_1 - \dot{h}_2}{1 + \frac{\dot{h}_1 - \dot{h}_2}{h_p} (\Delta t)_n}
\]  

where

\( \dot{h}_1, \dot{h}_2 \) = the healing rates generated by the nonpolar (\( \Gamma_{LW} \)) and polar (\( \Gamma_{AB} \)) surface energies.
\[ \dot{h} = \text{the actual healing rate;} \]
\[ (\Delta t)_b = \text{the rest period between load applications;} \]
\[ h_p = \text{a factor that varies between 0 and 1 and represents the maximum degree of healing that can be achieved by the asphalt binder.} \]

The theories explaining the two healing rates were developed by Lytton in this project \((\dot{h}_1)\) and Schapery \((\dot{h}_2)\) in reference [1989]. The forms of these two theoretical relations are given above in Equation [6] for \((\dot{h}_1)\) and Equation [5] for \((\dot{h}_2)\).

The forms of these relations (equations 5 and 6) become more complicated when the glassy compressive compliance of the asphalt mixture, \(D_{\infty}\), is not zero. Because of their greater complexity, they will not be reported here.

A striking difference between the two formulations is in the ratio of the surface energy \(\Gamma\) to the healing integral \(H_w\). The early healing rate depends largely upon \(\dot{h}_1\), which, in turn, depends upon \(H_w/\Gamma_{LW}\). The long term healing rate slows down to approach \(\dot{h}_2\), which depends upon the ratio \(\Gamma_{\Lambda 0}/H_w\), the reciprocal of the healing rate governed by the nonpolar surface energy.

The empirical evidence of these relations comes from the healing index, HI, measurements (Williams et al, 1998). Although the healing index is a normalized, dimensionless number and is not directly based on the actual length of the zone that is healed, it is still an indication of the rate at which healing proceeds. The rates of change of healing index were determined by non-linear regression analysis. The relationship between \(\dot{h}_1\), the early healing index rate, and the nonpolar surface energy component, \(\Gamma^{w}\), is shown in Figure 10. The relationship between \(\dot{h}_2\), the long term healing rate, and the polar surface energy component \(\Gamma^{p}\), is shown in Figure 11. The two relations reveal the inverse and direct relations predicted by Equations [6] and [5], respectively.
Figure 10. Relation Between the Early Healing Index Rate, $h_1$, and the Nonpolar Surface Energy.

Figure 11. Relation Between the Long Term Healing Index Rate $h_2$, and the Polar Surface Energy.
The rate of crack healing per load cycle, \( \frac{dh}{dN} \), is given by an equation that is similar to equation [8], as shown below:

\[
\frac{dh}{dN} = \dot{h}_2(\Delta \Gamma)_h + \frac{(\dot{h}_1 - \dot{h}_2)(\Delta \Gamma)_h}{1 + \frac{\dot{h}_1 - \dot{h}_2}{h_p}(\Delta \Gamma)_h} \tag{8}
\]

The value of \( h_p \) was found empirically to depend upon the ratio of the surface energies, \( \frac{\Gamma_{pol}}{\Gamma_{nonpol}} \), the polar divided by the non-polar component. Figure 12 shows this empirical relation which suggests the possibility that maximum healing may be achieved by an asphalt binder with a surface energy ratio less than 0.5. The authors recognize that more data are required to establish a trend. This is only part of the picture, however, since it is certain that \( h_p \) must also depend upon the compliance of the asphalt mix. All of the relations suggest a very productive line of further inquiry into the healing properties.

Figure 12. Empirical Relation Between \( h_p \) and the Ratio \( \frac{\Gamma_{pol}}{\Gamma_{nonpol}} \).
In summary, the total healing rate is the result of the external energy contribution which is converted into the formation of the "closed surface". The rate at which this happens is the sum of two effects explained by Lytton and Schapery, respectively. Lytton's theory explains the resistance offered by the Lifshitz-Van der Waals component, and Schapery's theory explains the contribution to be expected from the polar interactions across the fracture surface and within the resulting mixture by polar forces and acid-base components. These two mechanisms act from the very beginning of the crack-face contact, but it is anticipated that the Lifshitz-Van der Waals component comes to equilibrium far sooner than does the acid-base component. This is the reason for the continuation of the long-range effect (slope $h_2$) after the additive effect of the short-range effects are taken into account.

An inverse relationship between Lifshitz-Van der Waals surface energy and healing, Figure 9, and a direct relationship between acid-base surface energy and healing, Figure 10, implies that the acid base component is favorable to healing whereas the LW component is not. The healing potential of a binder is thereby maximized if the acid-base component is maximized and the LW component is minimized. Statistical analysis of variance across the compositional matrices in Table 1 indicates significantly ($\alpha = 0.005$) that a low amphoteric content and a high aromatic content would exhibit higher acid-base surface energies and lower LW surface energies. This would promote better healing. Each of the bitumens studied exhibited greater LW components than acid-base components; and so, for this set of bitumens, it is also implied that a lower overall surface energy is beneficial to healing.

The interaction which promotes excellent cohesive healing is complex as is illustrated for the five bitumens studied here. Perhaps the best way to express the desired surface energy properties of a binder to promote good healing properties is a low total surface energy with a high acid-base component and a low Lifshitz-Van der Waals component.

**Effect of Miscellaneous Additives**

A surprising trend was encountered. The addition of two polymer systems, low density polyethylene (LDPE) and styrene butadiene styrene (SBS) reduced the healing ability of the two bitumens (AAD and AAM) evaluated. The addition of hydrated lime (HL) produced the same trend for bitumen AAM. However, HL actually improved the healing index of bitumen AAD. The addition of HL improved the healing indices of both aged bitumen systems (AAD and AAM) but improved AAD more than AAM.

The negative effect on the healing index of the addition of LDPE and SBS is not what was expected. However, it is logical that an additive can act as a filler system that interrupts the ability of the pure bitumen to re-establish contact and to heal. While the additive may actually
have a positive effect on fracture, it may inhibit healing. An explanation of the negative impact of the polymer additives on healing may rest in the effect of the polymer on the compositional make-up of the bitumen. Polymer networks in bitumens are swollen by the bitumen as the more compatible components of the bitumen are partially absorbed into the polymer causing it to swell. The rest of the bitumen is left with a higher asphaltene (highly interactive) component. The bitumen with a higher asphaltene concentration is less likely to flow and heal. The polymer additive may have a positive effect on retarding crack growth (e.g., crack-pinning) but a negative effect on healing.

The effect of HL, as summarized in Table 6, is perhaps the most interesting. The HL is much more effective in the AAD bitumen than in the AAM.

Table 6. Summary of Healing Indices for Mixture with Bitumens AAD and AAM.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Bitumen</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Healing Indices</td>
<td>Healing Indices</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AAD</td>
<td>AAM</td>
<td></td>
</tr>
<tr>
<td>Tank</td>
<td>0.23</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Aged</td>
<td>0.23</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>Tank - 12.5% Lime</td>
<td>0.28</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Tank - 20% Lime</td>
<td>0.30</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Aged - 12.5% Lime</td>
<td>0.34</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>Aged - 20% Lime</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

This is verified in dynamic shear rheometer (DSR) testing where HL also demonstrates a more compatible and effective interaction with AAD than with AAM. In the unaged systems, the effect of HL on AAM is to actually depress the healing index (from 0.52 to 0.30). When AAM is aged, the ultimate or maximum value of healing index diminishes from approximately 0.51 to 0.31. The addition of HL to the aged binder system is to slightly increase the ultimate healing index from about 0.31 for the aged control (unmodified) system to about 0.33 for the aged HL - modified AAM. The effect of HL on the aged AAD bitumens is quite pronounced. The HL significantly improves the healing index from about 0.23 for the aged system to about 0.34 for the aged AAD with 12.5% HL.

Thus, HL appears to be a physiochemically interactive additive which is bitumen specific in its effect on the rheological properties of the binder system and reduces the effect of aging and
inhibits the ability to diminish the healing protocol of the bitumen.

Based on the experimental results it appears that healing is favored by a bitumen that exhibits a “mobile polarity.” Polarity is defined as a high $\Gamma_{AB}$ value (together with a low $\Gamma_{AW}$ value). Mobility implies the ability to move or flow. As an illustration, consider AAM. This bitumen has a very low asphaltene content yet a relatively high $\Gamma_{AB}$ value. The low asphaltene component allows AAM to exhibit mobility in that it is not highly associated but well dispersed. Any alteration of AAM (by means of additives) reduced healing possibly because mobility is compromised through dilution or absorption of molecules within the polymer matrix which alters AAM’s polar mobility.

On the other hand, HL improves the healing of both aged bitumens (AAM and AAD) but AAD much more so than AAM. Perhaps HL’s interaction with the functionalities produced in the aging process (of AAD - a highly associated bitumen) may improve the “system’s” overall polar mobility.

FIELD EVALUATION OF TEST SECTIONS AT THE FHWA TURNER-FAIRBANK HIGHWAY RESEARCH CENTER

Selected Pavements

Four pavement sections were selected. These sections consisted of full factorial combinations of two thicknesses (102 mm and 204 mm) of two types of asphalt layers (AC 5 and AC 20) placed on a homogeneous and consistent subgrade prepared to a depth of 457 mm.

ALF Test Procedure

The ALF applies cyclic loading with a period of 10 seconds per cycle. The wheel on the ALF weighs 53.4 kN and is 318 mm wide with a tire pressure of 689.5 kPa. The position of the wheel was controlled to produce normally distributed wandering transversely to the direction of traffic. Wander was introduced in the loading sequence to minimize rutting and accentuate the distress mode of fatigue cracking. The pavements were subjected to repetitions of a group of loading cycles followed by a 24-hour rest period. During the ALF loading and rest periods, the pavement temperature was maintained at 20°C using a temperature control system associated with the ALF. This temperature control system along with other details regarding the ALF setup as well as details of the testing protocol are presented in Kim and Kim, (1997).

Surface wave tests were performed to determine the in situ stiffness of the pavements as a measure of damage during the ALF loading procedure. Surface wave measurements were recorded before any load was applied, immediately after each group of loading and at the end of the 24-hour rest periods.
Fatigue Damage Growth

In approximately 70% of the cases the phase velocity increased after the rest period. This increase may be attributed to relaxation, steric hardening or healing of microcracks. In this analysis no attempt was made to distinguish the proportional amount of healing due to each of these mechanisms. Instead all aspects were linked together and called microdamage healing. Kim points out in Williams et al., (1998) that work by Sias (1996) on beam fatigue testing as asphalt concrete samples subjected to rest periods follow a very similar trend to what is seen on the ALF sections.

In order to quantify healing in the ALF sections, another form of the healing index was used. In this case the healing index (HI) is defined as:

\[
HI (\%) = \frac{V_{after} - V_{before}}{V_{before}}
\]  

where

\[V_{before} = \text{phase velocity after completion of each loading group and}\]
\[V_{after} = \text{phase velocity after a 24-hour rest period.}\]

Figure 13 presents this form of the healing index at each position of the surface velocity measurement. Regardless of the pavement type, the trend is that a greater HI is recorded closer to the centerline of the tire path. This trend suggests that more fatigue damage results in a greater magnitude of microdamage healing. Because the location of the load was normally distributed, the probability that the wheel loads each point is as follows:

- Center (positions 1 and 5): 0.61
- 15.24 cm (position 2): 0.46
- 30.48 cm (position 3): 0.19
- 45.72 cm (position 4): 0.04
Position 2 is expected to coincide with the highest level of surface shear stresses as it is in the proximity of the edge of the tire. Since surface induced fatigue damage is highest under the edge or wall of the tire, it is consistent to see a greater opportunity for healing in the most fatigue damaged section of the loading path.

**US 70 in North Carolina**

Elastic moduli were determined from stress wave analysis for two pavements: US 70 in North Carolina and the MnRoad Project (Kim et al., 1997). Data captured over various times and temperatures on US 70 show that after a 24 hour rest period the elastic modulus is substantially higher than the modulus recorded before the 24 hour period. US 70 was subjected to considerable traffic before introduction of the 24 hour rest period and was hence damaged to some level by traffic.

The MnRoad project showed no changes in elastic modulus after a 36 hour rest period. The striking difference is that the MnRoad pavement had not been subjected to significant truck traffic and was hence essentially undamaged when the 36 hour rest period was introduced. This comparison seems to provide impressive evidence for the effect of microdamage healing on actual pavements.
CONCLUSIONS

Primary Experiment

1. The rate of fracture and the rate of healing have been described by Schapery (1998) from the first principles of fracture theory. The fundamental explanation relates asphalt component and mixture properties to fracture (i.e., surface energy of the bitumen and aggregate and mixture compliance). Lyttton et al, 1998, offers an alternative interpretation of healing based on Schapery’s fracture explanation. Both Schapery’s and Lyttton’s explanations of healing are based on first principles and relate fracture healing to surface energy of the bitumen and the aggregate and the compliance of the mixture. The primary experiment established the importance of surface energy of the bitumen to healing potential. A unified model of healing, which marries Schapery’s and Lyttton’s models was successfully used to explain how two components of surface energy (Lifshitz Van der Waals and acid-base) relate to healing.

2. Bitumens with high acid base surface energy components are better long-term healers than those with low acid base surface energy components. Therefore, it is good to have a bitumen with a high acid base surface energy component. Bitumens with high Lifshitz Van der Waals surface energy components inhibit short term healing. Therefore, it is good to have a bitumen with a low Lifshitz Van der Waals component of surface energy.

3. Based on the contrast-comparison statistical analysis of the primary experiment, bitumens with high aromatic content yet low amphoteric content possess the favorable surface energy components which promote good short and long term healing. AAM is an example of a good healer and is a highly aromatic bitumen; yet it has a very low asphaltene content. This may mean that bitumens with “mobile aromatics”, like AAM and AAG, are more amenable to healing than bitumens which are polar yet where the polarity is “immobilized” through a high, interactive asphaltene content, which is perhaps promoted by the presence of amphoteric. The effect of hydrated lime, which may interrupt the effect of highly polar and immobilizing molecules seems to support this hypothetical conclusion.

4. The quantification of healing via the healing index may be confounded by other effects such as molecular structuring, temperature build-up during cyclic loading and temperature dissipation during rest periods, plastic deformation during loading and stiffness differences among bitumens evaluated. Each of these factors was carefully considered in this study. Although these factors are important, they do not diminish
or replace the dominant effect of healing.

5. Testing from which the healing index was calculated was performed at temperatures between 20°C and 21°C. Back calculations of material properties using the micromechanics fracture and healing model (MFHM) developed by Lytton et al. (1998) demonstrates that damage at these temperatures is primarily due to microcrack development and growth and that recovery or healing is primarily due to microcrack healing. At temperatures above about 25°C, the MFHM proved that this was not the case and plastic deformation damage dominated. This leads to the conclusion that the healing discussed in this paper is dominated by recovery or healing at microcrack interfaces. The MFHM model, as noted in the text, uses easily measured continuum material properties. It promises better predictions of pavement performance and, by recognizing the most sensitive material properties will allow better roads to be built while making better use of the available supplies of bitumen.

Secondary Experiment

The secondary experiment was designed to evaluate the effects of mixture variables which might influence the type of fracture induced within the mixture and the rate of fracture and rate of healing within the mixture. From the general experiment, several conclusions were drawn as presented in the following paragraphs.

6. The research team felt that polymer modification would enhance microdamage healing as reflected in the healing index. However, the general trend with bitumens AAD and AAM was for the polymer additives (LDPE and SB copolymer) to diminish the effects of healing. Although this was surprising, it can possibly be explained if the polymer absorbs certain bitumen components which result in an enrichment of the remaining bitumen phase (perhaps with polar and interactive asphaltenes). This bitumen phase, enriched with polars and interactive molecules, may be less likely to flow and heal. In this sense the modified bitumen would behave similar to an aged bitumen. The LDPE does not normally interact significantly with bitumen through swelling. However, some swelling does occur and the LDPE bundles probably act as filler which applies significant steric hindrance which may well resist healing.

7. Hydrated lime (HL) can act as a filler in asphalt. It also has the ability to reduce the effects of oxidative aging. The effect of HL on the healing index when bitumen AAM was used was to diminish the healing index as the other additives did. However, the effect of adding HL to bitumen AAD was to enhance the healing
index. This seems to be a logical trend if one considers that the effect of adding hydrated lime to AAM (a highly aromatic bitumen with a very low asphaltene content) maybe to act as a filler or inclusion which may inhibit healing. On the other hand, the addition of HL to bitumen AAD (a highly associated bitumen and one with a high asphaltene fraction) may enhance the healing ability because the HL adsorbs or interacts with some of the more polar asphaltene fractions in the bitumen which may enhance flow and healing properties of AAD. Rheological tests carried out separately at Texas Transportation Institute show that HL is much more effective in altering the high temperature rheology of bitumen AAD when compared to bitumen AAM. Apparently, HL acts as a filler which may have a coupling effect with AAD through physico-chemical surface interactions. These interactions may work to promote resistance to high temperature flow and also enhance healing.

8. Aged AAD and AAM systems both benefit significantly in terms of healing capability by the addition of HL. Apparently, the HL offers a mechanism for both bitumens (albeit better for AAD than for AAM) to interact with oxidation products so that the effects of these oxidation products does not inhibit the ability to flow and heal.

Field Evidence of Microdamage Healing

9. Evidence of microdamage healing from field experiments was documented from surface wave testing performed on US 70 in North Carolina, the Turner-Fairbanks Accelerated Loading Facility in McLean, Virginia, and the MnRoad Project. The documentation of healing in these pavement tests is consistent with laboratory measured microdamage healing.

10. Healing of asphalt concrete pavements in the field is more difficult to measure than under controlled conditions but can be detected by stress wave tests. The fact that healing does occur and can be measured in the field during rest periods suggest that the performance and service life of the pavement will be increased if rest periods between design loads are longer.
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