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Induction healing of fatigue damage in asphalt test samples

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HIGHLIGHTS

- We damage asphalt test samples with indirect fatigue tests.
- We heal the test samples with induction heating.
- There is an optimum damage level for healing.
- Asphalt test samples extend their lifetime by 30%.
- Bitumen suffers ageing damage during induction heating.

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ABSTRACT

To promote asphalt self-healing, asphalt mixture can be heated via induction heating. This technique consists in adding electrically conductive and magnetically susceptible particles (e.g. steel) into asphalt mixture; then, with the help of an induction heating machine asphalt mixture can be heated. When the temperature of asphalt mixture is above a certain threshold (between 30 °C and 70 °C, depending on the type of bitumen), microcracks start self-healing. Induction healing has been previously demonstrated for repairing asphalt mixture test specimens broken in two pieces, but this technique has never been used for repairing microcracks caused by fatigue damage. In this article, the optimum moment and temperature needed to repair asphalt mixture under fatigue damage have been experimentally determined. With this purpose, Marshall test specimens have been damaged through indirect tensile fatigue tests and healed via induction heating. Finally, damage and healing have been quantified through computed tomography scan tests.

1. Introduction

Asphalt mixture is one of the most common types of pavements used in the world. It is a composite material made of aggregates, filler and bitumen. Asphalt mixture suffers damage by many factors such as traffic loads, weather, oxidation, UV light, etc, which may be the cause of cracks. Initially, cracks in asphalt mixture have a micrometric size, but they may grow very fast due to traffic circulation and environmental stresses. For this reason, preventive maintenance treatments must be used to extend the life of asphalt pavements.

Moreover, cracks in asphalt mixture can repair themselves without human intervention [2,3]. Self-healing of asphalt mixture occurs in periods without traffic and under high temperatures, starting between 30 °C and 70 °C depending on the type of bitumen used. For this reason asphalt mixture can be classified as a thermally induced self-healing material [1]. The main healing mechanism of asphalt mixture is the capillary flow of the bitumen through the cracks at high temperatures [1,3]. This is a very slow process and cracks may need many days to fully self-heal.

To promote asphalt mixture self-healing, different methods have been developed, such as encapsulated rejuvenators [4], or induction healing [5–8]. To use this last method, electrically conductive and magnetically susceptible particles (e.g. steel) must be added during the mixing process [8]. These particles improve also the electrical conductivity of asphalt mixture [9]. In the induction heating method, an induction heating apparatus generates alternating electromagnetic fields. When asphalt mixture with electrically conductive particles embedded is under the influence of the electromagnetic field, eddy currents are induced in the steel particles

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and heat is generated. In this way, only the steel particles are heated, and the heat diffuses from them through the mixture [8].

A self-healing road using this principle was built in the past [10], but the optimum time for induction heating the road is not yet clear. For this reason, the aim of this research is to have a first insight of when and for how long asphalt mixture under fatigue damage has to be induction-heated to recover part of its original properties. With this purpose, indirect tensile fatigue tests have been used for damaging the test specimens. Then, damaged test samples have been induction heated during different heating times. The healing recovery has been defined as the relationship between the increase of the number of cycles resisted by the test samples after healing and the number of cycles resisted by unheated test samples. Finally, damage and healing recovery have been observed by means of computed tomography scans.

2. Experimental method

2.1. Materials

Virgin bitumen 70/100 pen and dense asphalt mixture were used in the 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). Furthermore, 6% by volume of cast steel particles (size between 0.60 mm and 1.40 mm) were added to the asphalt mixture.

2.2. Test specimens preparation

21 kg of asphalt mixture were prepared in a laboratory mixer, at a mixing speed of 120 rpm. This process was repeated 12 times. All the materials were first heated into the oven at 160 °C and then mixed during 3 min at the same temperature.

The mixture of asphalt mixture was used to make cylindrical Marshall specimens of 101.7 mm diameter, approximately 60 mm height and 1190 g weight. Immediately after placing the materials in the moulds (at 160 °C), they were reheated to 160 °C and compacted with a Marshall hammer, applying 50 blows on each face of the specimens.

2.3. Indirect Tensile Fatigue test (ITF)

To define the maximum load and temperature to be applied in the ITF tests, indirect tensile tests at 5 °C, 10 °C, 15 °C and 20 °C were conducted. The measurements were taken from 12 test specimens, 3 for each temperature analysed. The equipment used to measure the resistance was a Universal Testing Machine (UVP). The indirect tensile strength of the specimen was determined by applying a load at a rate of 10 mm/min. The ultimate tensile strength of the test samples was 23.25 kN, 19.43 kN, 13.15 kN and 10.32 kN, respectively, for each one of the temperatures studied.

Based on these results, the temperature of the ITF tests was defined as 10 °C and the maximum load applied at each cycle was 7 kN, which is approximately 35% of the ultimate tensile strength of the test samples. In addition, the minimum load was 0.32 kN. The equipment used was a Wille uniaxial compression/tension testing machine, with a maximum load application of 10 kN. The test frequency was 10 Hz. The breaking of the test samples was defined as the moment when the cylinder displacement was 2 cm.

2.4. Temperature and induction heating measurements

The temperature change in the asphalt mixture 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 (Fig. 1(a)). The air temperature during the process was 20 °C. The distance from the test samples to the coil was 2 cm. Finally, the temperature of the circular specimens was calculated as the surface temperature of the specimens.

Table 1
Composition of dense asphalt mixture.

Sieve size (mm)	Aggregate weight % Retained	Cumulative aggregate Weight % retained
4.0–8.0	28	28
2.8–4.0	14	42
1.0–2.8	26	68
1.0–0.25	16	84
0.25–0.063	8.5	92.5
<0.063	7.5	100
Steel particles	(% of Weight of mixture)	19.4
Bitumen 70/100	(% of Weight of mixture)	6

2.5. Average lifetime of the test samples

The average lifetime of the test samples was described by performing ITF tests, at 10 °C, to 15 test samples until failure. The number of cycles until 50% probability to break was calculated by taking logarithms of the number of cycles until failure and by making the average of the logarithms.

2.6. Healing measurements

To evaluate asphalt mixture self-healing, 8 groups of 10 test specimens were first damaged by means of ITF tests. ITF test were stopped after 1000, 1600, 2826, 3090, 3355, 3619, 3884 and 5838 cycles for each group of 10 test specimens. Later, each test sample was introduced in a box filled with sand (Fig. 1(b)), and they were let to rest for 1 h at 20 °C. This was done to avoid deformations during induction heating. After this, every group of test specimens was induction heated during 20 s and they were let to rest during 3 h at room temperature, each test sample in one sandbox. Finally, the test specimens were extracted from the sandbox, introduced in a climatic chamber at 10 °C during 3 h and they were tested until failure in the same climatic chamber as before.

Additionally, 9 groups of 10 specimens each were tested under ITF until 2826 cycles and heated during 0 s, 5 s, 7.5 s, 10 s, 15 s, 17.5 s, 20 s, 22.5 s and 25 s. After this, each test sample was let to cool down during 3 h at room temperature. Finally, the test specimens were extracted from the sandbox, introduced in a climatic chamber at 10 °C during 3 h and they were tested until failure.

The healing level of Marshall test specimens (Healing index: *HI*) after a number of cycles (N_P) was defined as the relationship between the increase of the number of cycles after healing and the number of cycles for having a 50% probability of breaking the test samples before healing ($N_{0.5}$):

$$HI = \frac{N_P - N_{0.5}}{N_{0.5}} \quad (1)$$

2.7. Effect of induction on asphalt mixture ageing

To determine if ageing plays a role on the healing of asphalt mixture under induction heating, Marshall test specimens were heated under induction until they reached 80 °C, 120 °C, 160 °C, 180 °C and 200 °C, respectively. One test specimen for each temperature analysed. The coil was at 2 cm from the surface of the test specimens. Moreover, one test sample was not heated, as a reference.

2.8. Rheological measurements

To determine the healing properties of asphalt binder and the influence of induction heating on its ageing levels, asphalt binder was recovered from the mixtures by rotary evaporator. Moreover, the rheological properties of bitumen were evaluated by analysing its flow behaviour at constant temperature. For this, a Physica MCR 301 dynamic shear rheometer in an 8 mm diameter parallel plate configuration with a 2 mm gap was used. Oscillatory frequency sweeps were carried out over a range of 0.001–0.1 Hz at a reference temperature of 20 °C under strain amplitude of 0.1% within the linear viscoelastic region. The complex viscosity (η^*) as a function of frequency (ω) was recorded automatically during the tests.

2.9. X-ray computed tomography (CT scan)

In order to observe asphalt mixture self-healing, X-ray tomography on different samples has been employed. For that, representative damaged Marshall test samples until 2826 cycles, before and after 10 s induction-heating were selected.

The X-ray source was operated with an acceleration voltage of 450 kV and a current of 1.55 mA. The sample was mounted on a rotational table in a distance of 11.8 mm from the X-ray source at a 0.4 mm nominal focal spot size. The distance between the X-ray source and the X-ray detector was 1499.75 mm. The pixel size obtained was 101.1 µm.

Finally, reconstructions of the microstructure were prepared by segmenting the materials found in a specific volume, based on simple thresholding. With this simple method, aggregates, bitumen and air voids could be readily separated.

3. Results and discussion

3.1. Heating rate of asphalt mixture test samples

In Fig. 2, the temperature evolution of a representative asphalt mixture test sample under induction heating versus time is shown.