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Evaluation of self-healing of asphalt concrete through induction heating and metallic fibers

Yashwanth Pamulapati [a], Mostafa A. Elseifi [b,*], Samuel B. Cooper III [c], Louay N. Mohammad [d], Omar Elbagalati [a]

[a] Louisiana State University, United States
[b] Department of Civil and Environmental Engineering, Louisiana State University, United States
[c] LTRC, United States
[d] Department of Civil and Environmental Engineering, LTRC, United States

HIGHLIGHTS

- Aluminum fibers were used to achieve healing through induction heating.
- Specimens with steel coupled better to induction than specimens with aluminum.
- Cracks with width of 0.639 mm completely healed after the recovery period.
- Loading capacity of the specimens was measured before and after the recovery period.

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ABSTRACT

While healing through induction heating is promising, the effectiveness of this technology is yet to be demonstrated as limited studies have been conducted to study the recovery of cracking damage and fracture resistance properties 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 the results of the study, it was found that the control mix and the mix prepared with aluminum fibers exhibited greater ultimate load at failure prior to healing than the specimens with steel fibers. Yet, differences were not statistically significant. The induction heating experiment was conducted successfully and showed the feasibility of inducing Eddy currents in the metallic fibers without contact to the specimens. After healing, the control mix had the highest ultimate load after healing although it was not successfully heated through Eddy currents; yet, differences were not statistically significant. This indicates that other healing mechanisms were present that allowed the control specimens to heal during the recovery period. Healing efficiency was the highest for the control specimen as it approached 85%. 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 recovery period.

1. Introduction

Asphalt pavements are prone to cracking due to many factors such as traffic loadings, construction deficiency as well as severe environmental conditions. Cracks are detrimental to pavements in many ways by either weakening its mechanical properties, or lowering its durability by creating pathways for water to enter the structure and accelerate its deterioration and the need for repair. Cracking is also the main cause of many pavement distresses (e.g., stripping in asphalt concrete [AC] layers, loss of subgrade support, etc.). The rehabilitation of pavement damage caused by cracking failure is usually costly. Therefore, there is a critical need to evaluate and implement emerging technologies, which may enhance the cracking resistance of asphalt concrete.

Healing of asphaltic materials is an intrinsic property that has been reported in the late 1960s and was noticed to occur at high

* Corresponding author.
E-mail address: elseifi@lsu.edu (M.A. Elseifi).

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temperatures and with long rest periods between loads [1,2]. Furthermore, phenomenon such as binder thixotropy allows the 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 [4]. 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 [5].

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 have attempted to accelerate the healing of asphaltic materials by adding conductive materials in the asphalt mixture. A number of studies conducted in Europe have attempted to take advantage of induction heating in accelerating healing mechanisms in asphaltic materials [7,17,6]. When conductive asphalt concrete samples are heated electrically, the heat generated through the induction heating mechanism can influence the asphalt mastic resulting in partial or complete healing of the damaged section of the mixture.

Although induction-heating approach appears promising, the effectiveness of healing through induction heating is yet to be demonstrated as many influencing variables such as heating time, frequency of the current, magnetic permeability, 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 can be used to assess the overall effectiveness of this approach.

2. Objectives

The main objective of this study was to test the hypothesis that a new generation of asphaltic materials could be artificially healed 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. Laboratory tests were then 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. Healed specimens were loaded to failure to assess whether part of the load-carrying capacity was recovered. Microscopic analysis was conducted on the laboratory specimens to assess healing of the cracks at the microscopic level. It is noted that this study was the first attempt to use aluminum fibers to achieve healing through induction heating; aluminum fibers may reduce the added weight to the mix as compared to steel fibers. Furthermore, digital image analysis of crack healing through induction heating was conducted for the first time in this study.

3. Background

Qiu et al. studied the healing properties of asphalt binder using a two-piece healing (TPH) test and the Dynamic Shear Rheometer (DSR) [9]. In this test setup, the crack healing process was stimulated by pressing two asphalt pieces until the DSR gap was closed. After the gap was closed, the increase in the complex shear modulus during healing time (rest period) was used to quantify healing efficiency of the binder. It was observed that healing occurs in two phases – initial healing phase and time-dependent healing phase. Attempts were also made to describe the healing mechanisms in asphalt binder using a five-stage model that explains the healing process in terms of surface rearrangement, surface approach, wetting, diffusion, and randomization similar to what is observed with thermoplastic polymers [10].

At the macro-level, healing of AC was quantified through the increase in stiffness as well as the improvement in fatigue life of the mixture when rest periods are used during laboratory testing [11]. Palvadi et al. studied the fatigue damage and healing characteristics of fine-aggregate mix (FAM) by subjecting laboratory specimens to cyclic torsion and different rest periods [5]. The viscoelastic continuum damage (VECD) theory was used to quantify healing efficiency in FAM mixes as a function of rest periods and damage level. 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 [12,13]. Thixotropy in asphalt binder has been linked to the softening and decrease in stiffness that is observed during cyclic fatigue tests and the recovery of stiffness during rest periods [14].

3.1. Applications of induction heating to asphaltic materials

Induction heating is defined as the process of heating an electrically conductive material using electromagnetic induction [15]. This phenomenon is based on Eddy currents, which are generated when an alternating current is applied to the conductor, such as copper wire, a magnetic field develops in and around the conductor and vice versa [16]. The benefits of induction heating are that the heating process occurs rapidly and no contact is required with the surface; however, the depth of penetration usually drops quickly away from the surface.

Applications of induction heating to asphaltic materials have mostly focused on evaluating the effects of steel fibers on the electrical resistivity and induction heating speed in porous asphalt concrete. Liu et al. [7,17] showed that induction heating could 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 to make them electrically conductive [7,17]. 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, it was concluded that the samples with lower percentage of fibers showed higher resistivity and samples with steel wool type 000 showed better conductivity. Results showed that ITS value increased with the increase in volume of fibers until an optimum volume of fibers after which ITS value decreased because of reduction in asphalt mastic thickness with the increase in fibers. From the induction-heating test, authors have concluded that induction-heating temperature is related to electrical resistivity and ITS values of the samples. Furthermore, the samples with optimum content of fibers coinciding with ITS and resistivity tests showed faster heating rates. Finally, it was concluded that induction heating increased the heating rate in conductive porous asphalt concrete and 10% volume of steel wool type 000 was considered as optimum values to be used in asphalt concrete samples to obtain superior results.

Garcia et al. [18] studied the effectiveness of induction heating on asphalt binder with different volumes of electrically conductive particles and sand-bitumen ratios. Induction heating test was conducted to examine the effect of fiber volume content in the samples; steel wool, of type 000, with diameters between 0.00635 mm and 0.00889 mm were used. 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 induction heating test indicated that electrical conductivity of the mastic increased with