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Effect of porosity on infrared healing of fatigue damage in asphalt

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HIGHLIGHTS

- Porosity is a key factor to understanding fatigue healing in asphalt.
- Percolation of air cavities marks a distinction between different behaviours.
- Satisfactory healing is only achieved with air voids sufficient to percolate.
- Thermal expansion of bitumen can produce damage in dense asphalt mixes.
- Thermal treatments can significantly prolong fatigue life of porous mixes.

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ABSTRACT

Nowadays most of our roads are made of asphalt mixes, a complex visco-elastoplastic material with self-healing properties. The present paper explores the effect of air voids content and their interconnectivity on the capacity of asphalt mixtures to heal fatigue cracks when a thermal infrared treatment is applied. Results showed that the percolation of air voids is required to optimise healing results. In samples with a lower content, the thermal expansion of bitumen and its flow through cracks can exceed the pore network's capacity. As a consequence, the internal pressure can increase enough to produce material damage instead of healing.

1. Introduction

Road pavements are infrastructures that must face a long series of damaging agents, such as traffic loads, environment or climate influences, drainage deficiencies, material quality problems and construction deficiencies [1]. Nowadays, most of them are made of hot mix asphalt (HMA) [2], a mix of aggregates and bitumen blended at a temperature between 160 °C and 180 °C [3]. Heating the materials at such temperatures involves high fuel consumption, as well as a series of consequent economic and environmental impacts, like the emission of greenhouse gases and chemical pollutants to the atmosphere [4]. Additionally, such impacts persist during the road's service life, as long as maintenance operations are required [5].

One of the most common failure mechanisms in asphalt pavements is the development of fatigue damage, an accumulation of damage and deterioration of structural capacity produced by a series of repeated loads. This type of damage can be affected by different factors, such as type of loading [6], loading frequency [7,8], working temperature [9,10] and bitumen content in the mix [11]. However, one of the main mix parameters that define the fatigue performance of asphalt pavements is the air voids content and porosity. According to [12] it should be, at least 3% to obtain satisfactory results, however such content is usually selected according to other design requirements, such as type of layer, needed permeability or surface texture.

In order to reduce these impacts, different approaches have been addressed over recent years, such as the development of more durable pavements [13,14] or the use of recycled materials [15,16]. Also the development of materials with self-healing properties, is a research field that sharply grew over the last years [17,18]. The intrinsic self-healing capacity of asphalt mixtures has been studied since the 1960s when it was observed that bitumen can flow through cracks healing damage [19]. However,

Abbreviations: HMA, Hot Mix Asphalt; CT-Scan, X-ray computed tomography scan; LVDT, Linear Variable Differential Transformer.

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this natural process at ambient temperature is slow and has little effectiveness and efficiency. For this reasons, the topic has gained importance over the last decade with the development of advanced techniques, which can accelerate the process and minimise the time the road needs to be closed to traffic loads [18]. As binders with low viscosity can flow more easily through cracks [20], these innovations usually consist of reducing the viscosity in different ways, such as by heating the material [21] or by releasing encapsulated rejuvenators inside it [22].

Different authors have reported that the initial strength properties of asphalt mixtures can be almost completely recovered by increasing its temperature by means of electromagnetic induction [10], microwaves [23], or infrared radiation [24]. Nevertheless, previous works considered just the healing of single and complete cracks that split specimens in two halves. In the case of fatigue microcracks, authors such as [25] stated that, in dense asphalt mixtures (5% air voids), healing can only recover part of the fatigue damage, as plastic deformations occur during the test, and the material becomes brittle. This leads to increases in the stress generated in the area close to the repaired crack, producing a new premature failure. Additionally, [2] also reported partial increases of up to 31% in fatigue life of dense mixtures because of induction heating.

On the contrary, in the case of porous asphalt, the healing capacity of fatigue cracks by electromagnetic induction can be significantly increased [10]. Hence, it seems clear that the air voids content greatly influences the asphalt mixture's healing capacity, but the reasons behind such behaviour are still unclear. Some reasons include that during fatigue tests, dense mixes might be more prone to experiencing permanent deformations that separate both sides of the cracks making their healing difficult [25], while porous asphalt might be more prone to present an opposite reduction in air voids (densification) [3]. In an investigation on microwaves and induction heating of asphalt, [23] also reported that during the process, the total content of air voids does not change. However, it does affect their position inside the material, reducing the healing level that can be achieved with the number of heating cycles. Finally, [24] also hypothesised that the internal pressure generated by bitumen expansion, together with a limited pore network, which is present in dense mixtures, may significantly affect the healing behaviour, even producing internal damage in the samples.

To all this variability, it must be added that the healing phenomenon in fatigue damage has not been yet studied in depth. Hence, the main objective of the present research is to understand, at a fundamental level, the effect of air voids content in the healing capacity of fatigue damage in asphalt mixes. For that, the natural heating effect, produced by the Sun on asphalt roads, was considered and parameters, such as (1) extension of fatigue life; (2) optimum number of cycles to apply the thermal treatment (N_{opt}); (3) evolution of internal pore structure during both damaging and healing processes; and (4) material thermal expansion, were studied for a wide range of asphalt mixes with different air voids contents.

2. Materials and methods

2.1. Description of materials

This study investigated five different types of hot mix asphalt. As specified in Table 1, and in order to obtain materials with different air voids contents, each mix was manufactured with a different gradation, all of them in compliance with Standard BS EN 13043:2013. To keep the same amount of effective bitumen in the mix and based on laboratory experience, its content was progressively reduced at the same time as the amount of fine particles decreased in the mix, as also seen in Table 1. By applying the Standard EN 12697-8:2003 on five samples of each material, the average air void contents obtained were 5%, 10%, 13%, 21% and 26%, respectively. According to American Standards [26], and in terms of resistance to water-damage, these air voids contents can be classified as *Pessimum* (between 5% and 12%, representing most common types of asphalt concrete) and *High* (>12%, representing open-graded mixtures normally designed as surface friction or draining base courses).

Table 1
Gradations, bitumen, and air voids content in the studied asphalt mixes.

Size (mm)	(%) Passing	(%) Passing	(%) Passing	(%) Passing	(%) Passing
31.5	100	100	100	100	100
20	99.1	99.1	99.1	99.1	99.1
16	91.3	91.2	91.2	95.5	91
14	83.3	82.9	82.9	88.1	78.2
10	62	58.8	58.8	53.4	27.6
8	54.1	48.7	48.7	36.3	17.9
6.3	47.8	40.7	40.7	23.1	13.5
4	34.3	29.5	29.5	17.8	11.4
2.8	28.7	25	25	16.6	10.6
2	23.7	20.8	20.8	14	9
1	17	15	15	10.2	6.7
0.5	12.9	11.3	11.3	7.9	5.2
0.25	10.2	9.1	9.1	6.3	4.3
0.125	8.1	7.2	7.2	5.1	3.5
0.063	6.5	5.7	5.7	4.1	2.9
Bitumen*	4.7%	4.5%	4.2%	3.3%	2.7%
Air voids*	**5%**	**10%**	**13%**	**21%**	**26%**

*% contents by weight of total mix.

The type of bitumen was 40/60 pen for all the mixes and the aggregate was crushed limestone with maximum size 20 mm.

2.2. Specimens preparation

The present research's test specimens were prismatic 150 × 60 × 50 mm^3 beams obtained by cutting 306 × 306 × 50 mm^3 slabs into eight pieces, using a radial saw blade, which is suitable for concrete and stone materials. The slabs were manufactured by mixing the pre-heated materials at 160 °C for two hours, and compacting them with a roller compactor. Finally, in order to detect small cracks during the fatigue tests, a uniformly white marking spray paint was applied to one of the lateral 150 × 60 mm^2 sides.

2.3. Three point bending fatigue test

The present investigation carried out fatigue tests by subjecting asphalt beams to dynamic cyclic loads under 3-point bending conditions. Such test configuration was selected to produce clean vertical cracks at the midpoint of the specimens, easy to assess and replicate in different samples. In order to remove the characteristic effect of permanent deformations in this type of tests, an elastic membrane was placed under the specimens.

The loading wave oscillated at a frequency of 4 Hz between a maximum value of 2.5 kN and a minimum of 0.15 kN, which ensured consistent contact between actuator and sample. A resting period of 0.15 s was included between consecutive loading pulses. Finally, the tests were carried out at the 20 ± 1 °C.

During the tests, the lateral previously white-painted side of the specimens was continuously observed using a static camera with a f/2.8 aperture and a 12 MP resolution taking a picture every 40 loading cycles. By using the free image processing software ImageJ, the total length of emerging cracks could be accurately measured in each picture until the sample split in half. This study's adopted