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Induction healing of asphalt mixes with steel slag

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ABSTRACT: Asphaltic mixes are self-healing materials since they have the capacity to close internal micro-cracks at higher temperatures or under external force. To trigger their self-healing, asphalt mixes modified with inductive agents can be heated and in that way healed through applying alternating magnetic fields with the aid of an induction coil and this technique is named induction healing. This paper assesses the potential of implementing induction healing in an existing asphalt pavement with steel slag. Cores have been drilled from a field section of a mix with steel slag and were fatigue damaged in an indirect tensile test and healed via induction. The material induction healing potential has been visualized through different X-ray CT scans over the thickness of samples. The induction heating speed of asphalt mixes with steel slag was evaluated as well. The main conclusion in this study was that the total fatigue life of asphalt with steel slag can be enhanced with induction heating. The efficiency of micro-cracks closure was the same over the thickness of asphalt mixes and in combination with the high heating speed (~1.8 °C /sec), induction becomes a very promising alternative for various pavement operations.

1. INTRODUCTION

An asphalt concrete mix is a combination of mineral aggregates, filler and bitumen. The aggregate particles act as the structural skeleton of the pavement and the bitumen as the glue of the mix. Factors such as the type of aggregates, air void content of mix, mix design and environmental conditions play a significant role in the performance of asphalt mixes and, in particular, of mixes developed for surface layers. Mixes constructed with the same type of bitumen may show large differences in serviceability. For this reason, many efforts are being made worldwide to develop new materials and design specifications for durable surface layers.

Thin surface layers with high air void content have been proposed as material solution for quiet pavement surfaces. Typically a thin layer of high air-void content at the top of an asphalt pavement is constructed to provide good skid resistance, low splash and spray, absorb tire-pavement noise and to provide good riding smoothness for the passing vehicles. Previous researches (Kandhal and Mallick 1998, Lu and Harvey 2011) have shown that indeed these mixes offer considerable advantages as quiet and roadway safety surface layers contributing to (a) noise reduction, (b) reduction of water splash and spray behind vehicles, (c) visibility enhancement of pavement markings and (d) reduction of night-time surface glare in wet weather. However, traffic and environmental conditions degrade the material properties in time, especially of surfacing layers with high voids content. The policies on applying thin asphalt layers vary considerably from country to country and substantial differences are apparent between different regions in the same country; not necessarily correlated with the climatic conditions (Kragh et al. 2011).

In the Netherlands, given the fact that the traffic intensity on the Dutch motorways is very high, open-graded surface mixes have been utilized but their lifetime is limited comparing to other mix types (Verra et al. 2003). Hence, during the years, Dutch authorities and contractors have tried to address the short lifetime of surface open-graded pavement layers by designing and developing special mixes. One characteristic example of these surface layers is the Two Layer Porous Asphalt with 0/16 and 0/8 aggregate matrix in the bottom and top layer, respectively. This structure with 0/8 chipping size (thickness 30 mm) as top layer has the advantage of reducing traffic noise to 4-6 dB(A) compared to 2-3 dB(A) reduction by Single Layer Porous Asphalt (thickness 50 mm) (DWW 1997).

However, nowadays the demand for durable materials for thin surface layers is still high, since the durability of mixes with high voids content is much shorter than that of dense-graded asphalt mixes, mainly due to ravelling. The loss of aggregate particles from the surface is called raveling and is initiated by the micro-cracks formation in the (mortar) bridges between the aggregates. To prevent and subsequently delay this damage type from the surface of mixes, the electro-magnetic induction technology has been introduced and extensive research has been conducted by adding various inductive agents into the mixes (Liu et al. 2010, Liu et al. 2012, Liu et al. 2013, Garcia et al. 2013, Apostolidis et al. 2016, Apostolidis et al. 2017). For example, a field trial with a porous asphalt surface layer containing very small steel fibres was constructed successfully on motorway A58 in the Netherlands and the efficiency of the induction technology as a treatment method has been evaluated (Liu et al. 2013). Nevertheless, the induction healing studies are limited on investigating fiber-type additives in the laboratory without having field evidence on the healing potential of more financial attractive and environmental friendly materials, such as the waste steel slag particles.

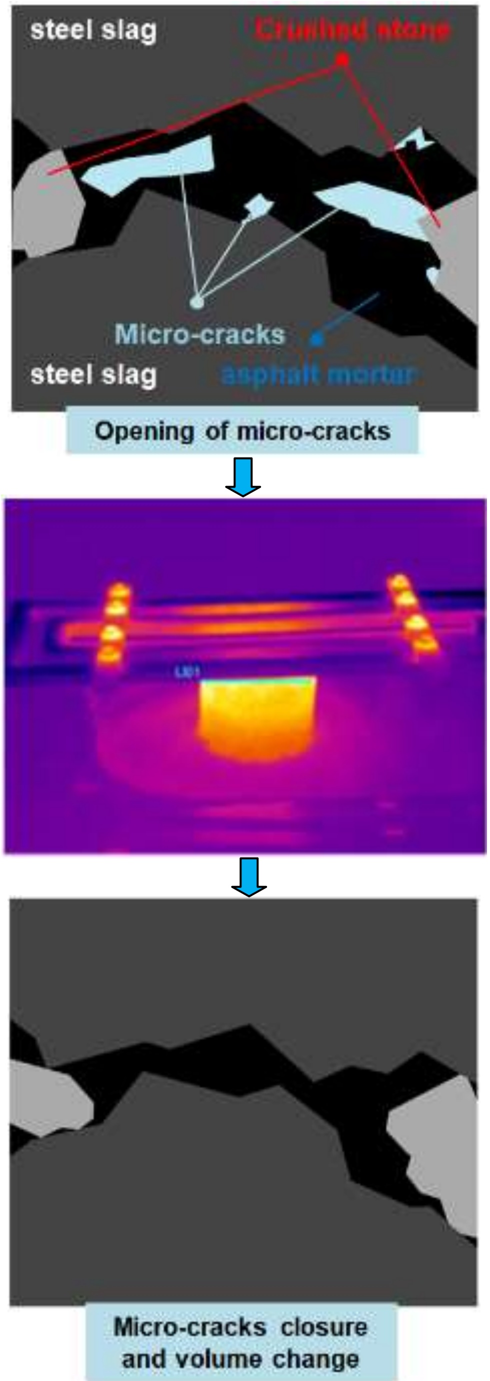

Figure 1. Induction healing of asphalt mixes with steel slag.

A Microville mix surface layer of 20 mm thickness with steel slag has been paved in motorway A31 at North Holland, the Netherlands. The aim of this project was to study the potential of utilizing the electro-magnetic induction for healing of a Microville surface mix with steel slag, Figure 1. As mentioned before, the concept of utilizing induction technology to extend the service life of asphalt mixes has been attempted before for mixes with steel fibres and a field trial exist. However, the application of this technology for mixes containing steel slag pushes the technique beyond the current state-of-the-art. Core specimens were drilled from the field section and a laboratory investigation has been conducted to investigate the induction healing potential of these mixes.

2. MATERIAL AND METHODS

2.1 Material and sampling of field cores

Field cores, cylindrical samples of 150 mm diameter, were obtained from the field to perform indirect tensile strength and fatigue testing, electro-magnetic induction heating and to study the effect of heating on healing of the mix. The Microville asphalt mix (air voids between 18.0 % and 22.0 %) consisted of steel slag (size between 6 mm and 2 mm) of 77%, crushed sand (size of 2 mm) of 18%wt, weak limestone filler (size of 63 μm) without calcium hydrate of 5%wt and Sealoflex modified bitumen of 6.2%.

2.2 Induction heating

The electro-magnetic induction heating tests were conducted at an ambient temperature of 20 ^{o}C utilizing a Huttinger generator of 0.55 kV supplied power and under an alternating magnetic field of 64.5 kHz frequency. The distance between a two single-turn induction coil and the top surface of the core samples was fixed at 20 mm. Samples were induction heated for 60 sec. During the induction heating process, the increase of the temperature on the surface of core samples was monitored with an infrared thermometer.

2.3 Induction healing

The maximum load applied at each cycle of the load-controlled indirect tensile fatigue (ITF) tests was 1.8 kN which is about 35% of the tensile strength of the unheated samples. The test frequency was 2 Hz. The obtained fatigue resistance of these tests was used as reference for evaluating the stiffness recovery after electro-magnetic induction. The fatigue test was continued until failure of the sample. To examine the induction healing potential of mixes with steel slag, the extended fatigue life of damaged asphalt mix cylinders was investigated in ITF test.

The original fatigue of the cores was measured in the previously descripted fatigue tests. After the fatigue test, the cores were heated under an alternating magnetic field to 100°C and rested at 20°C for 24 hours. The extra fatigue life of the healed samples was measured again by applying the same stress level. Three subsequent damage-healing cycles were performed to examine the induction healing potential. In order to visualize the material healing triggered by induction heating, X-ray computed tomography was used on two different samples and CT scan images were obtained.

3. RESULTS AND DISCUSSION

3.1 Induction heating speed

The induction heating rate was obtained by monitoring the temperature increase with an infrared thermometer at the top surface of the sample. Figure 2 shows the average temperature that developed over a certain time during induction heating process which increased from room temperature to 105 ^{o}C in 60 seconds. However, it should be noted that the induction heating rate is not related to the proportion of steel slag in the mixes since every single steel slag particle is a heating unit under the alternating magnetic fields. In the present work, the samples were heated in-homogeneously over the thickness of sample resulting in-homogeneous micro-crack closure. This phenomenon is clearly shown in the induction healing sub-chapter.

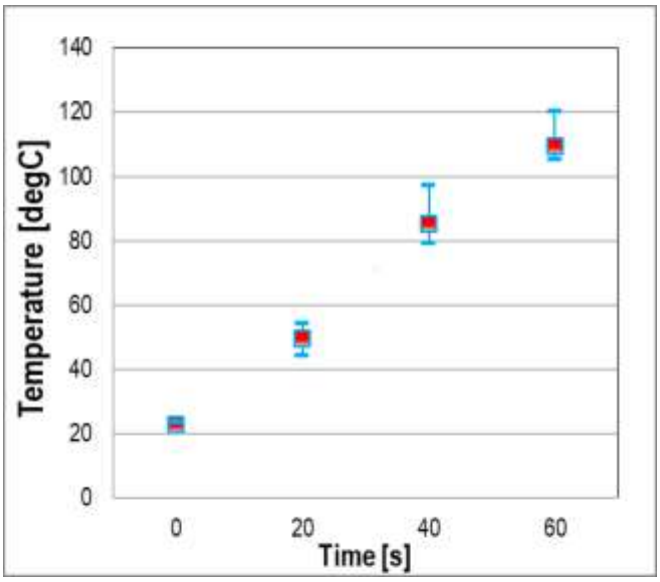

Figure 2. Temperature increase during induction heating.

3.2 Induction healing

Figure 3 shows the fatigue results of the unhealed and the healed asphalt mixes with electro-magnetic induction. The original fatigue curve depicts a life of 2.204E4 cycles until fracture of unhealed sample. Another sample was fatigued up to a certain stiffness reduction (in this case 25%) and induction heated. The stiffness was recovered after induction heating at 85 ^{o}C. The induction heating attributed to closure of micro-cracks making this technique a possible preventive maintenance solution against the loss of particles from the pavement surface. The second fatigue test was stopped after the material showed a rapid decrease of stiffness and induction heating was applied for a second time. A further fatigue life extension was reached after the second induction healing instance. However, due to difficulties during testing of samples, the test was finished without continuing the induction healing in a third cycle.

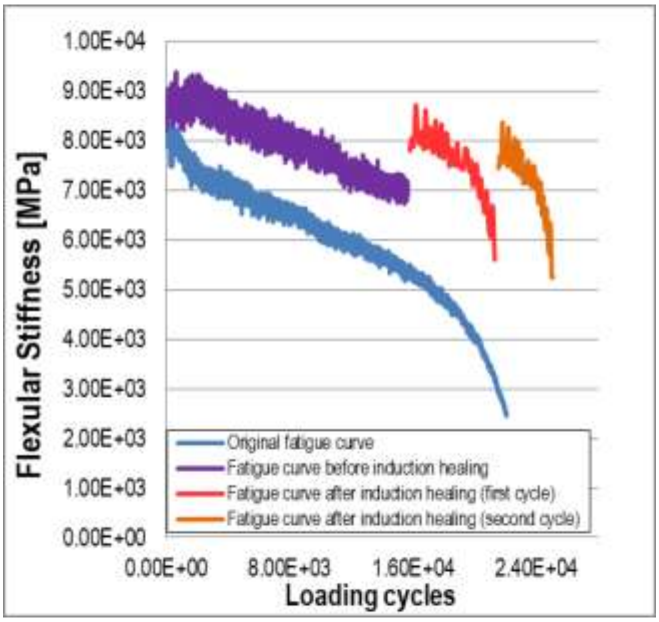

Figure 3. Fatigue life of core samples.

Additionally, it was observed that the micro-cracks were closed by induction heating (Figure 4). Different positions over the thickness of a sample were examined before and after induction heating using a CT scanner. The steel slag particles were heated up and the surrounding asphalt binder softened bringing the micro-cracked surfaces in contact. This observation was apparent over the whole thickness of the sample, which is different compared to the healing performance with steel fibre reinforced asphalt mixes. The healing effect of inductive mixes with steel fibres was different from top to bottom of the sample, because the intensity of the applied magnetic field from the induction coil decreases over the thickness of the sample (Liu et al. 2013). Higher temperature results faster capillary flow rate of asphalt binder and higher healing effect of damaged material (Garcia 2012). Therefore, the micro-cracks closure is a temperature dependent process which can be accelerated by applying induction power of high intensity. In this research, the significant induction healing effect at the bottom of the studied sample demonstrates also the potential of utilizing the induction technology as maintenance tool for defects, such as the bottom-up cracking, and during the pavement construction to assist with the compaction of low temperature asphalt mixes (Zhou et al. 2017).

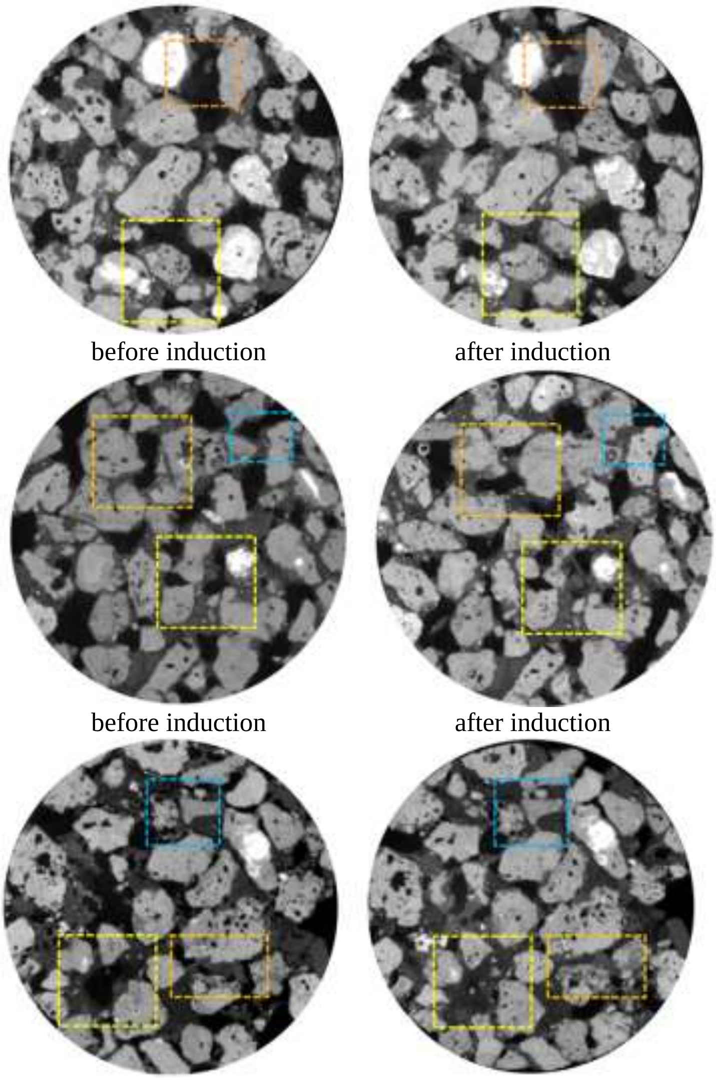

Figure 4. CT scans of core samples.

4. CONCLUSIONS

The induction heating speed, the strength recovery due to induction heating and the induction healing potential of asphalt mixes with steel slag specially developed for thin surface pavement layers were examined. The main conclusion from this study was that the micro-cracks were closed and the air voids were consolidated by applying the electromagnetic induction resulting in recovery of stiffness to the initial stiffness level and consequently slight fatigue life extension (~15%). Due to difficulties during artificial healing testing, the tests were not continued in a third healing cycle even if the material was not damaged until fracture in the third fatigue test. Finally, the efficiency of micro-cracks closure was the same over the thickness of samples. In combination with the high induction heating speed (~1.8^{o}C/sec), the potential of induction heating for various pavement operations becomes very promising.

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