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16. Abstract

Asphalt binders have an inherent ability to reverse damage in the form of micro-cracks that is caused due to the repeated action of external loads. This reversal occurs during rest periods between load cycles. The phenomenon of crack reversal is referred to as autogenous or self-healing. The main objective of this project was to apply established principles of healing to investigate a novel technique to accelerate reversal of accumulated micro-crack in asphalt mixtures. This technique was developed and evaluated using a laboratory scale set up. Laboratory tests were used to evaluate the impact of thermal treatment on the fatigue cracking life of asphalt mixtures. Results from this study indicate that for two out of the three different types of asphalt mixtures, intermittent application of the thermal treatment resulted in approximately 50% increase in the fatigue cracking life of the mixture.

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Laboratory Investigation of a Novel Method to Accelerate Healing in Asphalt Mixtures Using Thermal Treatment

by

Amit Bhasin

Atul Narayan

Dallas N. Little

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Southwest Region University Transportation Center

Center for Transportation Research

University of Texas at Austin

Austin, Texas 78712

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ABSTRACT

Asphalt binders have an inherent ability to reverse damage in the form of micro-cracks that is caused due to the repeated action of external loads. This reversal occurs during rest periods between load cycles. The phenomenon of crack reversal is referred to as autogenous or self-healing. The main objective of this project was to apply established principles of healing to investigate a novel technique to accelerate reversal of accumulated micro-crack in asphalt mixtures. This technique was developed and evaluated using a laboratory scale set up. Laboratory tests were used to evaluate the impact of thermal treatment on the fatigue cracking life of asphalt mixtures. Results from this study indicate that for two out of the three different types of asphalt mixtures, intermittent application of the thermal treatment resulted in approximately 50% increase in the fatigue cracking life of the mixture.

EXECUTIVE SUMMARY

The mechanical properties and performance of asphalt mixtures deteriorate due to the combined action of external loads, environment, and chemical changes within the asphalt binder that occur over time. The frequency and cost of pavement maintenance and rehabilitation is dictated by the frequency and extent of deterioration of asphalt mixtures in flexible pavements.

Asphalt binders used in the construction of flexible pavements have an inherent ability to reverse damage that occurs in the form of micro-cracks due to the repeated action of external loads. This reversal occurs during rest periods between loading cycles. The phenomenon of crack reversal is referred to as autogenous healing or self-healing. Fundamental research in the past has provided evidence and established mechanisms of self-healing in asphalt pavements. Autogenous healing that occurs during rest periods can be accelerated by increasing the temperature of the asphalt binder and/or applying stresses that facilitate closure of the microcracks.

The main objective of this project was to apply established principles of healing to investigate a novel technique to accelerate reversal of accumulated micro-crack in asphalt mixtures. This technique was developed and evaluated using a laboratory scale set up. Laboratory tests were used to evaluate the impact of thermal treatment on the fatigue cracking life of asphalt mixtures.

In this investigation, cylindrical asphalt concrete specimens were tested in tensile fatigue with and without rest periods. A group of test specimens were also subjected to thermal treatment by elevating the specimen temperature during rest periods. Results show that for two of the three asphalt mixtures, subjecting the specimens to a thermal treatment significantly improved the fatigue cracking life of asphalt mixtures. For the third asphalt mixture, researchers believe that improvement in the fatigue cracking life could be obtained by refining the temperature used for the thermal treatment.

The findings from this study provide proof of concept for the use of thermal treatment to carry out accelerated self-healing in asphalt mixtures and extend its serviceable life. It is recommended

that future studies focus on the optimal selection of temperature, influence of aging, and limited field trials to further develop this concept.

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Chapter 1. Introduction and Background

1.1 Introduction

The mechanical properties and performance of asphalt mixtures used in pavements deteriorate due to the combined action of external loads, environment, and chemical changes within the asphalt binder that occur over time. The economic impact of reducing pavement deterioration is evident from the fact that approximately $10 billion are spent every year for pavement maintenance.

Asphalt binders have an inherent ability to reverse damage caused by the formation of microcracks under external loads. This reversal occurs during rest periods between loading cycles. The phenomenon of crack reversal is referred to as autogenous healing or self-healing. Fundamental research in the past has: (a) provided evidence of healing in laboratory asphalt samples and in pavements, (b) established mechanisms of healing, and (c) reconciled differences in fatigue cracking performance in the laboratory vs. field performance. Furthermore, recent research has shown that, in certain types of asphalt binders, healing can promote an endurance limit effect, where fatigue damage does not manifest in the life of the pavement. Autogenous healing that occurs during rest periods can be accelerated by increasing the temperature of the asphalt binder and/or applying stresses that facilitate closure of the microcracks.

The main objective of this project was to apply established principles of healing to investigate a novel technique to accelerate reversal of accumulated microcrack in asphalt mixtures. This technique was developed and evaluated using a laboratory scale set up. Laboratory tests were used to evaluate the impact of thermal treatment on the fatigue cracking life of asphalt mixtures.

1.2 Background and Literature Review

Nucleation, coalition, and growth of microcracks due to the repeated action of external loads is the primary mechanism of failure due to fatigue cracking in asphalt pavements. Asphalt binders have the inherent ability to reverse the microcracks that are formed under the action of external loads. In order for the microcracks to reverse or heal, the asphalt mixture must be allowed to rest for a period of time at temperatures above its glass transition temperature.

Depending on the type of asphalt binder and the duration of the rest period between loads, healing can substantially offset the damage caused by the action of repeated loads. Little et al. (2001), Kim et al. (2003), Kim and Roque (2006), and Carpenter and Shen (2006) have used different methods to demonstrate the positive impact of healing that occurs during rest periods.

Williams et al. (2001) demonstrated this positive impact of healing using non-destructive evaluation methods. Previous research focused primarily on establishing evidence of healing during rest periods or explaining the role of healing in pavement life based on laboratory results. For example, the SHRP report by Lytton et al. (Lytton et al. 1993b) employs healing to explain, in part, the three to hundred fold increase in fatigue cracking life observed in field when compared to laboratory results.

Bhairampally et al. (2000) demonstrated that the inclusion of rest periods between compressive load cycles extended the time to tertiary damage and that this extension depended on the type of asphalt. Their work concluded that the transition from the secondary phase to the tertiary phase of dynamic compressive creep is related to development and growth of microcracks. Further work by Little and Masad (2006) has shown this to be true using computer assisted tomography. Bhairampally et al. (2000) also demonstrated that a filler (in this case, hydrated lime) successfully controlled the rate of damage in the compressive mode of loading because of crack pinning and also accentuated the effect of healing of microcracks in the mastic.

Lytton et al. (1993a) made one of the earliest attempts to incorporate healing in the evaluation of fatigue life of pavements based on material properties. Fatigue life determined in the laboratory, $N_{f(lab)}$, is typically multiplied by a shift factor, SF, in order to estimate fatigue performance of the mixtures in the field, $N_{f(field)}$, as follows:

$$N_{f(filed)} = N_{f(filed)} \text{ x SF} \tag{1}$$

Large variations in the value of shift factors have been reported in the literature. Lytton et al. proposed that healing of asphalt mixtures contributed to the shift factor. They also proposed that the total shift factor was a geometric combination of the shift factor due to healing, SF_h, shift factor due to residual stresses, SF_r, and shift factor due to dilation, SF_d, as follows:

$$\mathrm{SF} = \mathrm{SF}_h + \mathrm{SF}_r + \mathrm{SF}_d = \left[1 + a(t_r)^b\right] + \mathrm{SF}_r + \mathrm{SF}_d \tag{2}$$

where, the shift factor due to healing is expressed as a function of the rest period between load cycles recorded in seconds, and *a* and *b* are healing coefficient and exponent, respectively. This model was calibrated using laboratory and field data to obtain values of *a* and *b* for asphalt mixtures from different climatic zones. The shift factor for healing obtained from these parameters varied from 1.09 to 2.7 for a 30 second rest period. This approach demonstrated the importance of incorporating healing in prediction of pavement performance based on laboratory data.

Little, Lytton and co-workers (Little et al. 2001; Lytton et al. 2001) further improved the above methodology by determining the healing potential of individual asphalt binders using methods previously described. The measured healing potential was then used to represent the rate of healing in an asphalt binder as:

$$\frac{dh}{dN} = fn\left(t_r, h_1, h_2, h_\beta\right) \qquad (3)$$

where, t_r, is the rest period, and h_1, h_2, and h_β are the short term healing rate, long term healing rate, and maximum healing achieved by the binder, respectively. The three terms related to healing were found to be empirically correlated to the different surface free energy components of the asphalt binder. The rate of healing per load cycle, $\frac{dh}{dN}$, which is analogous to the rate of crack growth, $\frac{dc}{dN}$, allows one to include healing in the determination of fatigue cracking life of the material based on principles of fracture mechanics. The improvements in this methodology over the previous approach are:

1) the contribution of healing was incorporated in a fatigue cracking model based on principles of fracture mechanics instead of the use of a shift factor, and
2) the propensity of different asphalt binders to heal at different rates was accounted for by measuring the healing index of the binders individually in laboratory experiments.

Bhasin et al. (2009; 2008) demonstrate that healing in asphalt mixtures is a two step process. They proposed a model for healing that is based on the previous work done by Wool and O'Connor (1981) and Schapery (1989). This model represents healing as a convolution of wetting and intrinsic healing processes that occur across a crack interface. Mathematically, this is expressed as a convolution integral of the intrinsic healing function, $R_h(t)$, and the wetting distribution function, $\varphi(t, X)$, as follows:

$$R = \int_{\tau=-\alpha}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau)}{d\tau}d\tau \tag{4}$$

The process of the cracked surfaces coming into contact with each other is referred to as *wetting*. The rate of wetting is influenced by the mechanical properties of the material as well its surface free energy. The strength gained by a wetted crack interface over time is referred to as *intrinsic healing*. In this context the intrinsic strength gain, $R_h(t)$, can be defined as the ratio of a mechanical property of interest, for the volume enclosing the crack at time *t*, to the mechanical property of the intact material without damage.

The first step in the healing process, i.e., wetting of the two faces of a nano crack, is represented by a wetting distribution function φ (*t*, *X*) as described in the convolution integral (Equation 1). Schapery (1989) developed a relationship between the crack closing speed and material properties such as the work of cohesion and compliance parameters. Based on this relationship, the wetting distribution function or rate of wetting of a crack surface can be shown as follows:

$$\frac{d\phi(tX)}{dt} = \dot{a}_b = \beta\left[\frac{1}{D_1 k_m}\left\{\frac{\pi Wc}{4(1-\nu^2)\sigma_b^2\beta}D_0\right\}\right]^{-\frac{1}{m}} \tag{5}$$

In Equation 2, W_c is the work of cohesion; ν is the Poisson's ratio; σ_b represents the stresses at the crack surfaces; $\dot{a}_b$ is crack closing speed; *β* is the healing process zone; D_0, D_1, and *m* are creep compliance parameters which can be obtained by fitting $D(t) = D_0 + D_1t^m$; and k_m is a material constant that can be computed from *m*.

Bhasin et al. (2008) recommended a modified form of the Avrami equation for the intrinsic healing function. The parameters for this model could be determined using a simple DSR based. This modified form of the Avrami equation, shown below, introduces a constant, R_0. The constant is required to represent the instantaneous strength gain across wetted crack surfaces due to their interfacial work of cohesion.

$$R_h(t) = R_0 + p(1-e^{-qt^r}) \tag{6}$$

Equation (3) represents the sum effect of: i) instantaneous strength gain due to interfacial cohesion at the crack interface, represented by the parameter R_0 , and ii) time dependent strength gain due to inter-diffusion of molecules between the crack surfaces, represented by $p\left(1-e^{-qt^r}\right)$, where, p, q, and r are material related parameters that define the time dependent strength gain at the interface. The parameters q and r, represent the effect of healing that is due to the inter diffusion of molecules across the wetted crack interface. Values of these parameters are dictated by intrinsic material properties such as molecular weight and activation energy of diffusion. In addition, these parameters will depend on extrinsic properties such as pressure and temperature. Therefore, it is reasonable to hypothesize that increasing the temperature via a thermal treatment will significantly increase the rate of intrinsic healing and promote overall healing.

The rate of self-healing in asphalt mixtures depends on the type of asphalt binder and properties of the mixture. To this end, it is desirable to select materials that maximize the self-healing capabilities of the mixture. In addition to selection of materials with optimal healing properties, accelerated healing or accelerated reversal of accumulated microcrack damage in asphalt pavements may be achieved by briefly subjecting the pavement to elevated temperatures. A secondary benefit of subjecting asphalt mixtures to elevated temperatures after certain periods of time is that steric hardening within the asphalt binder is reversed. Therefore, application of thermo-mechanical treatment at periodic intervals can result in reversal or fatigue crack growth and extension of pavement life.

Chapter 2. Experiment Design

2.1 Research Approach

The main objective of this research was to evaluate whether or not it is possible to achieve accelerated healing in asphalt mixtures by means of thermal treatment. The main benefit of accelerated healing would be to partially reverse the cumulative fatigue damage that the sample would have accrued. This research is guided by the vision that, if successful, intermittent thermal treatments can be used as a form of preventive maintenance. The following is an overview of the research approach for this study.

A laboratory scale device was developed to apply thermal treatments to asphalt mixture specimens. The device encloses a six-inch tall asphalt mixture specimen with a four-inch diameter. This specimen is attached to a loading frame and subjected to direct tension loading to simulate fatigue crack growth. Thermal treatment, in the form of elevated temperature was applied to the specimens by stopping the test at specific intervals. The influence of the thermal treatments was evaluated using the increase in the mix's fatigue cracking life.

2.2 Mix Design and Specimen Fabrication

Initially, four different asphalt mixes were used for testing, each having a different asphalt binder. The five binders were obtained from the Strategic Highway Research Program (SHRP) – Materials Reference Library in Nevada. The SHRP designation for the selected binders was AAM-1, AAD-1, AAB-1, and AAF-1. Extensive information related to the physical and chemical properties of these binders, including healing characteristics, is available in the literature (Jones 1993). The design asphalt content was 4%. The same aggregate type was used for all four mixtures. Based on the literature review and hypothesis for the healing mechanism, the researchers believed that the type of asphalt binder was the most significant contributor to the healing in asphalt mixtures. Consequently, the most important factor in the experiment design was to include many different types of asphalt binders.

The mixes contained Type-C and Type-D aggregates and manufactured sand from Fordyce Aggregates. The mix with the AAM binder was dropped from the experiment design due to the limited availability of similar materials that would produce enough replicate specimens. A substitute filler was used with this mixture instead, so that there were enough specimens. However, this resulted in significantly different mixture properties.

The aggregates were separated into different fractions using standard sieves and then proportionally remixed to obtain a typical dense graded mix. The mix had insufficient amount of fines passing through #200 sieve, so fines were added from limestone screenings supplied by Colorado Materials, Inc. (Caldwell, TX). Figure 1 shows the aggregate gradation used for all the four mix designs. The optimum asphalt content was determined using the Superpave design method with a Superpave Gyratory Compactor (SGC) at 125 design gyrations and 4% air voids. The mixing and compaction temperatures used for each of the binders were obtained from ASTM D 4402, given in Table 1.

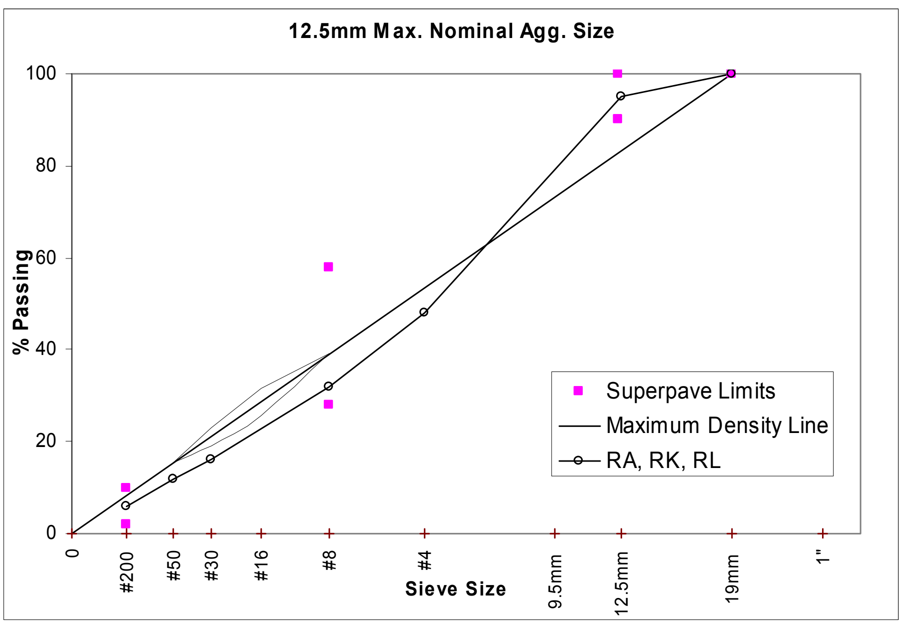

Figure 1. Aggregate Gradation for All Mixes.

Table 1: Mixing and Compaction Temperature

Asphalt Binder	Mixing Temperature (^{0}C)	Compaction Temperature (^{0}C)
AAB-1	146	120
AAD-1	140	125
AAF-1	148	124
AAM-1	160	133

The test specimens were prepared using the Superpave Gyratory Compactor (SGC) in a 101 mm diameter mold. The mechanical test was in the direct tension mode. Based on the literature, the minimum recommended aspect ratio (diameter : height) for samples subjected to direct tension tests is 1:2 (Chehab et al. 2000). Also, the minimum diameter of the cylindrical sample must be at least four times the size of the largest aggregate in the mix. Therefore, a test specimen with 75 mm diameter and 150 mm height was rationalized as appropriate. The finished test specimen was obtained by coring and sawing a 100 mm diameter and 175 mm high sample compacted using the SGC. The number of gyrations of the SGC was adjusted to achieve a target air void of 7±0.5% for the finished sample (after coring and sawing). Samples with air voids that did not fall in this range were discarded. Extreme care was exercised during sawing and coring operations to ensure proper sample geometry.

2.3 Mechanical Testing

The direct tension mode was selected to apply repeated loads since this mode most closely simulates the growth of fatigue cracks due to tension in an asphalt mixture specimen. To enable testing in direct tension mode, aluminum plates with fixtures that connect to the universal testing machine were glued to both ends of the sample using epoxy glue. Each sample was attached with three linear variable displacement transformers (LVDTs) with a maximum range of 1.8 mm to record permanent and resilient deformation. The LVDTs were mounted at a distance of 25 mm from either face of the sample with a total gauge length of 100 mm. Figure 2 (below) shows the set-up for conducting the tension tests, featuring a sample that failed in tension after a dynamic creep test.

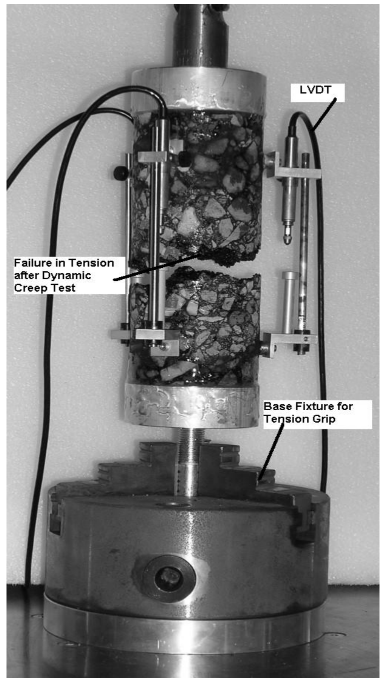

Figure 2. Test Set Up and Sample Failure for Dynamic Creep Test (Tension)

During the dynamic creep test in direct tension, the specimen was connected to the loading arm from the top and gripped using a mechanical chuck at the bottom via the aluminum end plates. Proper alignment of the sample was ensured during this process. The loading arm was continuously adjusted to ensure that the sample was not prestressed. A dynamic haversine loading was continuously applied at a high stress level until the sample failed in tension. In most cases, failure of the sample originated in the middle. Resilient strain and permanent deformation were continuously recorded during the test. The total number of cycles to failure was regarded as the fatigue cracking life of the mixture. Figures 3 and 4 show typical loading and response from the dynamic creep test in tension.

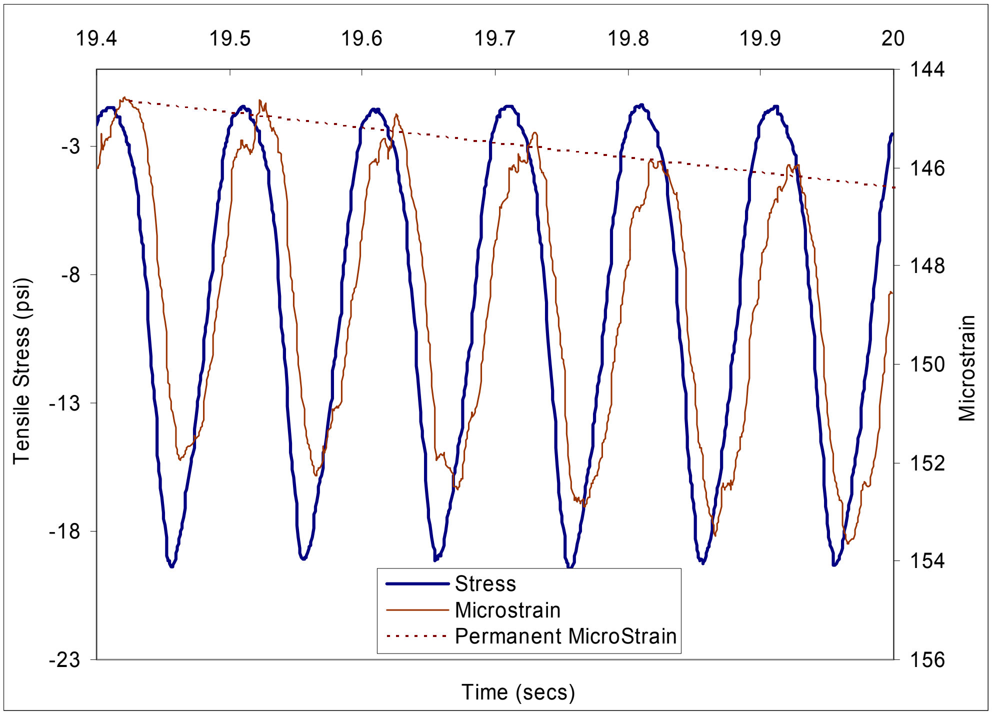

Figure 3. Typical Loading and Average Response from Dynamic Creep Test Without Rest Period

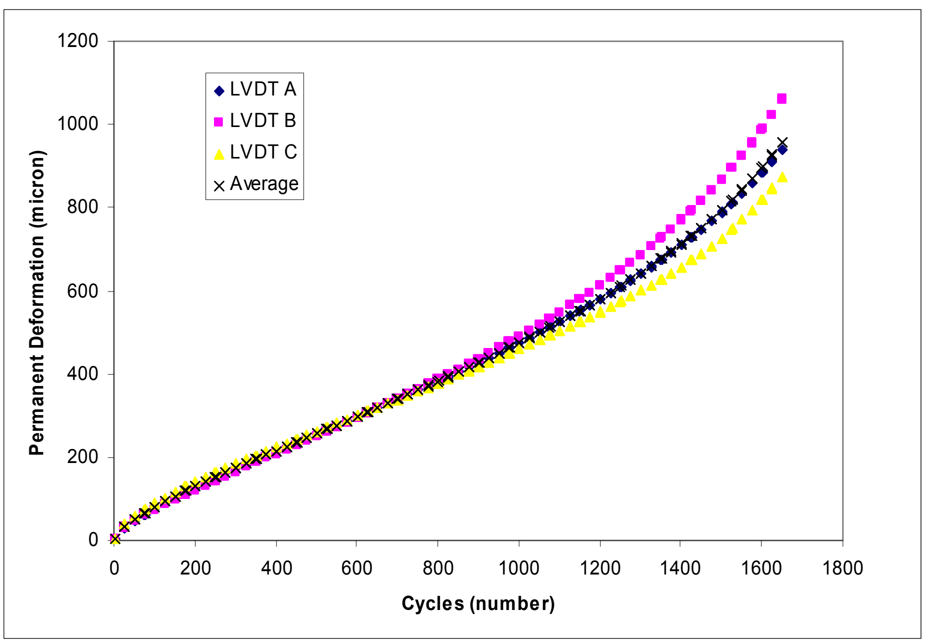

Figure 4. Curve Showing Accumulated Permanent Strain Versus Load Cycles

All the tests were performed using UTM-25, a universal testing machine from Industrial Process Controls, Ltd. This UTM has its own environmental chamber capable of maintaining temperature from -15° C to 60° C. The UTM-25 is capable of applying a tensile load up to 25 kN (Figure 5, below).

Figure 5. UTM-25 with the Environmental Chamber

2.4 Set-up for Applying Thermal Treatment

The environmental chamber was very large and took a significant amount of time to reach the desired elevated temperatures. Therefore, another insulated chamber with an attached electric heater was fabricated to apply thermal treatments. This chamber was designed to be large enough to accommodate the asphalt specimen but also small enough to heat quickly. The temperature inside this chamber was controlled using an Omega programmable temperature controller with a 10-segment ramp/soak program. The chamber was such that it would enclose the test specimen and use a convection to heat it to the desired temperature. Figure 6 (below) illustrates the test chamber with the programmable temperature controller.

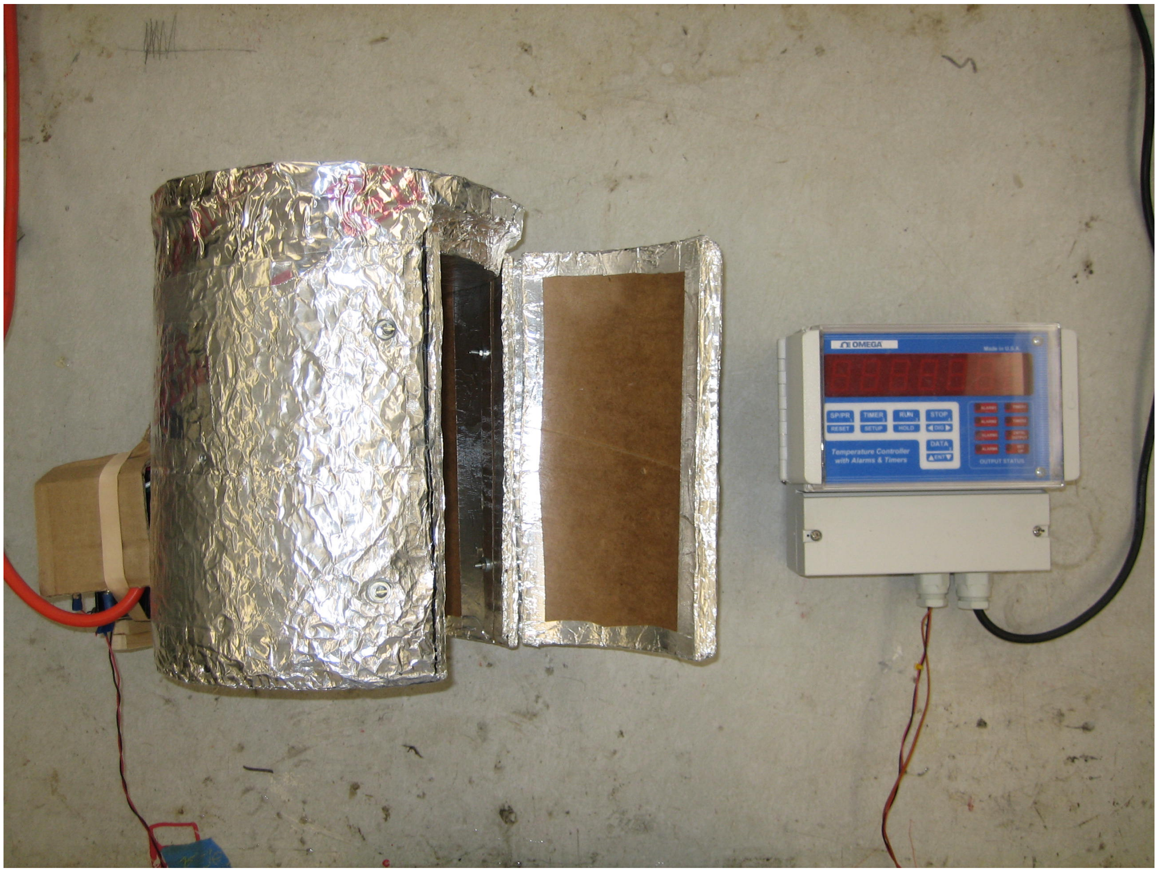

Figure 6. Chamber to Apply Thermal Treatment Directly to the Test Specimen

2.5 Test Protocol

Three different types of stress-controlled fatigue tests were conducted for each type of asphalt mix. In each of these three different types of tests, five asphalt specimens were tested to account for the variability. The three different types of tests and the rationale for conducting these tests are described below.

<u>Test Type 1</u>: The dynamic creep test in direct tension mode was conducted without any rest period at 22°C. This test was necessary to determine the fatigue cracking life of the asphalt

mixture as measured without any rest period. In other words, this is the fatigue cracking life of the mixture without any benefit from self-healing. The test was conducted by applying stress-controlled haversine loading with a frequency of 10 Hz. One or two trial specimens were used to determine the tensile stress amplitude such that the number of cycles to failure for that particular mixture was in the range of 45,000 to 60,000 cycles. This was important because very low stress levels could cause the test to run for a very long duration of time and very high stress levels would cause the specimens to fail in a few cycles increasing variability in the test results. This resulted in different stress amplitude for different mixtures. The objective of this study was not to compare the fatigue cracking performance of different mixtures but to evaluate the effect of thermal treatment on the fatigue cracking life of the same mixture. Therefore, the use of different stress levels for different mixtures was considered acceptable.

Test Type 2: The dynamic creep test in direct tension mode was conducted with intermediate rest periods. The test temperature and the temperature during the rest period were 22°C. The stress level for each mixture type was the same as that identified in the previous test type. For each mixture type, the rest period was applied after 50% of its average fatigue life (as measured without any rest period). For example, if the average fatigue life of the mixture was 60,000 cycles, then the rest period was applied after every 30,000 cycles. The duration of the rest period was one hour. After applying three rest periods, the specimen was then subjected to dynamic creep until failure without any further rest periods.

The rationale for conducting this test was as follows: Asphalt mixtures are known to regain strength due to self-healing even at temperatures of 22°C. Consequently, the test specimen would undergo self-healing irrespective of the application of thermal treatment. Therefore, it was necessary to determine the improvement in fatigue life of the mixture solely due to self-healing at the test temperature even when no thermal treatment is applied.

Test Type 3: This test was identical to test Type 2 with the only exception that the specimen was subjected to thermal treatment or elevated temperatures during the rest periods. Thermal treatment was achieved by raising the temperature in the inner chamber to 50°C at the start of the rest period using the programmable temperature controller. This temperature was then maintained for 20 minutes, after which heating was completely stopped. This was done to allow the temperature in the inner chamber reach that of the outer chamber, which in turn would allow rapid cooling of the specimen. Another 20 minutes of time was provided for cooling. In the remaining 20 minutes, the temperature of the inner chamber was again raised and held at 22°C prior to restarting the dynamic load application. The total rest period following this sequence was one hour. This temperature sequence was applied to several trial specimens prior to applying it to the test specimens. On the trial specimens, setting the inner chamber temperature to 50°C for 20 minutes resulted in an increase in the core temperature of the specimen to approximately 32°C. Also, the cooling sequence that followed resulted in the temperature at the core of the specimen to reach the test temperature of 22°C.

At the end of each type of test, data were collected from the UTM-25 controller and accompanying software. The most important metric of fatigue cracking in this case was the number of load cycles to failure of the specimen. Chapter 3 presents the results and discussion on the influence of thermal treatment.

Chapter 3. Results, Discussion and Recommendations for Future Work

3.1 Results

Table 2 presents the total number of load cycles to failure for the three asphalt mixtures along with the applied peak tensile stress. The results in Table 2 are based on an average of three to five replicate specimens. Results show that asphalt binders AAD-1 and AAF-1 exhibit considerable healing. The average fatigue life of the two asphalts increases 1.5 times during the one-hour rest periods. The average fatigue life approximately doubled when the thermal treatment was provided during this rest period. This shows that healing can be accelerated in asphalt pavements by applying the thermal treatment, and a significant fraction of the serviceable life of the pavement can be recovered. The mixtures with asphalt binder AAB-1 did not show any benefit of healing on the fatigue cracking life with or without the thermal treatment.

Table 2: Results

Type of asphalt	Applied stress (psi)	Number of cycles to failure		
		Test Type 1: Without rest periods	**Test Type 2: With rest periods but without heating**	**Test Type 3: With rest periods and heating**
AAD-1	35	57000	85000	122000
AAB-1	26.25	51000	48000	49000
AAF-1	35	66000	84000	135000

3.2 Discussion

The amount and rate of healing depend on several properties of the asphalt binder such as its healing potential, stiffness, and surface free energy. Healing also depends on the size of the cracks in the specimen. Size of the fatigue cracks dictates the distance of separation between the surfaces of the cracks; the greater the distance of separation, the lower the amount of healing. It also depends on the test conditions such as the temperature and the state of stress during the rest period.

Bhasin et al. (2008) have studied the effect of binder properties on the intrinsic healing of asphalt. They have used a dynamic shear rheometer to observe the amount of healing as a function of time when two surfaces of an asphalt binder are brought into contact. Their studies show that, when other things remain the same, AAD-1 exhibits the highest long-term healing followed by AAB-1 and AAF-1. However, this ranking is based only on the intrinsic healing properties of the binder. As discussed in Chapter 1, total healing in a mixture is a function of the wetting of crack surfaces and intrinsic healing properties of the binder. Therefore, considering the results from this study and the findings reported by Bhasin et al. (2008) one can speculate that AAB-1 performed poorly perhaps on account of its poor crack wetting characteristics. This explanation seems plausible when equation (5) is considered with the fact that at the test temperatures, the asphalt binder AAB-1 had a much higher stiffness as compared to asphalt binders AAD-1 and AAF-1 (Jones 1993).

3.3 Conclusion and Recommendations

In this investigation, cylindrical asphalt concrete specimens were tested in tensile fatigue with and without rest periods. A group of test specimens were also subjected to thermal treatment by elevating the specimen temperature during rest periods. Results show that for two of the three asphalt mixtures, subjecting the specimens to a thermal treatment approximately doubled the fatigue cracking life of asphalt mixtures. For the third asphalt mixture, it is speculated that the properties of the mix were such that it would not demonstrate significant amount of self-healing. Researchers believe that even for this mixture, some improvement in the fatigue cracking life would be evident if a higher temperature was used for the thermal treatment.

Researchers recommend that the use of thermal treatment to provide accelerated self-healing in asphalt mixtures and concomitant recovery of serviceable life be explored in more detail. Based on the experience from this research study, the following is a list of specific issues that need to be addressed in future research:

- Optimal selection of temperature for thermal treatment of the mixture based on the PG grade of the asphalt binder.

- Issues such as aging of asphalt binder during the thermal treatment process and its negative impact on performance, if any.
- Modeling the thermal properties of the asphalt binder to determine the realistic pavement thickness for which treatment can be beneficial.

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