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The influence of asphalt ageing on induction healing effect on porous asphalt concrete

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Abstract

Induction healing is a proven technology which is able to improve the self-healing capacity of asphalt concrete. Healing is achieved via electromagnetic current produced by passing induction machine, where steel asphalt constituents heat up which in turn soften the bitumen in the asphalt layer, allowing it to flow and close cracks, repairing the damage. This paper reports on the study which investigated the influence of ageing on the healing capacity of Porous Asphalt (PA) concrete. Porous Asphalt concrete mix was prepared first, then subjected to an accelerated (laboratory) ageing process using a ventilated oven. In order to further evaluate the induction healing efficiency of asphalt concrete, Semi-circular bending (SCB) and healing cycles were performed on asphalt concrete specimens. The results show that with an increase of the ageing level of porous asphalt concrete, the healing efficiency of the asphalt decreases.

Keywords: Induction heating; Asphalt; Semi-circular bending; Ageing; Self-healing

1 Introduction

Asphalt concrete when subjected to loading and environmental (ultraviolet radiation, oxidation and moisture damage) conditions leads to deterioration to its physical and mechanical properties, such as ageing [1-3]. On a molecular level, the ageing of asphalt involves synergy of several effects, such as: volatilisation, oxidation and steric hardening [3]. The volatilisation and oxidation result from the change in molecular structure, while steric hardening is a result of a molecular rearrangement [3]. In mechanical way, ageing of asphalt increases the stiffness and bitumen viscosity and eventually leads to ravelling and cracking in asphalt concrete [4-6]. The ageing effect of an asphalt concrete is influenced by time, temperature and asphalt concrete layer depth [7, 8]. Therefore, a higher temperature or longer exposure period increase the asphalt ageing level, which changes the rheology of asphalt binder and reduces its ability to flow.

The asphalt concrete possesses an intrinsic healing capacity which allows it to heal the damage itself during the rest period [9]. Researchers have found that the self-healing ability of asphalt concrete is largely affected by the ambient temperature, which a higher temperature not only increases the self-healing rate but also shortens the healing period for a full recovery [9-11]. This healing effect can be illustrated by the time-temperature superposition of asphalt material in the following formulation [10]:

$$H(t,T) = 100 \times \left[1 + \left(\frac{m}{t \times a_T}\right)^{\frac{\log 2}{n}}\right]^{-\frac{n}{\log 2}} \quad (1)$$

$$\log a_T(T) = \frac{\Delta E_a}{2.303R}\left(\frac{1}{T} - \frac{1}{T_0}\right) \quad (2)$$

where:

m, n = model parameters;
a_T = time-temperature superposition shift factor;
ΔE_a = apparent activation energy, J/mol;
R = universal gas constant, 8.314 J /(mol·K).

Because of lower ambient field temperature, this self-healing effect of asphalt concrete is usually limited.

In the past 10 years, the induction healing has been intensively investigated as a novel method to achieve crack healing and eventually prolong the service life of an asphalt concrete [12-17]. The induction healing has been demonstrated to have a significant crack healing effect in asphalt mastic, porous asphalt concrete, dense asphalt concrete and reclaimed asphalt pavement (RAP) [18-20]. Healing is initiated within the asphalt by sending an alternating current through the coil and generating an alternating electromagnetic field. When the conductive

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asphalt specimen is placed beneath the coil, this electromagnetic field induces currents flowing along the conductive loops formed by steel fibres. The current causes steel fibres to heat up which heats the aged bitumen and softens it, allowing it to flow and close the cracks, and to repair the damage. This method can be repeated if damage returns [9]. The induction heating method has a significant advantage in healing efficiency over the other existing self-healing technologies, such as: rejuvenator encapsulation, for asphalt concrete and it has already been applied in field trials [9, 21, 22].

Up to now, most researches investigating induction healing effect in asphalt used testing samples prepared with virgin asphalt mixes, which means the intrinsic healing capacity of the tested mixture is relatively high and can be easily stimulated via induction heating [12-16, 18]. However, the optimum time to apply induction healing in asphalt concrete is at the crack (microcracks) initiation stage [9]. At this time, the asphalt concrete experiences aging, and its intrinsic healing capacity is reduced, this also could lead to reduced efficiency of extrinsic (induction) healing system [10, 23, 24].

Gómez-Meijide et al [19] considered the ageing level of asphalt binder as an induction healing influencing factor by testing asphalt concrete prepared with artificially aged RAP. Gómez-Meijide et al concluded that the ageing effect reduces the effectiveness and energy efficiency of induction healing treatments [19]. However, they indicated that the ageing level of asphalt mixture could affect the compaction rate of asphalt concrete [19], so that the inhomogeneous compaction rates of the tested asphalt concrete samples could not fully show the ageing effect on induction healing treatments.

The key objective of this study was investigation of the influence of ageing on asphalt concrete induction healing efficiency. Since porous asphalt is prone to ageing due its open structure, and shows better induction healing potential [19], it is selected as the mixture type in this study. At first, the porous asphalt concrete slabs were subjected to an accelerated laboratory ageing in order to simulate the in-situ asphalt ageing. Nano CT scan was employed to visualize the distribution of steel fibres within an asphalt mix. Then, the induction healing efficiency of SCB specimens were investigated, and the results between aged and virgin specimens were compared. The results demonstrate that the effect of ageing could have a huge impact on induction healing, which not only reduces the possible healing cycles but also reduces the healing efficiency.

2 Methods

2.1 Porous asphalt concrete

In an effort to evaluate the effect of ageing on the healing efficiency of the asphalt induction healing, a PA asphalt mix was designed (Table 1). All aggregates (including sand) used in this paper were limestones or by-product of limestones. The 70/100 bitumen was used as asphalt binder and the filler type Wigro 60k was used. The steel fibres used in the asphalt mix has a diameter of 40 μm and an average length around 1.4 mm. The advantage of using these short fibres is to allow these fibres homogeneously distributed in the porous asphalt concrete, thus avoid clogging.

In this study, two porous asphalt slabs were prepared in Rosmalen Heijmans infra BV with a designed void content of 20%, following the standard PA 0/11 according to the Rationalisatie en Automatisering Grond-, Water- en Wegenbouw (RAW) 2005 which was used in effort to produce PA asphalt mix typically used as asphalt wearing courses used in The Netherlands [25, 26]. The steel fibres were added with an extra volume in a ratio of 6:100 with the volume of bitumen. The calculated porous asphalt composition is shown in Table 1.

Table 1. Mix Composition of Porous Asphalt Concrete

Mix Constituent	% Content in Mix
16 mm	7.97
11.2 mm	62.00
8 mm	7.97
5.6 mm	1.78
2 mm	6.47
500 μm	2.06
180 μm	0.66
125 μm	0.66
63 μm	4.22
Bitumen(70/100)	4.32
Fibres(excl.)	1.88

Two asphalt slabs with size of 50×50×5 cm were prepared and one of them was aged in a ventilated oven following an artificial ageing method which was used by Tabaković [27] and Xu [28]: kept in a ventilated oven at 135°C for 4 hours and then a 4 days period under 85°C, which simulates the field ageing of 15 years.

After preparation of the porous asphalt concrete, a cylinder sample with 33.5 mm in diameter and 48.5 mm in height was drilled and scanned with a Nano CT scanner at resolution of 20 μmto investigate the distribution steel fibres in the PA mix.

2.2 SCB tests

In the laboratory, the SCB test is widely used to investigate cracking performance of asphalt concrete [9, 29, 30]. In this paper, the SCB samples were acquired by drilling and cutting from the asphalt slabs. As shown in Fig. 1a, the SCB specimens have the diameter of 100 mm, the width of 50 mm, the height of 50 mm and a notch size of 2×10 mm.

A universal testing machine (UTM) with a temperature control chamber was employed for the SCB tests. According to EN 12697-44:2010 [31], the SCB tests were performed under 0 °C with a displacement control of 5 mm/min and the support span was 80 mm (Fig. 1b). For each testing condition, at least 6 samples were tested.

2.3 Induction healing

The induction healing were performed using an induction machine which has a capacity of 50 kW and at a frequency of 70 kHz. Fig. 2a shows the top view of the SCB specimen under induction healing. The distance between the induction coil and healing specimen was kept at 5 mm (Fig. 2b). In order to achieve an effective and homogeneous healing on all the specimens, the induction healing temperature was carefully controlled to reach 85 °C (Fig. 2c), which is regarded as the optimum temperature for induction healing. An infrared camera was used to monitor the whole induction healing process to control the induction healing process and avoid overheating on SCB specimens.

2.4 Bending and healing cycles

In order to evaluate the healing efficiency of the SCB specimens, a bending and healing programme was followed:

Step 1: The initial peak load of the specimen was measured by the first SCB test, followed by a 4 hours resting at 23 °C to allow the fractured specimen reached room temperature;

Step 2: The fractured two parts were gently put together and placed 5 mm below the induction coil. Then, the induction healing was conducted on both sides of the SCB specimen and the heated specimen was left at 23 °C for 4 h to let the temperature cooling down.

Step 3: Subsequently, a resting period of 12 hours on the specimen was conditioned on a plain surface at 23 °C. In order to create a constant confinement to ensure the close of cracked surfaces, the specimen was carefully wrapped with tapes during the resting period;

Step 4: The SCB test to acquire the strength recovery of the specimen after healing. If the peak load was higher than 100 N, step 2 to 4 would be repeated until the sample could not be healed anymore.

The induction healing effect was determined using induction healing index (IH), which was calculated with the peak load measured from three SCB tests:

$$\mathrm{IH} = \frac{C_x}{C_1} \times 100\% \quad (3)$$

where:

IH = the induction healing index (%),

C_1 = original peak load of the sample;

C_x = tested peak load after x cycles of healing.

3 Results

3.1 CT scan image

Fig. 3 shows one of the top view Nano CT scan images. In Fig. 3, shows all three different phases in the scanned porous asphalt, including steel fibres, aggregates and asphalt mastic. The steel fibres are presented in the brightest colour. That is due to the density of the steel fibres is 7.5 kg/m^3, which is significantly higher than aggregates and asphalt mastic (<2.8 kg/m^3). The small size of steel fibres allows uniformly distribution of the fibres within the asphalt mastic area, and with 6% of steel fibres, nearly every piece of mastic area contains steel fibres. As such, theoretically, as long as the induction energy can reach, all microcracks in asphalt mastic are able to be healed with induction healing. The figure further shows that by using steel fibres with a length of 1.4 mm, the traditional clogging problem during mixing can be solved.

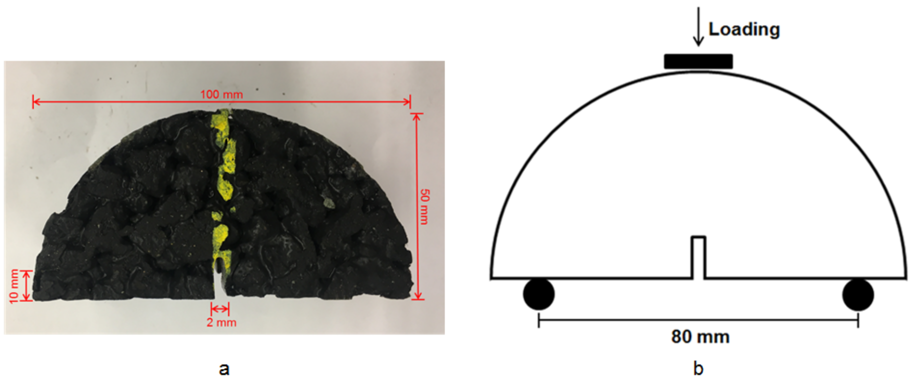

Figure 1. (a) SCB testing specimen; (b) loading on SCB samples.

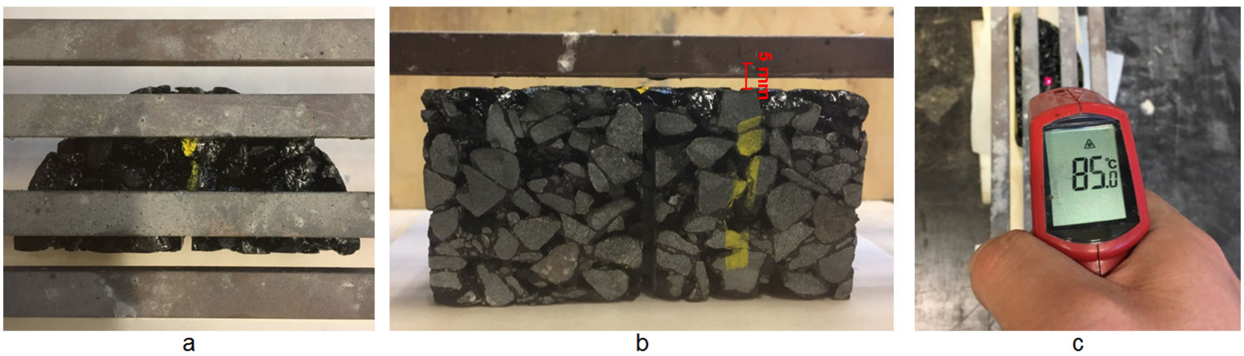

Figure 2. Tested SCB specimen under the induction coil: (a) top view; (b) front view and (c) surface temperature.

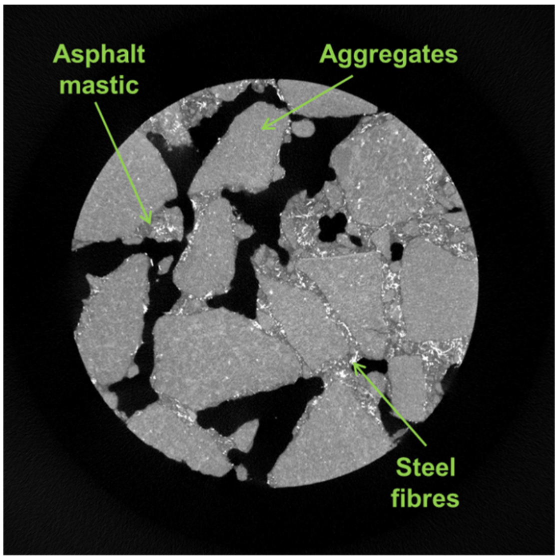

Figure 3. A top view image of CT scan on porous asphalt concrete with steel fibres.

3.2 Induction healing process

Fig. 4 shows the heat distribution throughout the full depth of the test specimen during the induction healing process. Fig. 4a illustrates an image of tests specimen prior the healing process at 23 °C. The specimen is shown in same colour as its surroundings under the infrared camera. The induction healing method used in this paper was applied in two steps:

I. When the induction healing starts, the alternating current through the coil generates an alternating electromagnetic field, leading to gradual temperature increase of the SCB specimen from the sample surface to the middle. This step lasted 90 seconds, and the infrared image shows that the temperature was the highest at the surface (Fig. 4d);

II. After one side heating was completed, the SCB specimen was turned over and the induction healing was applied on the other side for 60 seconds (Fig. 4c). Finally, after two-sided healing, the infrared image showed the SCB specimen can achieve a uniform distribution of temperature about 85 °C, thus optimum healed.

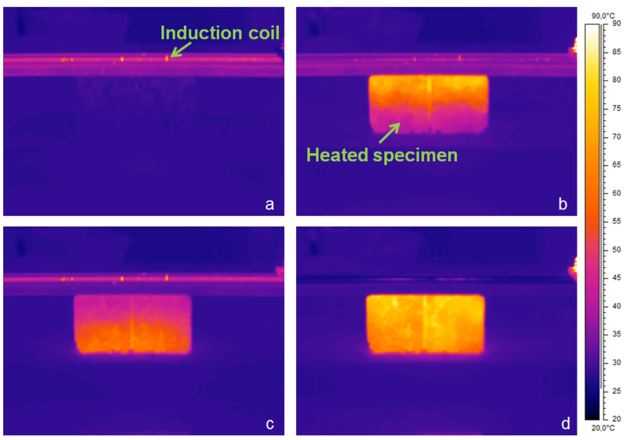

Figure 4. The healing process of SCB specimens: (a) heating start on one side; (b) one side heating complete; (c) Turn over and start heating on the other side and (d) the whole heating process complete.

In this way, the whole body of the heated sample reached 85 °C (Fig. 4d), which is referred as the optimum temperature for induction healing. Thus, overheating and insufficient heating were able to be avoided. In practice, an uniform heating can be achieved by using a two-layer asphalt structure which has more fibres in the bottom-layer.

3.3 SCB tests

Fig. 5a shows the peak load results from all SCB tests. In the beginning, the fresh PA specimens and the aged PA specimens have very similar initial peak load around 2.3 kN. As the number of bending and healing cycles increases, the regained peak load of all PA specimens decreases, which indicates a decreasing of fracture resistance. This general decreasing trend might because of the accelerated ageing of asphalt concrete by induction heating, which gradually deteriorates the self-healing capacity of PA mix and in turn decrease the induction healing efficiency (Fig. 5b).

After 6 healing cycles, the induction healing index of fresh asphalt specimens still reaches 73%, while the aged asphalt specimens remain only 25%, and some aged specimens cannot be healed with induction healing anymore. For aged PA specimens, the regained peak load is significantly lower than fresh ones. It might because, after the laboratory ageing, the self-healing capacity of the PA mix decreases, which means the high temperature produced from induction healing could not provide as much healing effect as the fresh PA mix.

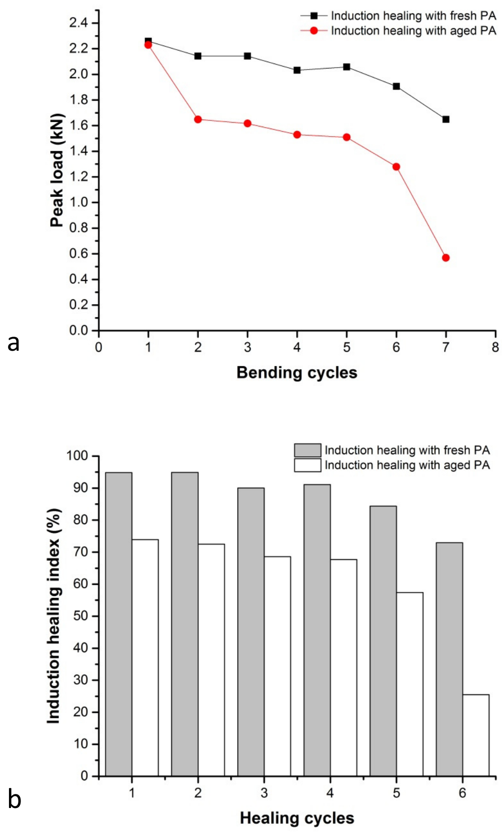

Figure 5. (a) Peak load of SCB specimens and (b) induction healing index of SCB specimens.

4 Conclusions

This study investigated the effect of asphalt ageing on induction healing, the following conclusions are drawn:

- The CT scan image indicates that incorporation of induction healing technology using steel fibres with a length of 1.4 mm can achieve a homogeneous distribution of steel fibres in asphalt concrete. With 6% of steel fibres, as fibres are able to spread in every pieces of asphalt mastic, theoretically, cracks in the asphalt mastic can be healed via induction healing;
- The induction healing procedure adopted in this study, by applying induction healing on both sides of a specimen, can achieve a homogeneous temperature distribution on asphalt concrete, thus optimum healing;
- the PA mix induction healing index decreased with increasing number of healing cycles, which illustrate that the high temperature produced by induction healing can help to improve the self-healing capacity of an asphalt concrete, which in turn could also accelerate the asphalt ageing process;
- The higher ageing level in asphalt concrete results in a further reduction of induction healing effect. Ageing of an asphalt concrete not only decreases its induction healing efficiency but also reduces its possible healing cycles.

Finally, recognised the significance of asphalt ageing effect on induction healing, researchers could develop the induction healing technology in a more scientific way that predicts the induction healing behaviour in combination with the long-term service life of an asphalt concrete. On the other hand, considering the findings in this paper, it inspires a new way to prolong the service life of asphalt concrete with self-healing asphalt: incorporating induction healing system with capsule healing system, by this means, the crack healing and aged binder rejuvenation are combined, as such, a longer extended life span is expected.

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