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Induction healing of dense asphalt concrete

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HIGHLIGHTS

- We examine the induction healing properties of dense asphalt concrete.
- We develop and prove a model for the healing properties of asphalt concrete.
- Healing of asphalt concrete depends on the capillary flow of bitumen through the cracks.

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ABSTRACT

Induction heating can be used for repairing cracks in asphalt concrete. With this purpose, electrically conductive particles have to be added to the asphalt mixture, which is then heated with an induction heating device. Since the factors affecting the induction healing of dense asphalt concrete are not well-known, in this article, different mixtures, with different lengths, quantities and diameters of steel wool fibres have been considered. It was found that there is a minimum temperature for healing asphalt concrete. Additionally a semi-empirical model, explaining asphalt healing through the capillary theory has been developed and fitted to the results.

1. Introduction

Bitumen starts behaving like a Newtonian fluid at temperatures ranging from 30 °C to 70 °C [1–4]. Above these temperatures, bitumen may start flowing through any possible crack open in the pavement, in a sort of capillary flow [5]. This happens naturally when the temperature is high enough, for example during summer, although it can be also promoted artificially by induction heating [6–9] or by microwave heating [10].

Induction heating of asphalt concrete is a technique that consists in heating electrically conductive particles, for example, steel wool fibres, previously mixed into the asphalt concrete mixture [7,8]. Then, with the help of an induction heating device, it is possible to heat the particles locally and, through heat diffusion, heat the binder and heal the cracks. In Ref. [8] it was discovered that a very small volume of fibres, more than 0%, serves to increase the temperature via induction heating. Moreover, in Ref. [9] it was shown that the increase of temperature in asphalt concrete due to induction heating depends more on the radius of the fibres than on their volume in the mixture. Besides, other parameters which have great influence on the heating rates are the frequency and intensity of the alternating magnetic field used [9].

The objective of this research is to define a theoretical frame for studying the induction healing properties of dense asphalt concrete. With this purpose, 25 different asphalt concrete mixtures, with the same aggregate distribution and amount of bitumen, but with 2 different average lengths of fibres, 4 different fibre contents, and 4 different diameters of steel wool have been prepared and their healing properties have been analysed. Moreover, a model has been explained and the healing properties of asphalt concrete explained.

2. Experimental method

2.1. Materials

A dense asphalt concrete mixture was used in this research. The mixture composition is shown in Table 1. The aggregates consisted of crushed basaltic material (size between 0.063 mm and 11 mm) and limestone filler (size < 0.063 mm). Virgin bitumen 70/100 pen was used.

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Table 1
Composition of the dense asphalt mixture [11,12].

Sieve size (mm)	Aggregate weight% retained	Cumulative aggregate weight% retained
11.2–8.0	15	15
8.0–5.6	15	30
5.6–4.0	10	40
4.0–2.8	10	50
2.8–2.0	10	60
2.0–1.4	7	67
1.4–1.0	6	73
1.0–0.5	9	82
0.5–0.25	6	88
0.25–0.09	5	93
<0.063	7	100
Bitumen 70/100	(% of Weight of mixture)	5.6
Steel fibres (% volume of Bitumen)	Length (mm)	Diameter (mm)
2% Fibres	2.5 and 7	0.02855 (Type 0000); 0.03642 (Type 00); 0.08389 (Type 1) and 0.15498 (Type 3).
4% Fibres		
6% Fibres		

Additionally, steel wool fibres were added to the mixture. The material used in the steel wool was low-carbon steel. These fibres had 4 different diameters, 0.02855 mm, 0.03642 mm, 0.08389 mm and 0.15498 mm and an average length after mixing and compacting of approximately1.5 mm. Finally, 4 different amounts of fibres were used: 0%, 2%, 4% and 6%, by total volume of bitumen in the mixture.

2.2. Test specimens preparation

The materials were mixed in a laboratory planetary mixer at a mixing speed of 312 rpm. The amount of material in each mixture was approximately 16 kg. Materials were first heated to 160 °C and then mixed during approximately 5 min. After the mixing, the mixtures were conditioned for 12 h in an oven at 160 °C. This was done to simulate extreme bitumen ageing conditions.

The 16 kg batch was used to prepare asphalt concrete slabs. These slabs were compacted by using a pneumatic laboratory wheel compactor [13]. After compaction, both faces of the samples were polished until they reached a height of 5 cm. From this, blocks of 25 × 25 cm^2 were sawn.

From these blocks, prismatic specimens of 12 cm × 5 cm × 5 cm were cut. Additionally, a 3 mm wide and 8 mm deep notch was created in the test samples; the notch was cut at the mid-point in the direction of the loading from the central axis of the sample.

2.3. Temperature and induction heating measurements

The temperature change in the asphalt concrete test samples was measured with a 640 × 480 pixels, full colour infrared camera. The induction heating experiments were performed with a 30 kW induction heating generator at a maximum frequency of 78 kHz. The air temperature during the process was 20 °C [12].

In this research the total temperature of the 12 cm × 5 cm × 5 cm specimens has been calculated as an average between the temperature at the bottom of the test sample and the temperature at the top surface, after 1 min heating. Moreover, the Newtonian cooling constants (ξ) of the 25 cm × 25 cm × 5 cm test specimens were calculated by observing their cooling rates during 20 min.

2.4. Bitumen rheology

The asphalt binder of the mixtures was recovered by rotary evaporator in order to determine the temperature when Newtonian behaviour occurs. With this objective, the dynamic shear properties of bitumen were measured with a dynamic shear rheometer in a configuration with 25 mm diameter parallel plates, with a 1 mm gap. Oscillatory frequency sweeps were carried out over a range of 0.001–0.1 Hz at temperatures from 30 °C to 70 °C under a constant strain of 0.1% within the linear viscoelastic region. The complex viscosity (η^*) as a function of frequency (ω) at different temperatures was recorded automatically during the tests.

2.5. Healing measurements

Induction healing of the asphalt concrete prismatic specimens was done as follows: first the tests specimens were numbered; then, they were randomly selected for heating during 0.5 min, 1 min, 1.5 min, 2 min and 2.5 min, respectively. Later, they were tested under three-point bending configuration at −20 °C at a deformation rate of 0.5 mm/min, stopping the tests when the force in the discharge curve of the beams reached 20 N. This load was enough to produce a crack of approximately 200 μm width crossing the specimen from the tip of the notch to the load application point. In Refs. [11,14], it was found that the 3-point bending strength of the different test samples can be considered independent of the characteristics and amount of the steel fibres in the mixture. In this research, it was found that the average 3-point bending strength of the beams was 6.61 kN and the standard deviation 0.75 kN.

Once cracks were created, the test specimens were let to rest during 2 h at 20 °C and heated during the time selected. Finally, the test samples were tested again under three-point bending. The healing level ($S(\tau)$) of asphalt mastic was defined as the relationship between the ultimate force of the test specimens during a three point bending test, F_0, and the ultimate force measured in the beams after the healing process $F_b(\tau)$, where τ is a parameter that gives an idea of the amount of energy in the asphalt concrete test sample during the healing process:

$$S(\tau) = \frac{F_b(\tau)}{F_0}, \qquad (1)$$

3. Theoretical background

3.1. Temperature evolution of the test samples

When an alternating current is applied across a conductive coil, an alternating magnetic field is created with the same frequency as the alternating current causing the field [14]. According to Faraday's law, if a magnetically susceptible and electrically conductive material, like for steel wool fibres, is located within a magnetic field, an electric current will be induced with the same frequency than the magnetic field and the intensity circulating through the coil [8]. When the electrical current meets the electrical resistance of the material, it will heat due to the Joule principle. As is explained in Ref. [5], an appropriate healing level is reached when bitumen is heated for a sufficient time above the temperature at which it behaves as a Newtonian fluid (T_{newt}).

Moreover, healing does not happen only during the time induction heating, but also during the cooling time, as long as the temperature of asphalt concrete is still above T_{newt} (see coloured area in Fig. 1). With this in mind, it is well known that the cooling of a hot body will follow an approximate exponential function [15], which is described by the Newton's law of cooling:

$$\frac{dQ}{dt} = \alpha A(T_{air} - T) \qquad (2)$$

where Q is the thermal energy, α is a heat transfer coefficient, taken constant as a simplification, A is the surface area across which the heat is being transferred, T is the temperature of the asphalt surface and T_{air} is the temperature of the environment.

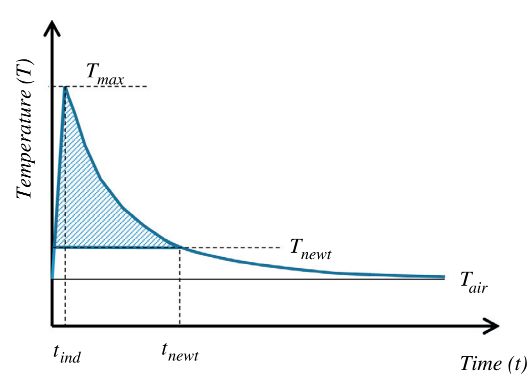

Fig. 1. Temperature changes in dense asphalt concrete due to induction heating.