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Evaluation of Self-Healing of Asphalt Concrete through Induction Heating and Metallic Fibers

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EVALUATION OF SELF-HEALING OF ASPHALT CONCRETE THROUGH INDUCTION HEATING AND METALLIC FIBERS

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
In partial fulfillment of the
requirements for the degree of
Master of Science in Civil Engineering

in

The Department of Civil and Environmental Engineering

by

Yashwanth Pamulapati

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ABSTRACT

Healing by means of induction heating is promising, however the effectiveness of this technology is yet to be demonstrated due to limited studies on cracking damage and fracture resistance property recoveries after healing. The objective of this study was to test the hypothesis that a new generation of asphaltic materials could be artificially healed while in-service by embedding metallic fibers in the mix and by applying a magnetic field at the surface.

To achieve this objective, an open-graded friction course (OGFC) was successfully designed and prepared to incorporate up to 5% steel and aluminum fibers by weight of the mix. Based on results of the study, it was found that the control mix and the mix prepared with aluminum fibers exhibited a greater ultimate load at failure prior to healing, than those specimens with steel fibers. Yet, differences were not statistically significant. The induction heating experiment was conducted successfully and showed the feasibility of inducing Eddy current in the metallic fibers without contact to the specimens.

After healing, the control mix displayed the highest ultimate load after healing, although unsuccessfully heated through Eddy current; yet neither were these differences statistically significant. These outcomes indicate that other healing mechanisms were present due to the recovery period, which allowed the control specimens to heal during the rest period. Healing efficiency showed the highest results for the control specimen that approached 85%. The healing efficiency for the specimen with aluminum and steel fibers was 72 and 62%, respectively. Microscopic image analysis demonstrated that induced cracks healed efficiently during the healing period.

Additionally, Loaded Wheel Track (LWT) test was conducted to analyze the rutting performance of the asphalt mixtures with steel and aluminum fibers. The results indicated that the mixture with a high percentage of steel fibers (5.0%) performed better than the ones with less content, while the mixtures with aluminum fibers did not perform well.

CHAPTER 1 INTRODUCTION

1.1 Background

One of the major distresses that directly affects the serviceability and quality of flexible pavements is cracking. Cracking appears at the pavement surface as longitudinal cracks and transverse cracks, as well as a combination of both that extends over the width of the pavement, thereby creating hazardous conditions for the road users. Water infiltration through the cracks may subsequently cause weakening and deterioration of the base and/or subgrade. Pavement distresses such as stripping in hot-mix asphalt [HMA] layers, loss of subgrade support, etc., are caused mainly through cracking.

Healing of asphaltic materials is an intrinsic property reported in the late 1960s, noticed to occur at high temperatures and with long rest periods between loads (Bazin et al. 1967 and Van Dijk et al. 1972). Furthermore, phenomenon such as binder thixotropy allows a time-dependent decrease in viscosity of the binder under shear and the recovery of viscosity when the flow is stopped. Healing was also used to explain the observed differences between laboratory and field fatigue performance (Carpenter et al. 2006). However, the micro-mechanisms responsible for healing were not clearly understood until the healing mechanisms were studied at different length scales in the last two decades (Palvadi et al. 2012).

While healing is an intrinsic property of asphalt binder, it is practically impossible to grasp the benefits of this characteristic in the field, as the flow of traffic is beyond the designer's control. Yet recent investigations attempted to accelerate the healing of asphaltic materials by adding conductive materials in the asphalt mixture. A number of studies conducted in Europe sought to acquire an advantage in induction heating by accelerating healing mechanisms in asphaltic materials (Qiu et al. 2011, Philips 1998).

Although Induction Heating (IH) approach appears promising, the effectiveness of healing through induction heating is yet to be demonstrated, since many influencing variables such as heating time, frequency of current, magnetic permeability, and depth of penetration may prevent the healing process to take place. Furthermore, limited studies have been conducted to study the recovery of cracking damage and fatigue resistance properties after healing, which may be used to assess the overall effectiveness of this approach.

This study explored a new paradigm to introduce a new class of asphaltic materials with the ability to self-repair, as well as to initiate damage restoration capabilities through induction heating. While this concept has been considered in recent years in Europe, it was one of the first attempts in the US (if not the first) to evaluate steel fibers heat-induction capabilities to heal asphaltic materials.

1.2 Problem Statement

Asphalt pavements are prone to cracking from many factors, such as traffic loadings and construction deficiency, as well as severe environmental conditions. Cracks are detrimental to pavements in many ways, by either weakening its mechanical properties, or by lowering durability by creating pathways for water to enter the structure, thereby accelerate both its deterioration and the need for repair. Cracking is also the main cause of many pavement distresses. Further, the rehabilitation of pavement damage caused by cracking failure is usually costly. Therefore, there is a critical need to evaluate and implement innovative technologies, which may enhance the cracking resistance of asphalt concrete.

This study will explore a promising, emerging technology that consists of using steel and aluminum fibers to induct heat in the mix, which in turn, allows the heated asphalt binder to flow and fill the cracks in the mix.

1.3 Objectives

The main objective of this study was to test the hypothesis that a new generation of asphaltic materials could be artificially healed while in-service by embedding metallic fibers in the mix and by applying a magnetic field at the surface. The secondary objective was to evaluate the influence of metallic fibers on rutting performance of the mixture.

1.4 Scope

To achieve the objectives of the study, laboratory tests were conducted to validate healing mechanisms through induction heating. Laboratory semi-circular specimens were prepared with varying contents of metallic fibers and were loaded monotonically to failure. Induction heating was then applied on the damaged specimens to stimulate healing mechanisms in the mix. By means of induction heating, the proposed self-healing mechanism utilizes the concept of Eddy currents and electrically-conductive fibers in order to generate a high temperature inside the composite material. The resulting high temperature would cause asphalt binder to flow and fill the cracks in the material. Healed specimens were then loaded to failure to assess whether a part of the load-carrying capacity was recovered. The study conducted a microscopic analysis on the laboratory specimens to assess healing of the cracks at the microscopic level. This study also utilized a Hamburg Loaded Wheel Track (LWT) test to evaluate the permanent deformation of OGFC mixtures.

1.5 Outline

This thesis is divided into five chapters. Chapter 2 presents a literature review on the principles of induction heating, induction heating applications to asphaltic materials, an evaluation of a self-healing mechanism through induction heating, and the use of the Hamburg LWT to measure the rutting performance of asphalt mixtures.

Chapter 3 describes the materials used and the methodologies adopted in the experimental program in order to evaluate the self-healing mechanism of asphalt mixtures. Additionally, this chapter also describes the methodology used to evaluate the laboratory rutting performance of the asphalt mixtures. Chapter 4 presents the test results, microscopic analysis, and the related statistical analysis of the test results. Finally, Chapter 5 summarizes and concludes this research work, as well as provides recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 Self-healing mechanism of asphalt binder

Healing of asphaltic materials represents an intrinsic property that was reported in the late 1960s, which was noticed to occur at high temperatures with long rest periods between loads (Bazin et al., 1967, Van Dijk et al., 1972), see Figure 2.1. Healing explains the observed differences between laboratory and field fatigue performances (Carpenter and Shen, 2006). However, the micro-mechanisms responsible for healing were not clearly understood until the healing mechanisms were studied at different length scales in the last two decades (Palvadi et al., 2012).

Figure 2.1 Crack healing process in asphalt concrete (Qiu et al., 2013)

Wool and O'Connor [1981] explained crack healing in polymers through five sequential stages, namely a) surface rearrangement, b) surface approach, c) wetting, d) diffusion, and e) randomization. A damaged polymer material with known mechanical properties was subjected to healing, relative to time (t_h), temperature (T_h), and pressure (P_h). Mechanical properties of both the healed material and virgin material were compared, using a dimensionless recovery ratio (R). Figure 2.2 presents a schematic model showing the five stages of healing on two random-coil chains on opposite crack surfaces. The healing mechanism was described, using a domain χ in a crack interface. The wetting distribution function ($\phi(t)$) was determined with respect to different types of damages in the polymer material, such as cracks, voids, crazes, etc. for three different cases, namely, initial wetting, constant rate wetting, and Gaussian wetting. A diffusion initiation function ($\psi(t)$) was introduced to prevent delay of healing rates; the intrinsic, healing function $R_h(t)$ equations for fractured stress, strain, and impact energy were derived by using a reputation model for healing. In addition, the convolution product of intrinsic healing function and wetting distribution function was used to determine the recovery ratio (R).

Equations affecting the mechanical properties during healing were derived at different conditions of χ , such as at $\chi < \chi^\infty$, $\chi = \chi^\infty$ and at χ^∞ (where, χ^∞ = complete recovery) to support the healing theory. The authors concluded that a diffusion stage contributes to the restoration of mechanical properties during healing; the recovery ratios obtained for strength, elongation, impact energy, etc., (which relate the material mechanical properties before and after healing) are function of time, temperature, pressure, molecular weight, and processing conditions.

Figure 2.2 Schematic diagram showing five stages of crack healing on opposite surfaces of two random coil chains (a) rearrangement, (b) surface approach, (c) wetting, (d) diffusion to a distance χ , (e) diffusion to a distance χ_{∞} and randomization (Wool and O'Connor, 1981)

Qiu et al. [2011] studied the healing properties of asphalt binder, using a two-piece healing (TPH) test together with the Dynamic Shear Rheometer (DSR). In this test setup, the study stimulated the crack healing process by pressing two asphalt pieces until the DSR gap closed. After the gap was closed, the increase in the complex shear modulus during healing time (rest period) was used to quantify the healing efficiency of the binder. It was observed that healing occurs in two healing phases – an initial phase and a time-dependent phase. Attempts were also made by Philips [1998] to describe the healing mechanisms in the asphalt binder by using a five-stage model that explains the healing process in terms of a) surface rearrangement, b) surface approach, c) wetting, d) diffusion, and e) randomization, similar to thermoplastic polymers. At the macro-level, a healing of asphalt concrete was quantified through an increase in

stiffness, as well as an improvement in the mixture's fatigue life when rest periods were used during laboratory testing (Kim, 1988).

Palvadi et al. [2012] studied the fatigue damage and healing characteristics of a fine-aggregate mix (FAM) by subjecting laboratory specimens to cyclic torsion, as well as different rest periods. The viscoelastic continuum damage (VECD) theory was used to quantify the healing efficiency in FAM mixes as a function of rest periods and the damage level. The amount of healing was quantified as a relative reduction in the healing parameter, S , based on the following equation:

$$\% \text{ Healing } (C, t) = \frac{(S_f - S_i)}{S_i} \times 100 \quad (1)$$

Where, C is the pseudo stiffness immediately before the rest period, t is the duration of the rest period, S_i is the internal state variable before the rest period, and S_f is the internal state variable after introducing the rest period. It is worth noting that healing can be confounded and confused with other spurious effects such as thixotropy, steric hardening, and viscoelastic short-term recovery of modulus (Santagata et al., 2013 and Shen and Lu, 2014). Further, thixotropy in asphalt binder was linked to the softening and decrease an observed stiffness during cyclic fatigue tests, as well as a recovery of stiffness during rest periods (Shan et al., 2011).

2.2 Principles of Induction Heating

Valery [2003] defined Induction Heating as the process of heating an electrically conductive material, using electromagnetic induction. This phenomenon is based on Eddy currents, generated when an alternating current is applied to a conductor such as copper wire, where magnetic field develops in and around the conductor, and vice versa (Hellier, 2013). The

benefits of induction heating are that a) the heating process occurs rapidly, and b) no contact is required with the surface; however, the depth of penetration usually drops quickly away from the surface.

Induction heating (IH) is a fast, efficient, and safe approach for warming conductive materials. The principle of the IH is similar to a transformer operation. An alternating current passes through a coil and generates an alternating magnetic field in the area around the coil. This varying magnetic field induces a voltage and consequently, a current in a secondary conductor. The conductor is an object that will be heated. As the alternating magnetic field induces voltage in the object, Eddy currents flow through the object, causing heat due to the resistance opposing the current. Hysteresis losses in ferromagnetic materials may also generate heat in the system, but this heat is negligible for non-ferromagnetic materials.

One of the main elements in induction heating is the inductor (coil) that generates the alternating magnetic field. A number of factors affect the magnetic field intensity and generated heat by the coil, inclusive of the number of turns, the enclosed area by the coil, and the coil operating frequency. Available methods of induction heating used in asphalt healing applications utilize high current bars and a copper coil that creates magnetic fields. In turn, the resultant, time-varying magnetic field induces voltage in small metal particles in the asphalt, and thus produces heat in the particles for healing purposes. This approach requires both high currents and long conducting bars in order to create a magnetic field strong enough for induction heating inside the asphalt.

By contrast, high frequency resonant convertors may be used to create high-frequency low currents in an inductor leading to a time-variable magnetic flux with the same frequency. Such a magnetic field can induce voltage in pieces of metal inside or in the close vicinity of the

inductor. The efficiency of induction heating and the amount of heat produced by this method rely on a well-tuned circuitry where the conductive elements (metal pieces in the asphalt) play a role. Moreover, the range of effectiveness of this method is small as opposed to the former method; thus the process can heat up pieces that either are very close or in the center of the heating coil (inductor).

2.3 Principles of Induction Heating to Asphaltic Materials

Liu et al [2010, 2011] and Garcia et al. [2011] demonstrated that when conductive asphalt concrete samples are heated electrically, the heat generated through the induction heating mechanism can influence the asphalt mastic resulting in a partial or complete healing of the damaged section of the mixture.

Figure 2.3 Principles of healing through induction heating (Liu et al., 2010, Liu et al., 2011, Garcia et al., 2011)

A review of the literature shows that researchers have focused mostly on evaluating the effects of steel fibers on the electrical resistivity and induction heating speed in porous asphalt concrete. Liu et al. [2010] demonstrated that induction heating may be used to heat conductive porous asphalt concrete. Steel wool of type 000 and steel fibers of type 1 were used in the porous asphalt concrete samples in order to make them electrically conductive (Liu et al., 2011). Effects of these fibers on electrical resistivity, indirect tensile strength (ITS), and induction heating were

tested on asphalt concrete samples with different volume of fibers. From the electrical resistivity test, the research concluded that the samples with a lower percentage of fibers showed higher resistivity, while the samples with steel wool type 000 showed a better conductivity. Results showed that the ITS value increased with the increase in fiber volume until attaining the optimum volume of fibers, after which the ITS value decrease, due to a reduction in asphalt mastic thickness, coupled with an increase in fibers. From the induction heating test, the authors have concluded that the induction heating temperature is related to both the electrical resistivity and the ITS values of the samples. Furthermore, the samples with an optimum fiber content, when coinciding with ITS and resistivity tests, show faster heating rates. Finally, the study concluded that induction heating increased the heating rate in conductive porous asphalt concrete, and that a 10% volume of steel wool type 000 was considered to be an optimum value for use in asphalt concrete samples in order to obtain superior results.

Garcia et al. [2011] studied the effectiveness of induction heating on an asphalt binder with different volumes of electrically conductive particles and sand-bitumen ratios. An induction heating test examined the effect of fiber volume content in the samples using steel wool, type 000 with diameters between 0.00635 mm and 0.00889 mm. The Gel-Permeation Chromatography (GPC) method was used to analyze the changes in molecular weight distribution of asphalt concrete samples, due to induction heating. The results from the induction heating test indicated that the mastic electrical conductivity increased with an increase in fiber volume content; however, the addition of more fibers after a certain point (where the temperature does not increase) did not affect the conductivity, see Figure 2.4. Furthermore, it was observed that addition of more fibers in the asphalt concrete could result in the formation of clusters. Results from chromatographic tests suggested that the induction heating did not change the

molecular weight distribution in the samples. Garcia et al. (2011) also evaluated healing effectiveness by breaking and healing the samples repeatedly at low and high temperatures. Results from the stress-strain curves before and after healing indicated the medium resistance of the samples to be about 90% of the original sample, and after five cycles of healing, 70% of the original resistance. Based on these results, the study concluded that an optimum volume of conductive fibers is extant in the mixture above or below that point where the electrical resistivity either remains constant or drops to that of a non-conductive material.

Figure 2.4 Maximum reachable temperatures at three different heating times for different volume of fibers (Garcia et al. 2011).

Garcia et al. [2012] used an Arrhenius equation, as well as equations derived from various induction heating mechanisms such as a) thermal capacity, b) thermal radiation, c) convection heat, and d) conduction heat to develop a model in order to study the induction heating times required to achieve complete healing of cracks in asphalt concrete:

$$C' = D \cdot B' (h) - A' T_{\text{air}}^4 - B' T_{\text{air}} \quad (2)$$

Where,

$$A' = \frac{\varepsilon \sigma A_r}{C_{th}}; B' = \frac{h_c A_r}{C_{th}}; D = \frac{\pi r^4 L \mu_m B_r \omega^2}{16 \rho C_{th}} - \frac{\varepsilon \sigma A_r T_{air}^4}{C_{th}} - \frac{h_c A_r T_{air}}{C_{th}}$$

By examining the parameters of the equation derived, the authors infer that parameters A' and B' depend on the intrinsic properties of the material, and parameter C' depends on the properties of the induction heating machine used, the electrical characteristics of the mixture, and the testing temperature. From these results, the research observed heat gains and heat losses are two main factors affecting induction heating of which heat gains tend to rely mainly on the radius of the fibers and on their volume in the mixture.

Garcia et al. [2009] conducted an experiment to evaluate the optimum volume of conductive fibers in the asphalt mixture. A porous asphalt mixture was used, together with steel wool of type 00 as conductive material in the mixture. Various samples with diameters of 100 mm and varying thickness between 60.62 and 66.45 mm were prepared, using three different modes, adding 2%, 4%, & 6% of fibers in the first preparation mode, while adding 4% fibers in the second and third preparation modes. The experiment prepared asphalt mixtures in the first mode with two different mixing times of 1.5 minutes with 3.5 minutes, and performed a second mode of preparation in a continuous asphalt plant in two ways; first, the conductive fibers were mixed with bitumen before adding the aggregates and second, the fibers were added to the asphalt mixture. In the third mode, fibers were premixed with bitumen, and the aggregates were added later. The study adopted these modes of preparation in order to validate the lab-compacted specimens and field-cored samples. An indirect tensile test conducted on the lab prepared samples indicated that fiber volume and mixing time do not affect the mechanical resistance of the asphalt mixture; the results were observed to be similar with plant-mixed and field-cored samples. The mixtures containing 2% steel fibers with 1.5 or 3.5 minutes of mixing time, as well

as 4% steel fibers with 3.5 minutes mixing time were observed to resist the development of clusters, as indicated by CT-scanning. The mixing time, length, and diameter of the fibers were concluded to have a significant effect on the clusters formation and temperature of induction heating in the asphalt mixtures.

Liu et al. [2013] evaluated the induction healing mechanism of steel-wool reinforced porous asphalt concrete using bending fracture tests on elastic foundation. Bending fracture tests were conducted on porous asphalt beams (50 x 50 x 450mm) prepared with 4% steel wool of type 00 and 5.2% bitumen by weight of the aggregates. The notched beam specimen was placed on an elastic foundation setup, developed in order to prevent permanent deformation during the test and thus close the cracks during unloading. The test procedure consisted of (1) fracturing of specimen at 5°C with a displacement loading speed of 50 mm/min; (2) heating of fractured specimen with induction heating; and (3) fracturing of healed beam on elastic foundation at the same displacement loading speed. A fatigue life extension test was conducted at different temperatures (30, 50, 70, 85, and 100°C) to investigate the effect of low, medium, and high temperatures on the healing rate; a higher healing rate was achieved at 85°C; however, further heating resulted in swelling and drainage problems. At this temperature, the asphalt concrete beam was observed to display the highest strength recovery. Figure 2.5 presents the strength recovery ratios at different healing temperatures. The authors observed that reheating the samples does not decrease the strength recovery characteristics of the mix; i.e., the mix can be reheated if cracks reappear. Furthermore, the cyclic fracturing-healing does not accumulate damage in the samples.

Figure 2.5 Strength recovery ratios at different healing temperatures (Liu et al. 2013)

Garcia et al. [2013] studied the effect of steel wool fibers on the porosity and electrical conductivity of dense asphalt concrete. A total of 25 different types of mixtures of same aggregates gradation and bitumen content were prepared using steel wool fibers (type 1, type 3, type 00, and type 000), with four different percentages (0%, 2%, 4%, and 6%), and with two different lengths (short fibers with average length of 2.5 mm and long fibers with an average length of 7 mm). The microstructure of asphalt concrete with the addition of different volumes and length of fibers was studied using X-ray microtomography. The authors observed that the length of fibers after compaction remained independent of the initial length, despite suffering both shear and tension stresses as well as impacts during the mixing and compaction process, see Figure 2.6. Fibers were observed to cluster during the initial phase of mixing and then grow with an increase in amount and decrease in diameter of the fibers. The authors observed no improvements in the flexural strength and particle loss of the asphalt mixture, due to the addition of steel wools. However, the addition of a higher percentage of fibers increased the air void content, which in turn increased the particle loss resistance of the asphalt mixture; yet, this

increase in particle loss resistance was no significantly higher than that of the mixture without steel wool fibers. As a result, the authors concluded that a uniform distribution of fibers on asphalt mixtures can be achieved if fibers of shorter length and larger diameter are used; an addition of 6% or higher volume of fibers with a minimum diameter of 0.15498 mm (type 3) also can be added for better distribution and to obtain higher induction heating rates.

Figure 2.6 Average length of fibers before and after mixing and compacting (Garcia et al. 2013)

2.4 Healing of cracks through Induction Heating

Garcia [2012] explained the self-heating behavior of asphalt mastic with conductive fibers using Arrhenius equation. The study calculated a required, apparent, activation energy by breaking and healing asphalt mastic beams at different temperatures; activation energy was calculated by using the time shown in complete recovery. Using steel wool of type 000 (7.5% by weight of the mixture) as conductive fibers, the test samples were subjected to a three-point bending to generate cracks crossing the specimen from the tip of the notch to the load application

point. The samples were then heated for a period of time, ranging from seconds to hours at different temperatures (15°C, 30°C, 40°C, 50°C, 70°C, 90°C, and 100°C). Finally, the samples were tested again under three-point bending to measure the resistance to failure. The healing level of asphalt mastic was quantified by a ratio of ultimate force of the beams before and after healing in the three-point bending test. CT-Scan test results, performed to observe the healing process, indicated that the healing of asphalt mastic initiates from the contact points of the cracked area, due to the capillary phenomena; healing was observed to be faster in deeply buried cracks. The healing rate of asphalt mastic was observed to increase with the increase in temperature; however, the mastic must be heated for a fixed time and above a certain temperature. A linear relationship was observed between the activation energy for capillary flow and the capillary diameter. The authors concluded that the Arrhenius equation may be used to predict the healing times of asphalt mastic at different temperatures.

Garcia et al. [2009] analyzed the conductivity of asphalt mastic with the addition of electrically conductive fillers and fibers, namely graphite and wool; steel wool of type 000 was used as conductive fiber, and graphite was used as a filler in the asphalt mortar. The behavior of asphalt mastic subjected to induction energy was investigated in more than 120 asphalt mortar specimens with different sand-bitumen ratios and volumes of conductive particles. Additionally, a 3D nano CT-scan reconstruction model technique investigated the distribution of electrically conductive materials. The authors concluded that the effect of both parameters, i.e., the sand-bitumen ratio and the volume of conductive particles, cannot be examined individually. There does exist an optimum volume of fibers in a sand-bitumen ratio for each mix, above or below a point where the resistivity increases, which in turn decreases the conductivity of asphalt mortar. Figure 2.7 presents the electrical conductivity surface of asphalt mortar, depending on both the

sand-bitumen ratio and the total volume of conductive additives. Three samples were prepared with different volumes of fibers and fixed sand-bitumen ratios in order to validate the electrical conductivity; the authors concluded that every mix should be separately analyzed by a) increasing the volume of fibers to obtain optimum conductivity, and by b) adding small proportions of filler to stabilize the resistivity. The sand-bitumen ratio was discovered to be the key design factor of the conductive mixtures; for each sand-bitumen ratio, there exists an optimum volume of conductive fillers, above which the fibers begin to cluster in the mixture, and below which the mixture becomes non-conductive.

Figure 2.7 Electrical conductivity surface of asphalt mastic against the sand-bitumen ratio and the total volume of conductive additives (Garcia et al. 2009)

2.5 Loaded Wheel Tracking (LWT) test applications on asphalt mixtures

Mohammad et al. [2007] evaluated the performance of HMA mixtures, based on laboratory tests and prediction models. Thirteen HMA mixtures were prepared with various mix designs for different volumes of road as per the LADOTD specifications for Roads and Bridges.

Performance tests such as a) dynamic modulus, b) flow time/static creep test, c) flow number, and d) Hamburg-type loaded wheel tracking (LWT) tests were conducted on these mixtures.

Figure 2.8 shows the rut depths at 20,000 passes, as evaluated from the LWT test for the 13 mixtures. The study observed that almost all of the mixtures performed well with a rut depth less than 6.0 mm, which satisfied LADOTD specifications, with the exception of two mixtures with rut depths of more than 10mm. Furthermore, statistical analysis was conducted on all the performance test results. The resulting conclusion revealed that the general ranking of mixes from LWT test were marginally different in comparison to the other tests.

Figure 2.8 Hamburg-type loaded wheel tracking test results – rut depth at 20,000 passes (Mohammad et al. 2007)

In a study on the use of bio-binder technologies in asphalt mixtures, Mohammad et al. [2013] prepared different mixtures with various contents of bio-binder, and compared the results with a mixture prepared with unmodified binder. Laboratory tests such as the Hamburg loaded-wheel test, the modified Lottman test, the semi-circular bending (SCB) test, and the thermal stress restrained specimen (TSRST) test were conducted to evaluate the rutting performance, moisture resistance, and fracture resistance of the prepared mixtures. The rutting performance of

the mix was assessed using a Hamburg-type Loaded Wheel Tester (LWT). A T-test was conducted to compare the modified mixtures to the one with a conventional mixture. Figure 2.9 shows the rut depth after 20,000 passes for each mixture, together with the associated statistical grouping. The conclusion was that mixtures prepared with PG 67-22 and PG 76-22 binder show a significant improvement in rut depths with the addition of green asphalt binder.

Figure 2.9 Loaded wheel tester results (Mohammad et al. 2013)

Kim et al. [2013] compared laboratory-measured rutting performance indicators (such as Rut Factor (RF), Flow number (Fn), and) rut depth) to the measured field rutting behaviors of 15 Louisiana asphalt pavement sections. This research was conducted over eight field projects, together with various sections from each location. Twenty different asphalt mixtures were prepared with different binders and altered reclaimed asphalt pavements (RAP). The rut depth was calculated using the Hamburg Loaded Wheel Tester (LWT) test for all the mixtures, and then compared to the field rutting performance of the pavement sections estimated after 20 years of service life. Ranking and quantitative analysis were performed on the projected field rutting behaviors. The conclusion was that a strong correlation exists between field and LWT rut depths.

Cooper et al. [2014] evaluated laboratory performance of asphalt mixtures containing recycled asphalt shingles (RAS) including stone-mastic asphalt (SMA). The study utilized the LWT test on the mixtures to evaluate the resistance to permanent deformation and moisture susceptibility. Three asphalt mixtures, containing two different types of RAS (PCWS and MWS) and SMA, were compared to the conventional mixture. Furthermore, the research conducted a statistical analysis to evaluate the results. Figure 2.10 shows the average permanent deformation depth for the asphalt mixtures tested. Results showed that the average rut depths were below the 6.0 mm rutting depth threshold used in Louisiana. Furthermore, the study concluded that the addition of RAS to the mixtures showed a better rutting performance.

Figure 2.10 Rut depth vs. asphalt mixture types (Cooper et al. 2014)

In a research conducted by Kabir et al. [2012], Louisiana OGFC mixtures were evaluated based on their laboratory and field performances. In order to capture the rutting potential and moisture susceptibility of OGFC mixtures, a Hamburg LWT test was conducted on the mixtures. The asphalt mixtures were designed using high grade asphalt cement with grade PG 76-22m for

US 71, I-20, and US 171 projects. Cellulose fibers were used not only to prevent a drain-down of asphalt cement, but also to produce an improved reinforcement against rutting and cracking.

Results from the LWT test indicated that the laboratory specimens for US 71 and US 61 test sections performed better with less rut depths, whereas laboratory specimens for US 171 showed a drastic increase in rut depths and specimens failed after 5300 passes of loaded wheel. However, the conclusion presented that even though specimens failed to pass LWT specification requirements during the lab test for US 171, the mixture design showed a comparable rut resistance in the field.

CHAPTER 3 METHODOLOGY

3.1 Identification and characterization of steel fibers suitable for use in asphalt concrete

The objective of this task was to explore different types of steel fibers that could be used in the preparation of self-healing asphalt concrete. To achieve this objective, a review of the literature review was conducted to identify previously-used steel fibers in the preparation of self-healing asphalt concrete specimens. Steel fibers are available in various grades and sizes varying from 0.001 to 0.02 in. In addition to steel fibers, this study evaluated the use of aluminum as an induction healing agent. As necessary, the collected fibers were ground to powder-size, which would allow the additive to uniformly blend in the mix, see Figure 3.1.

Figure 3.1 Processing of steel and aluminum pieces before mix preparation

3.2 Preparation and characterization of asphalt concrete specimens

The objective of this task was to design and to prepare asphalt concrete specimens with varying contents of metallic fibers. Porous asphalt concrete was selected as the mix design of choice in the experimental program since it often exhibits durability and raveling problems. OGFC mixtures contain large amount of coarse aggregate and small proportion of fine aggregate creating high percentage of air voids. Because of the high air void content in the mixture, OGFC provides numerous benefits when compared to regular dense graded mixes (Putman 2012, King et al. 2013):

- a) Minimize the hydroplaning potential during heavy rainfall;
- b) Reduce vehicle splash and spray behind vehicles;
- c) Improve visibility and wet skid resistance;
- d) Reduce traffic noise emission;
- e) Reduce urban heat island effect.

Although it offers numerous advantages over conventional mixtures, pavements constructed with OGFC mixtures often experience premature distresses such as cracking, raveling, and clogging of air voids, etc. Hence, durability of OGFC mixtures need to be improved. In this study, a new class of asphaltic materials was evaluated, which has the capabilities to self-heal under induction heating with the addition of conductive fibers such as steel or aluminum.

3.2.2 Mix Design

Mix design was prepared in accordance to ASTM D 7064/D 7064M-08 “Standard practice for Open-Graded Friction Course (OGFC) Mix Design.” A mix design commonly used

in Louisiana for OGFC was selected and modified to incorporate metallic fiber contents ranging from 2.5 to 5.0% by weight of the mix. There were three primary components in the mix design: material selection, selection of aggregate gradation, and determining the optimum binder content. Limestone and granite were selected as coarse aggregate along with manufactured sand as fine aggregate. Polymer modified PG 76-22 was selected along with the addition of cellulose fibers to reduce draindown of binder in the mixture; cellulose fibers were added at a rate of 0.2% by weight of the mix. A Superpave gyratory compactor was used to prepare specimens to meet requirements. A description of the measured Volumetrics are described in Table 3.1. A CoreLok testing device was used to measure the bulk specific gravity of compacted asphalt mixture specimens.

Table 3.1 Description of measured volumetrics

Specimen	% AC	G _{sb}	G _{mm}	G _{mb}	V _a	VMA	VFA
Avg	6.5	2.658	2.436	2.044	16.1	28.2	42.9
1	6.5	2.658	2.436	2.014	17.3	29.2	40.7
2	6.5	2.658	2.436	2.062	15.4	27.5	44.3
3	6.5	2.658	2.436	2.056	15.6	27.8	43.8

Figure 3.2 provides a graphical representation of the blended aggregate gradations used in the study.

Figure 3.2 Aggregate gradation curve

To evaluate the distribution of steel fibers, particle-size analysis was conducted in accordance with ASTM D 422-63, Standard Test Method for Particle-Size Analysis of Soils. Table 3.2 presents the particle size distribution of the steel fibers. This gradation was used in alternating the aggregate proportions in the asphalt mixtures with different percentage of fibers.

Table 3.2 Particle Size Distribution for Steel Fibers

Sieve Number	Sieve, mm	Sieve, in	% Passing
3"	75.0	3.0	100.0
2"	50.0	2.0	100.0
1-1/2"	38.1	1.5	100.0
1.25	31.8	1.25	100.0
1"	25.0	1.0	100.0
3/4"	19.0	0.75	100.0
1/2"	12.5	0.5	100.0
#4	4.75	0.187	100.0
#10	2.00	0.0787	100.0
#40	0.43	0.0165	34.9
#200	0.08	0.003	9.6

3.2.3 Job-Mix Formula

Table 3.3 presents the job mix formula for the prepared OGFC mixes. As shown in this table, the binder content was kept constant in all mixes while a slight reduction in fine content was necessary to accommodate the metallic fibers content in the mix. Corelok was used to measure the bulk specific gravity of the prepared specimens. The air voids content was slightly below the target air voids for OGFC, which usually ranges from 18 to 24%. However, it was comparable between the different mixes. The AC content met the minimum requirement of 6.5% for this type of mix.

Table 3.3 Description of the Job Mix Formula

Parameter	Mixture ID			
	76CO	76Fe2.5%	76Fe5.0%	76A15.0%
G _{mm}	2.436	2.436	2.436	2.436
G _{mb}	2.039	2.014	2.021	2.002
V _a [%]	16.3	17.4	17.1	17.8
Total %AC	6.5	6.5	6.5	6.5
19.0 mm	100	100	100	100
12.5 mm	93	93	93	93
9.5 mm	71	72	72	72
4.75 mm	18	19	20	20
2.36 mm	10	11	12	12
1.18 mm	9	10	11	11
0.600 mm	8	10	11	11
0.300 mm	7	7	6	6
0.150 mm	5	5	6	6
0.075 mm	4.1	3.8	3.5	3.7

Table 3.4 presents a description of the specimens prepared for this study. Two specimens of each mix type were prepared to minimize variability in the test results. To identify the fiber distribution in the specimen, a cylindrical sample was cut in half and trimmed along the flat base of the specimen. The distribution of steel fibers inside a test specimen is shown in Figure 3.3.

Table 3.4 Description of the Evaluated Mixes

Mixture ID	Description
76CO	Conventional OGFC mixture with Polymer-Modified PG 76-22
76Fe2.5	OGFC mixture with PG 76-22 and 2.5% steel fibers
76Fe5.0	OGFC mixture with PG 76-22 and 5% steel fibers
76Al5.0	OGFC mixture with PG 76-22 and 5.0% aluminum

Figure 3.3 Distribution of metallic fibers inside a test specimen

3.3 Testing and characterizing the microscopic properties of the prepared blends

The objective of this task was to load the prepared specimens until failure and to characterize the microscopic properties of the prepared asphalt concrete specimens in the cracked areas. Cracking potential of the prepared mixes was assessed using semi-circular unnotched specimens. The semi-circular specimens were loaded monotonically up to the fracture point under a constant, cross-head deformation rate of 0.5 mm/min in a three-point bending load configuration, see Figure 3.4(a). Test temperature was selected to be 25°C. A microscopic analysis was conducted using light microscopy (Zeiss SteREO Lumar. V12 microscope) in order to assess the cracking patterns in the specimen after failure. Figure 3.4 illustrates the test stages carried out in the microscopic analysis of the test specimens.

Figure 3.4 Microscopic visualization of the surface cracks on asphalt concrete test specimen ((a) Specimen subjected to load for fracture, (b) cracked surface of the specimen, (c) Microscopy visualization, and (d) Analysis of cracks

3.4 Stimulate healing mechanisms through Induction Heating

The objective of this task was to stimulate and characterize the self-healing capabilities of asphalt concrete test specimens with or without metallic fibers. A specially-designed, single position, multi-turn helical coil was built to generate the required heating for the application and is installed to the induction system, see Figure 3.5 (a). Initial tests were conducted to optimize the power delivered to the samples in order to reach the desired temperature, by monitoring the time required to heat the specimen to a temperature of 110°C.

Figure 3.5 Induction-heating heating experiment for cracked test specimens

Due to the varying contents of metallic fibers, high content specimens heated relatively quickly compared to specimens with low to no metallic fibers. The coil was set in a horizontal position with the specimen set inside, resting on a thermo-resistive plate. The temperature of the specimen was monitored by means of an Infra-Red (IR) camera throughout the duration of the induction experiment, see Figure 3.5 (b). After heating, the specimens were characterized once more using microscopic analysis and were then loaded to failure in order to predict the healing

efficiency of the prepared mixes, as well as to evaluate whether the specimens had recovered a portion of their fracture resistance through induction heating and other healing mechanisms.

3.5 Hamburg Loaded Wheel Tracking (LWT) test

To determine the rutting characteristics of the OGFC mixtures considered in this study, a Hamburg LWT test was conducted in accordance with AASHTO T 324-04 “Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA).” This test consists of rolling a 703 N steel wheel across the surface of specimens submerged in 50°C water. Linear Variable Displacement Transducers (LVDTs) were used to measure the permanent deformation; data is collected and recorded continuously throughout the test.

Figure 3.6 Hamburg Loaded Wheel Tracking (LWT) test sequence

CHAPTER 4 DISCUSSION OF TEST RESULTS

4.1 Fracture Resistance of Laboratory Specimens

Figure 4.1 illustrates typical test results from the fracture resistance test for the control mix and the mix with 5% steel fibers. As shown in this figure, the vertical load applied to the sample gradually increased as the displacement, controlled through the actuator, progressively increased. The specimen resisted the applied displacement up to the fracture point and then started to fail; afterward, the required load to induce the controlled displacement gradually decreased until total failure of the specimen was reached. To assist in the analysis of the data, polynomial models were fitted to the measurements, see Figure 4.1a. While there was no practical use for these models, the models allowed reducing fluctuation in the measurements and noises in the raw data. The coefficients of determination for these models were greater than 0.9 for all cases.

(a)

(b)

Figure 4.1 Typical Test Results from the Fracture Resistance Test for (a) Control and (b) Mix with 5% Steel Fibers

Table 4.1 presents the ultimate load and associated displacement for the different mixes evaluated in this study. Repeatability of the measurements was acceptable, with a coefficient of variation (COV) ranging from 4.8 to 13.2% with an average of 8.0%.

Table 4.1 Fracture Resistance Test Results before Healing

Mix ID	Specimen ID	P_{ult} (lb.)	Average P_{ult} (lb.)	Displacement (δ_{ult}) at P_{ult} (in.)	Average δ_{ult} (in.)
76CO	1	230.3	210.6	0.1267	0.1422
	2	190.9		0.1577	
76Fe2.5%	1	181.0	170.3	0.1993	0.1994
	2	159.6		0.1995	
76Fe5.0%	1	174.4	181.8	0.1340	0.1233
	2	189.2		0.1126	
76Al5.0%	1	222.1	214.7	0.1230	0.1219
	2	207.3		0.1207	

Figure 4.2 illustrates a comparison of the mean ultimate load for the conventional and mixes with metallic fibers prior to healing. As shown in this figure, the control mix (76CO) and the mix prepared with aluminum (76Al5.0%) exhibited greater ultimate load at failure than the specimens prepared with steel fibers.

Figure 4.2 Fracture Resistance Test Results prior to Healing

4.2 Healing through Induction Heating

Laboratory specimens were subjected to induction heating until the specimens reached a surface temperature of 110°C (230°F). Induction heating experiments were conducted at the Ambrell Corporation in New York. In this experiment, an alternating current was passed through a coil to generate an alternating magnetic field in the area around the coil. This varying magnetic field induced a voltage and consequently current in the metallic fibers inside the specimen. As the alternating magnetic field induced voltage in the specimen, Eddy currents flowing through the metallic fibers caused heat, due to the resistance opposing the current.

Figure 4.3 compares the thermal profiles of three specimens: the control specimen containing no metallic fibers, the second specimen containing steel fibers (5.0%), and the third specimen prepared with 5.0% aluminum fibers. As shown in this figure, the control specimen did not heat throughout the experiment while kept under a magnetic field for 35 minutes, see Figure 4.3(a). In contrast, the specimen with 5.0% steel fibers reached the target temperature after only 10 minutes, while the specimen with 5.0% aluminum fibers took 20 minutes to reach the target temperature, see Figure 4.3(b and c).

(a) 76CO

(b) 76Fe5.0

Figure 4.3 Thermal Profiles of Laboratory Specimens under Induction Heating

Table 4.2 presents the required heating time for each laboratory specimen to reach a temperature of 110°C. The temperature measuring interval was set at five minutes in the experiment, which explains why the specimens with 2.5 and 5.0% steel fibers required a comparable induction heating time in order to reach 110°C. It was observed that while the specimens with aluminum were successfully heated, they required a longer heating time to reach 110°C. This may be due to the fact that the electrical resistivity of aluminum is $2.65 \times 10^{-8} \Omega \cdot m$ at 20°C, while the electrical resistivity of steel is $76.0 \times 10^{-8} \Omega \cdot m$, which would allow a faster heating of the specimen at the same fiber content.

Table 4.2 Laboratory Induction Heating Time to Reach Target Temperature

Mix ID	Specimen ID	Induction Time (minutes)
76CO	1	Did not heat
	2	Did not heat
76Fe2.5	1	10
	2	10
76Fe5.0	1	10
	2	10
76Al5.0	1	35
	2	30

4.3 Healing Quantification

After the induction heating experiment, specimens were loaded once more monotonically, using the semi-circular bending test setup until failure. It is worth noting that some specimens were damaged during the induction heating experiment, due to excessive heat and therefore could not be tested after healing. The recovery period between the first loading stage and the second loading stage was 14 days. Table 4.3 presents the measured ultimate load and terminal displacement for each specimen type after the induction heating experiment.

Figure 4.4 illustrates a comparison of the mean ultimate load for the control and modified mixes after healing. As shown, the control mix (76CO) and the mix prepared with aluminum (76Al5.0%) appeared to exhibit a greater ultimate load at failure than the specimens with steel fibers.

Table 4.3 Fracture Resistance Test Results after Healing

Mix ID	Specimen ID	P_{ult} (lb.)	Average P_{ult} (lb.)	Displacement (δ_{ult}) at P_{ult} (in.)	Average δ_{ult} (in.)
76CO	1	179.3	176.9	0.1387	0.1221
	2	174.4		0.1055	
76Fe2.5%	1	N/A	-	N/A	-
	2	N/A		N/A	
76Fe5.0%	1	113.5	113.5	0.1066	0.1066
	2	N/A		N/A	
76Al5.0%	1	154.7	154.7	0.1815	0.1815
	2	N/A		N/A

Figure 4.4 Fracture Resistance Test Results after Healing

Figure 4.5 illustrates a comparison between the ultimate load before and after healing. It is interesting to note that the control mix presented the highest ultimate load after healing, although it was unsuccessfully heated through Eddy currents, as shown in Table 4.3. This

indicates that other healing mechanisms were present due to a long recovery period, which in turn allowed the control specimen to heal during the rest period.

To quantify healing efficiency, measured ultimate loads before and after healing were used to estimate the healing efficiency as follows:

$$\text{Healing Efficiency (\%)} = \frac{P_{\text{ult after healing}}}{P_{\text{ult before healing}}} \times 100 \quad (1)$$

Where,

$P_{\text{ult after healing}}$ = measured ultimate load of the damaged specimen after healing; and

$P_{\text{ult before healing}}$ = measured ultimate load of the specimen before healing.

Figure 4.5 Comparison of the ultimate load before and after the induction heating experiment

Based on Equation (1), a specimen would exhibit 100% healing efficiency, if the fracture failure load is recovered entirely after the healing phase. Figure 4.6 presents the calculated

healing efficiency for the different specimen types. Results presented in this figure show that the control specimen exhibited the maximum healing efficiency, which approached 85%.

Figure 4.6 Calculated Healing Efficiency for the Different Mix Types

Before and after healing the semi-circular specimens, light microscopy images of selected locations were acquired to compare the qualitative geometries of the cracked areas. Figure 4.7 presents the captured microscopic images before and after inducing healing and the recovery period. As shown in this figure, all specimens exhibited healing of cracked areas including the control specimens. For the control specimens, cracks with width as large as 0.639 mm appeared to have completely closed after the recovery period. The observed healing of the cracks is in agreement with the measured loading capacity of the specimens after the recovery period.

(a) 76CO: Control Mix

(b) 76Fe5.0%: Mix with 5% Steel Fibers

(c) 76Al5.0%: Mix with 5% Aluminum

Figure 4.7 Microscopic Images of Cracked Areas after Loading (Left) and after the Recovery Period (Right)

Crack widths were measured before and after Induction Heating. Figure 8 compares the measured crack widths before and after induction heating (IH) as determined from digital image analysis using ZEN Digital Imaging software 2.0. The healing efficiency was calculated based on digital image analysis for each mix type and is presented on top of the columns after healing. As shown in this figure, the control mix specimens (76CO1 and 76CO2) showed the highest level of healing efficiency (average healing efficiency of 54%), followed by the mix with aluminum fibers (healing efficiency of 30.8%), and finally the mix with steel fibers (healing efficiency of 17.9%). The inferior performance of the mix with steel fibers may be due to poor bonding and load transfer between the steel fibers and the asphalt mixture components. However, further testing would be needed to confirm this assumption.

Figure 4.8 Measured Crack Widths before and after Healing

4.4 Toughness Index

Toughness Index (TI) is a dimensionless parameter, which is used to describe the toughening characteristics of different mixtures. The Toughness Index compares the performance of a material with that of an elastic perfectly-plastic material ($TI = 1$) and also to that of a brittle material ($TI = 0$). Area under the load versus displacement curve was used to evaluate the toughness index as follows:

$$TI = \frac{A_p}{\epsilon_p} \quad (2)$$

where,

A_p = Area under the load-displacement curve up to peak load;

ϵ_p = Displacement corresponding to the peak load.

Table 4.4 describes the results of Toughness Index (TI) for the different mixtures before and after the induction heating test, which were calculated based on the area under the load-displacement curves. Figure 4.9 compare the toughness index values for the control and modified mixes sample before and after induction heating. It was observed that the mixes with 5.0% steel fibers had the lowest TI values while mix with 5.0% aluminum fibers showed the best TI values as compared to the Control specimens.

Table 4.4 Toughness Index values for different mixtures

Mix Type	Test Condition	Peak Load (Kn)	Peak Disp. (mm)	Area (Kn-mm)	TI
76CO	Before IH	0.918	3.562	2.06	0.57833
	After IH	0.77	3.088	1.453	0.47053
76Fe-2.5%	Before IH	0.775	3.124	1.485	0.47535
	After IH	0.501	2.614	0.758	0.28998
76Fe-5.0%	Before IH	0.984	3.164	1.933	0.61094
	After IH	0.684	4.63	2.148	0.46393

Figure 4.9 Toughness Index before and after Induction Heating

4.5 Hamburg Loaded Wheel Track (LWT) Test Results

Figure 4.10 illustrates a comparison of the mean ultimate rut depth for the conventional and modified mixes based on the LWT test results. As shown in this figure, the mixtures prepared with steel fibers appeared to perform better than those with aluminum fibers. Mixtures prepared with aluminum (76Al5.0%) exhibited greater rut depths than those specimens with steel fibers.

Figure 4.10 Statistical Analysis of the mean rut depths

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

The objective of this study was to test the hypothesis that a new generation of asphaltic materials could be artificially healed while in-service by embedding metallic fibers in the mix, and by applying a magnetic field at the surface. If successful, self-healing through induction heating would result in a new class of asphaltic materials, one that is able to resist cracking propagation and damage, which present the main failure mechanism in flexible pavements. During the experimental program, an open-graded friction course was successfully designed and prepared to incorporate up to 5% steel and aluminum fibers by weight of the mix. The repeatability of the fracture resistance measurements was acceptable, with a coefficient of variation ranging from 4.8 to 13.2% and with an average of 8.0%. Based on the results of the experimental program, the following conclusions may be drawn:

- Prior to healing, the control mix and the mix prepared with aluminum fibers exhibited greater ultimate load at failure than the specimens with steel fibers.
- The induction heating experiment was conducted successfully, showing the feasibility of inducing Eddy currents in the metallic fibers without contact to the specimens. Eddy currents flowed through the metallic fibers, thereby causing heat due to the resistance opposing the current.
- Induction heating experiments showed that the specimens incorporating metallic fibers reached the target temperature, whereas the control mix did not heat after 35 minutes. Given their higher electrical resistivity, the specimens with aluminum required a longer heating time to reach 110°C than the specimens with steel fibers.

- After the rest period, the control mix presented the highest ultimate load after healing, although it was not successfully heated through Eddy currents; however, differences were not statistically significant. This indicates that other healing mechanisms were present due to a long recovery period, which allowed the control specimen to heal during the rest period.
- Healing efficiency was the highest for the control specimen as it approached 85%. The healing efficiencies for the specimen with aluminum and steel fibers were 72 and 62%, respectively.
- Microscopic image analysis demonstrated that induced cracks healed efficiently during the healing period. From the captured images, cracks with width as large as 0.639 mm appeared to have completely closed after the recovery period. The observed healing of the cracks is in agreement with the measured loading capacity of the specimens after the recovery period.
- The Hamburg Loaded Wheel Track (LWT) test showed that steel fibers did not affect the rutting performance of the asphalt mixture as compared to the control specimens.

5.2 Limitations and Disadvantages

The research began with the analysis of samples prepared with dense graded asphalt mixture design. PG67-22 asphalt binder was used to prepare the mixtures. Since dense HMA mixtures have very less air void content when compared to OGFC mixtures, it was difficult to incorporate fibers more than 0.75% by weight of the mixture. Samples were prepared with same fibers (Steel and Aluminum) but with three different percentages (0.25%, 0.5%, and 0.75% by weight of the mix) of fibers.

Specimens were cracked and were analyzed under induction heating. Specimens did not heat up even after subjecting to induction heating test for longer durations. Although semi-circular bending (SCB) test and loaded wheel track (LWT) test were conducted to evaluate

different mixtures, the analysis was not considered in this research as it did not meet the primary objective of the study.

5.3 Future Recommendations

Based on the results of this study, asphalt mixture healing through induction heating was demonstrated and this presents a promising technology. Yet because the conducted experiment was limited in scope, further testing is recommended through a comprehensive testing program. Furthermore, the use of different classes of steel and aluminum fibers would permit an improvement to the healing efficiency of asphalt specimens through induction heating. The evaluation of healing through induction heating in field applications should also be considered in future projects, especially at the Louisiana Accelerated Loading Facility (ALF).

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