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Effect of metallic waste addition on the electrical, thermophysical and microwave crack-healing properties of asphalt mixtures

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HIGHLIGHTS

- Fibres and shavings from metallic waste were added in asphalt mixtures.
- Electrical, thermophysical and microwave crack-healing properties of asphalt were evaluated.
- CT-Scan results showed that shavings were crushed during asphalt mixing process.
- Metallic waste addition did not improve thermal and electrical properties.
- Healing levels after microwave heating times of 40 s twice those obtained after 30 s.

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ABSTRACT

This paper aims to evaluate the effect of metallic waste addition on the electrical, thermophysical and microwave crack-healing properties of asphalt mixtures. With this purpose, asphalt mixtures with two different types of metallic waste, steel wool fibres and steel shavings, added in four different contents, were tested. Electrical and thermophysical properties of asphalt mixture specimens with, and without, metallic waste were measured. The spatial distribution of the metallic waste inside the asphalt mixture samples was evaluated by using X-ray computed tomography. In addition, crack-healing properties of asphalt samples using microwave radiation heating were assessed at two different healing times, 30 s and 40 s. To quantify the efficiency of the healing process, five healing cycles were carried out for each asphalt sample. The main results showed that asphalt mixtures with shavings presented lower air void contents than mixtures with fibres. Moreover, fibres produced an increase in the electrical conductivity of the mixtures because long fibres in the mixtures form electrically conductive channels. In contrast, shavings did not have significant effect on the electrical properties of the mixtures. Likewise, it was proven that metallic waste reduced the thermal conductivity and the specific heat capacity of asphalt mixtures. Conversely, shavings decreased the thermal diffusivity of asphalt mixtures regardless of their content. Overall, it was found that the healing level reached by the asphalt mixtures tested by microwave radiation depends on the healing time and the type and content of metallic waste used. CT-scans results proved that the spatial distribution of metallic waste inside the asphalt mixture samples was not uniform and played an important role in the asphalt self-healing properties using microwave radiation heating.

1. Introduction

Asphalt mixture is the most used material for pavement construction; it is a composite material fabricated with aggregates and bitumen. Despite its good mechanical properties, an asphalt mixture deteriorates with traffic loads and environmental factors [1]. An alternative to improving the durability of asphalt is the addition of different types of fibres or particles that enhance the mechanical properties of the mixture. Some of the fibres or particles are products fabricated with the main purpose of material reinforcement [2–5], while others are waste obtained from industry [6]. In addition to the enhancement of the mechanical properties of the asphalt mixture, metallic fibres or particles from virgin materials, or from waste [7] can improve the electrical and thermophysical properties of asphalt mixtures [8]. This

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enhancement has led to the development of innovative asphalt pavements with advanced thermophysical properties and energy-harvesting purposes, that are used for solar collection [9], snow melting [10], and crack-healing by external heating [11–15]. García et al. [16] and Wang et al. [17] demonstrated the effectiveness of metallic fibres over other conductive additives in asphalt mixtures, concluding that their morphology and flexibility favour electrical and thermal conductivity [18].

Thermal conductivity in asphalt mixtures increases with the addition of metallic fibres because they absorb more thermal energy than aggregates, thus increasing the total heating rate of the composite material [19]. Nevertheless, the fibre content has to be limited to approximately 6–8% of the bitumen volume, to avoid the formation of fibre clusters that decrease thermal conductivity and porosity [20]. Recently, researchers used the electrical and physical properties of fibres to create asphalt mixtures with crack-healing capabilities by external heating with electromagnetic induction [11] or microwave radiation [12–15]. For the induction heating, an electrical current is applied to conductive coils, creating an alternating electromagnetic field that generates a current in the metallic fibres added to the asphalt mixtures, increasing their temperature by polarisation effects [21]. For the microwave heating, radiation creates electromagnetic waves that produce a change in the orientation of the polar molecules of the asphalt mixture [13], in particular metals, producing an internal friction in the material structure that increases its temperature. The crack-healing capability of this type of mixtures is promising. Sun et al. [21] compared the strength recovery of mixtures with fibres heated by microwave and induction, concluding that the healing performance of asphalt samples heated with microwave was slightly better than samples heated with induction. This was previously demonstrated by Norambuena-Contreras and García [13] who, in addition to the crack-healing properties, studied the internal structure of this type of asphalt mixtures using X-ray microtomography, concluding that virgin metallic fibres modify their internal structure, increasing or decreasing the porosity of the material. Only recently, has attention been paid to the use of solid waste in this type of mixture. Gonzalez et al. [14] evaluated the crack-healing performance of asphalt mixtures containing metallic waste and Reclaimed Asphalt Pavements (RAP), obtaining a strength recovery of approximately 50% by microwave heating. The researchers observed fibre clusters in the mixtures with high metal content, and thus a porosity increase of the mixture.

The review of the current literature has concluded that although there are different studies on the physical and mechanical properties of asphalt mixtures containing metallic fibres, the available data about the electrical, thermophysical, and crack-healing properties of asphalt mixtures containing metallic waste, is still very incipient. For example, a limited research topic in the literature concerns the optimum contents and types of metallic waste to yield asphalt mixtures with advanced properties. The importance of the disposal of metallic waste lies in the fact that metals persist in the environment for a long time before oxidising and degrading. Hence, it is important to find new applications to use this waste, like the replacement of virgin materials or the improvement of the electrical, thermophysical and crack-healing properties of asphalt mixtures containing metallic waste.

This paper presents an extensive experimental programme carried out with the objective of evaluating the effect of the metallic waste addition on the electrical, thermophysical, and microwave crack-healing properties of asphalt mixtures. With this purpose, asphalt mixtures with different contents of steel wool fibres and steel shavings, which are solid waste from the metal industry, were evaluated in the laboratory study. The electrical and thermophysical properties of asphalt mixtures measured in the laboratory were: electrical resistivity; specific heat capacity; thermal diffusivity; and thermal conductivity. In addition, the spatial distribution of the metallic waste and its integrity inside the asphalt mixture samples were evaluated by using X-ray computed tomography. The crack-healing properties of asphalt samples using microwave radiation heating were measured applying different heating times. A total of five crack-healing cycles was applied to the asphalt samples in order to quantify the efficiency of the healing process, as further described in the article.

2. Materials and methods

2.1. Materials

The aggregates gradation (Table 1) was selected to prepare a dense asphalt mixture. The aggregates were classified into three fractions: coarse aggregate or gravel (density 2.779 g/cm^3), fine aggregate or sand (density 2.721 g/cm^3), and filler (density 2.813 g/cm^3). The bitumen content of all the mixtures was 5.3%, by mass of aggregates. The penetration and density of the CA-24 bitumen were 56 dmm (25 °C) and 1.039 g/cm^3, respectively. Two types of metallic waste were added to the asphalt mixtures: steel wool fibres (Fig. 1a) and steel shavings (Fig. 1b). Steel wool fibres were composed of low-carbon steel with density 7.180 g/cm^3, and steel shavings were obtained from austenitic stainless steel with a density of 7.980 g/cm^3. The metallic waste contents by total volume of the bitumen were 2%, 4%, 6%, and 8%. In total, nine different asphalt mixtures were manufactured: one reference or control mixture without metallic waste; four asphalt mixtures with fibres; and four asphalt mixtures with shavings. The aggregate gradation and bitumen content remained constant in the mixtures; only the metal waste content changed.

2.2. Manufacturing of asphalt mixture specimens

The aggregates were heated at 150 °C for 24 h before mixing. The bitumen and metallic waste were also heated at 150 °C, for 2 h before mixing. The mixtures were prepared in the metallic bowl of a mixing machine and were added to the metallic bowl in the following order: first, bitumen and metallic waste (fibres or shavings); second, coarse aggregate; third, fine aggregate; and finally, filler. The materials were mixed for approximately 3.5 min with a speed of 100 rotations per minute, keeping the metallic bowl temperature at 150 °C. After the mixing, the spatial distribution of the metallic waste was visually assessed and, if uniform, the mixture was poured into a pre-heated Marshall mould (dimensions approximately 100 mm in diameter and 60 mm in height), and then compacted with a Marshall Hammer applying 75 blows on each side of the specimen. After compaction, the Marshall specimens were left for 24 h at room temperature (approximately 20 °C), and when cool, extracted from the mould. A total of 81 Marshall specimens was manufactured for this study: 36 with fibres; 36 with shavings; and 9 reference specimens without metallic waste. With the aim of reducing variability in the electrical, thermophysical, and crack-healing characterisation of the mixtures, the two flat planes of each Marshall specimen were cut to reduce the roughness of the surface, obtaining samples with an average height of 40 mm. Once the electrical and thermophysical properties were measured, Marshall samples were cut through two planes to produce semi-circular samples, as described below.

2.3. Morphological characterisation of metallic waste

Metallic waste was morphologically characterised by optical and Scanning Electron Microscopy (SEM). The length of 120 fibres and shavings randomly selected was determined by taking photographs under a stereoscopic microscope with 35x magnification and measuring with the image processing software ImageJ®. The frequency histograms for the length of fibres and shavings are presented in Fig. 2. Moreover, diameter and thickness of the fibres and shavings were calculated as the average value of 50 measurements using a calibrated micrometer, with three repetitions for each measurement. It was determined that the fibres had an average

Table 1
Particle size distribution of aggregates used.

Sieve size (mm)	Aggregate mass % retained	Cumulative aggregate mass % retained	Mass (g)
12.5	16	16	176
10	13	29	143
5	24	53	264
2.5	16	69	176
0.63	17	86	187
0.315	4	90	44
0.16	3	93	33
0.08	2	95	19
<0.08	5	100	58

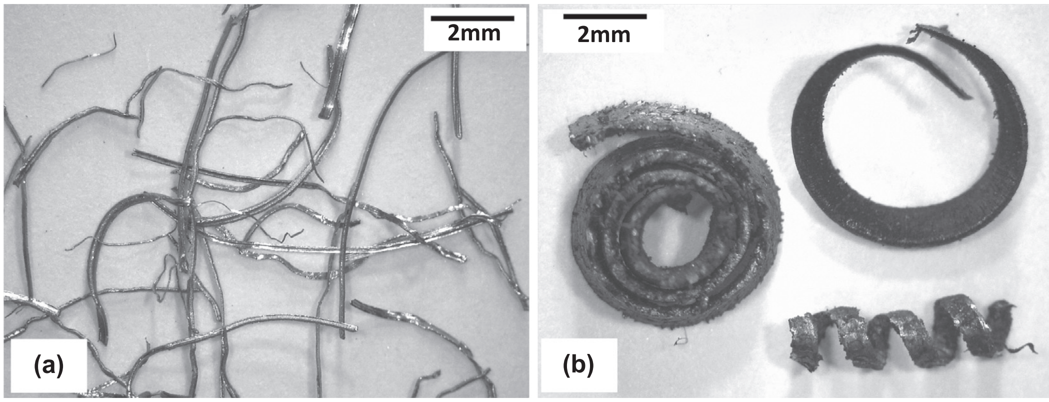

Fig. 1. Optical images of the metallic waste used: (a) steel wool fibres and (b) steel shavings.

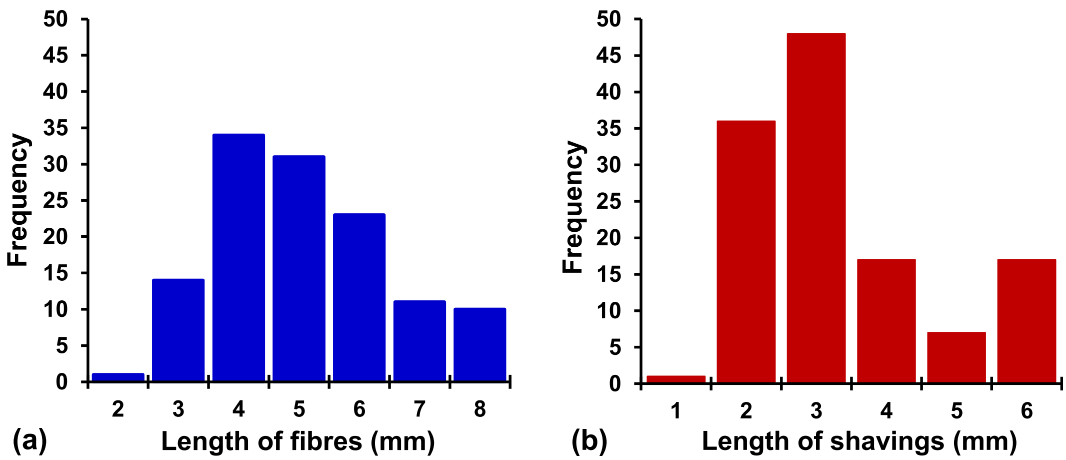

Fig. 2. Frequency histograms for the length of (a) steel wool fibres and (b) steel shavings.

diameter of 0.157 mm, with an average aspect ratio of 30, and an initial length range of 2–8 mm, (Fig. 2a), which implies that both short and long fibres were added to the asphalt mixture. Moreover, the shavings had an average thickness of 0.335 mm and initial length within the range 1–6 mm (Fig. 2b). Additionally, the surface aspect of the fibres and shavings was analysed through SEM images obtained using a Scanning Electron Microscope before, and after, the mixing and compaction processes, by dissolving a portion of asphalt mixture in a solution of toluene and extracting the fibres with a magnet.

2.4. Physical characterisation of the asphalt test samples

Bulk density and air void content of the asphalt mixture specimens with, and without, metallic waste were evaluated with the aim of analysing their influence on the thermophysical and microwave crack-healing properties of the samples. Bulk density was calculated as the relationship between the dry mass and the real volume of each sample. The dry mass and the real volume, including air voids, were obtained from water-submerged Marshall samples. The air void content (AVC) of each test sample was determined from the previous calculation of the bulk density. Thus, as the exact materials' density and content were known for each type of mixture, their maximum theoretical density without voids was calculated. Thus, AVC can be expressed according to Eq. (1):

$$AVC(\%) = \left(\frac{\rho_{mt} - \rho_a}{\rho_{mt}}\right) \times 100 \tag{1}$$

where ρ_a is the bulk density of each sample in g/cm^3, and ρ_{mt} is the maximum theoretical density of each sample without voids in g/cm^3. The reported bulk density and AVC of samples, is the average of 9 measurements for each mixture type.

2.5. Waste distribution by X-ray computed tomography

X-ray micro computed tomography was conducted on samples with different contents of metallic waste. Prismatic samples with dimensions approximately 20 × 20 × 50 mm were cut from the centre of semi-circular samples with 4% of metallic waste after the healing cycles. The X-ray micro-tomography was performed in a scanner operated at 160 kV and 200 μA, and the images were reconstructed at a spatial resolution of 25 μm (voxel side). The classification of voxels with the different types of materials in the asphalt mixture samples was achieved by segmenting voxel intensity values, with the aim of identifying the different fractions of the mixture components, in particular of the different waste used [14,22].

2.6. Electrical resistivity of asphalt test samples

With the aim of evaluating the influence of the type and content of metallic waste on the electrical resistivity of the asphalt mixture samples, the electrical resistance of all the test samples with, and without, metallic waste was measured (Fig. 3a). To do this, a megohmmeter with 5 ranges (50 V–1000 V), connected to two stainless steel electrodes plate with dimensions 10 × 15 cm was used. Each electrode was placed on opposite faces of the sample, ensuring that the samples were centred and the plates horizontally aligned. Additionally, to guarantee good contact between the plate and the sample surface, a small pressure of ~1 kPa was applied on the electrodes. This allowed the obtention of stable measurements, without noise, of the electrical resistance of the mixtures. After the measurement of the electrical resistance of each sample, the electrical resistivity was calculated applying the second Ohm's law:

$$\rho = \frac{R \cdot S}{l} \tag{2}$$

where R is the electrical resistance of each test sample in Ω; $S$is the plate electrode area in m^2; and l is the thickness of each asphalt sample in m. The electrical resistivity of each sample tested was determined as the average of three tests.

2.7. Thermophysical properties of the asphalt test samples

The effect of the type and metallic waste content on the thermal conductivity of all asphalt samples was measured using the thermal needle probe method, based on the transient linear heat source theory [23]. To perform this, a thermal analyser, composed of a handheld controller and a thermal sensor, was used (Fig. 3b). The thermal sensor was a needle (60 mm length and 3.9 mm diameter) with a measurement range of 0.1–6.0 W m^{-1} K^{-1}. To carry out the tests, the thermal sensor was covered with a polysynthetic thermal compound that reduces the presence of air

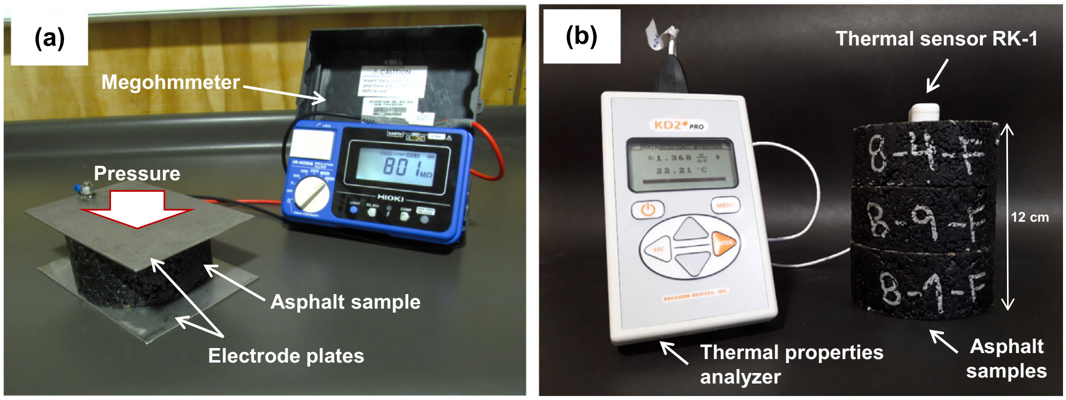

Fig. 3. Measurement of the (a) electrical resistivity and (b) thermal conductivity on the asphalt samples.

voids and the contact resistance between the sensor and the internal surface of the sample. Then, the sensor was embedded in the test sample previously drilled. Additionally, with the aim of providing adiabatic conditions during the measurement, the tested sample was placed on two other test samples with the same metallic waste content, thus ensuring the minimum sample height required by the sensor (Fig. 3b). The heat generated by the sensor inside of the sample produced a temperature variation, detected by the sensor and recorded by the testing device. Each test had a total duration of 10 min. Finally, the thermal conductivity (λ) of each test sample was calculated by using Eqs. (3) and (4) [24]:

$$T = m_1 + m_2 \cdot t + m_3 \cdot ln(t) \quad (3)$$

where T is the recorded temperature; m_1 is the environmental temperature during heating; m_2 is the varying rate of background temperature; m_3 is the slope of a linear relationship between the temperature; and t is the testing time.

$$\lambda = \frac{q}{4 \cdot \pi \cdot m_3} \quad (4)$$

where λ is the thermal conductivity of each sample in W m^{-1} K^{-1}; and q is the heat generated by the sensor in W/m. The thermal conductivity of each test sample was determined as the average of three measurements.

The specific heat capacity and thermal diffusivity are other thermophysical properties of the asphalt mixtures studied, that were calculated using the results from the thermal conductivity tests [25]. The specific heat capacity of each sample (C_p) can be interpreted as the energy needed to increase the temperature of the asphalt mixture by 1 °C, measured in J kg^{-1} K^{-1}. This variable was calculated using Eq. (5):

$$C_p = \frac{1}{m_{Total}}\left[m_{Ag} * C_{Ag} + m_B * C_B + m_{M.W} * C_{M.W}\right] \quad (5)$$

where m_{Total} is the total mass of each test sample in kg; C_{Ag} and m_{Ag} are the specific heat capacity and the mass of the aggregates in J kg^{-1} K^{-1} and kg, respectively; C_B and m_B are the specific heat capacity and the mass of the bitumen in J kg^{-1} K^{-1} and kg, respectively; and $C_{M.W}$ and $m_{M.W}$ are the specific heat capacity and the mass of metallic waste in J kg^{-1} K^{-1} and kg, respectively. $C_{M.W}$ takes the form of C_F in the case of fibres, and C_S in the case of shavings. The specific heat capacity of each component of the mixture was obtained from the literature: C_{Ag} = 908 J kg^{-1} K^{-1} [26], C_B = 1900 J kg^{-1} K^{-1}, C_F = 482 J kg^{-1} K^{-1} [13], and C_S = 450 J kg^{-1} K^{-1} [27].

Additionally, the thermal diffusivity of each asphalt sample (β) can be interpreted as the transmission speed of the heat energy, in m^2/s, through the asphalt mixture. The heat energy is transferred from higher to lower temperature zones, until a thermal balance is achieved. The thermal diffusivity is calculated using Eq. (6):

$$\beta = \frac{\lambda}{\rho_a * C_p} \quad (6)$$

where λ is the thermal conductivity of the sample in W m^{-1} K^{-1}; ρ_a is the bulk density of each test sample in g/cm^3, and C_p is the specific heat capacity of each asphalt test sample in J kg^{-1} K^{-1} according to Eq. (5).

2.8. Crack-healing properties of asphalt mixtures

The crack-healing properties of asphalt mixtures heated by microwave radiation containing metallic waste, were measured by means of 3-point bending tests. The strength of the mixtures was measured in semi-circular test samples obtained from Marshall samples, that were pre-conditioned at −20 °C for 24 h before testing to obtain a brittle fracture. A notch of 4 mm thickness and 10 mm height was cut centred in the bottom side of the test samples (Fig. 4). During the 3-point bending test the notch was orientated in the vertical load direction to locate the initial point of cracking at the tip of the notch. The procedure to measure the crack-healing of the samples consisted of the following steps (Fig. 4):

(1) Semi-circular test samples were placed on two supporting rollers separated by 80 mm. A vertical monotonic load at a speed of 0.5 mm/min was applied up to failure in the midpoint of the semi-circular arch of the sample (Fig. 4a). The loading machine was equipped with a 50 kN load cell.
(2) Once the bending test had finished, broken asphalt samples were left at room temperature for 2 h until they reached 20 °C, ensuring that the surface moisture resulting from freezing had completely evaporated (Fig. 4b). Then, the two parts of the sample were put together and heated using microwave radiation for two different heating times, 30 s and 40 s. These times were considered suitable for microwave healing based on previous research results [15]. All the tests were carried out using a 700 W microwave, and a working frequency of 2.45 GHz, equivalent to a wavelength of 120 mm (Fig. 4c).
(3) After heating, the samples were left at room temperature for 2 h. Later, the samples were conditioned at −20 °C for 24 h, and again tested in the 3-point bending test, completing a crack-healing cycle (Fig. 4d).

The healing level (HL) reached by each tested semi-circular sample was defined as the quotient between the peak load achieved by the sample after the healing process (F_{healed}), and the peak load achieved by the same sample before the first healing cycle ($F_{initial}$):

$$HL = \frac{F_{healed}}{F_{initial}} \quad (7)$$

Finally, a total of 5 crack-healing cycles was carried out for each asphalt sample to quantify the efficiency of the healing methodology. In summary, more than 1000 microwave-healing cycles were conducted in this research study.

2.9. Temperature distribution of the test samples after microwave heating

With the aim of knowing the temperatures reached by asphalt mixtures heated using microwave radiation, the surface temperature of the semi-circular test samples was measured using a 320 × 240 pixel full colour thermographic camera after each heating time. The surface temperature of each specimen was recorded for 10–12 s immediately after the 30 s and 40 s microwave heating was finished. To obtain representative results, the temperature was measured at 7 points of the sample surface, and the data was later analysed using specialised software (Fig. 4c).

3. Results and discussion

3.1. Effect of the metallic waste on the physical properties of asphalt mixtures

Fig. 5 shows the average results of the bulk density (BD) and air void content (AVC) of test samples with, and without, metallic waste. In this Figure, the maximum average BD was 2.373 g/cm^3, obtained for the reference mixture. The addition of metallic waste reduced the average BD in all the mixture types, compared to the reference mixtures. Additionally, the BD of samples with metallic waste slightly reduced with the increase of the waste content. This is explained by the change of the volume and mass of the mixture with the addition of the metallic waste, although the variation of the total volume was more significant than the variation of mass, compared to a reference mixture without metallic waste. Conversely, the AVC increased with the increase of metallic waste con-

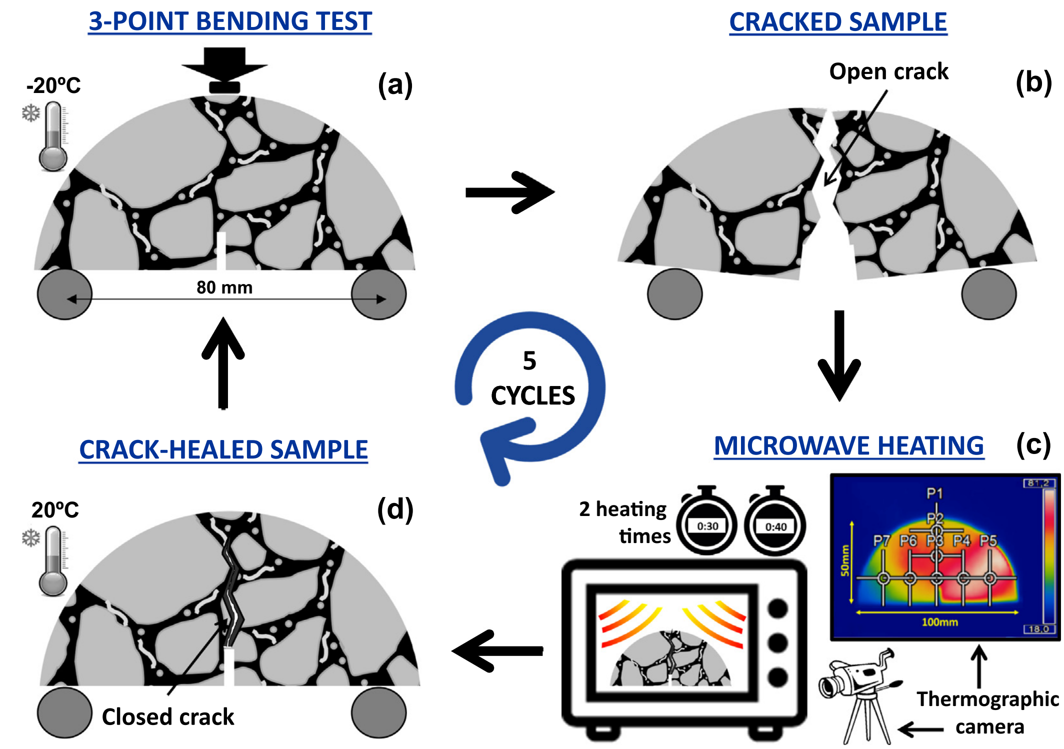

Fig. 4. Schematic representation of crack-healing cycles and measurement of the temperature distribution of the tests samples via microwave heating.

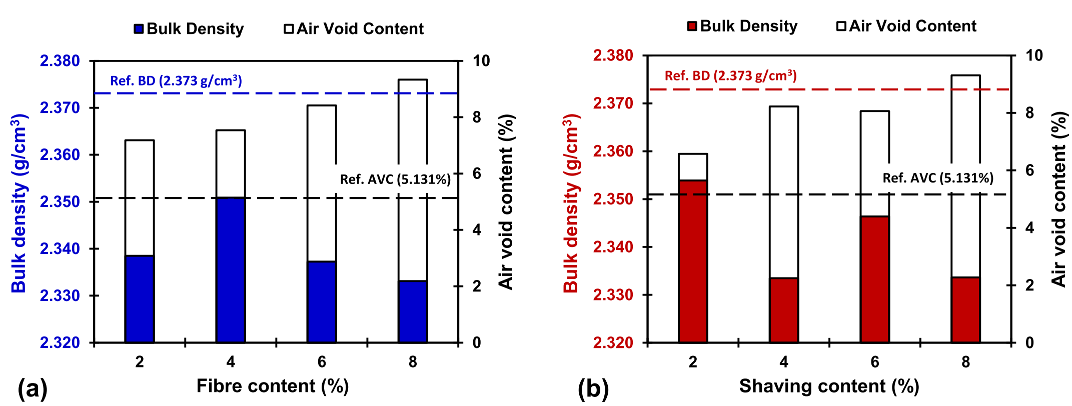

Fig. 5. Average results of bulk density (BD) and air void content (AVC) of asphalt mixtures with: (a) steel wool fibres, and (b) steel shavings.

tent. The lowest AVC was measured in the reference mixtures (5.13%), while the AVC values in mixtures with 2%, 4%, 6%, and 8% fibre content were 7.18%, 7.54%, 8.42% and 9.33% respectively (Fig. 5a). The AVC in mixtures with shavings was also higher than in the reference mixtures with 6.57%, 8.22%, 8.06%, and 9.31% for 2%, 4%, 6%, and 8% shaving contents (Fig. 5b). This behaviour is attributed to the lower total specific surface area of the mixtures without waste compared to mixtures with waste. It was also observed that mixtures with shavings have less AVC compared to mixtures with fibres. This is explained by the more brittle behaviour of the austenitic stainless steel metal shavings, compared to the metal steel fibres. Austenitic steel shavings fractured and reduced in size because of the mechanical crushing and cutting forces applied during the mixing and compaction of the mixtures (Fig. 6).

This hypothesis is supported by the CT-Scan reconstructions shown in Fig. 7. From this Figure, it can be seen that the steel fibres keep their initial morphology (Fig. 7a), while some steel shavings broke into smaller particles (Fig. 7b). This mechanical degradation reduced the ability of shavings to form clusters, and consequently reduced the occurrence of air voids in the mixtures. Nevertheless, the BD and AVC measured in mixtures with 8% metallic waste were very similar, 2.333 g/cm^3 and 9.33% for the mixtures with fibres, and 2.334 g/cm^3 and 9.31% for the mixtures with shavings. Likewise, these samples presented the highest AVC. Norambuena-Contreras et al. [28] reported similar results in asphalt mixtures with virgin metallic fibres, concluding that high contents of fibres can produce a poor distribution inside the mixtures.

3.2. Effect of the metallic waste on the electrical resistivity of asphalt mixtures

Fig. 8a shows the electrical resistivity measured for samples with different types and content of metallic waste and reference samples. The average electrical resistivity for the control or reference mixture was 3.27×10^8 Ωm, while the average electrical resistivity for samples with 2%, 4%, 6%, and 8% of fibres was 1.68

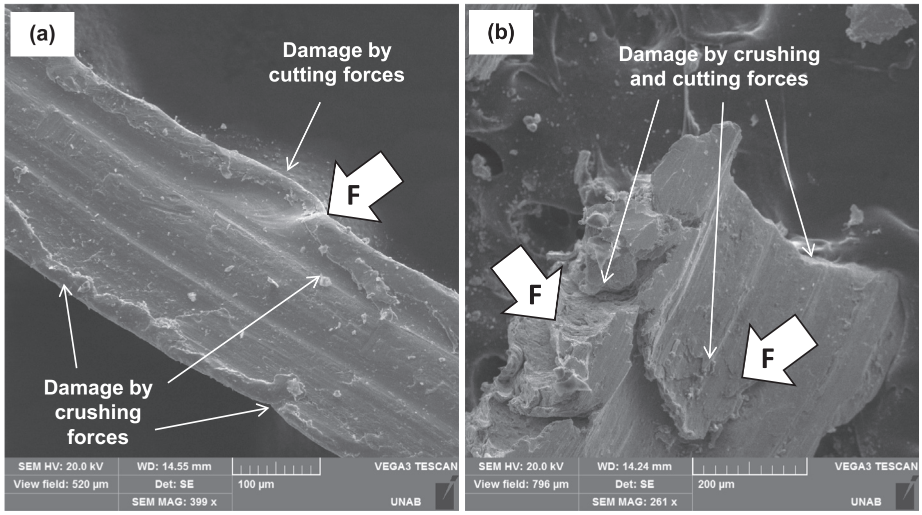

Fig. 6. SEM images (a) of steel wool fibres and (b) steel shavings after mixing and compaction process.

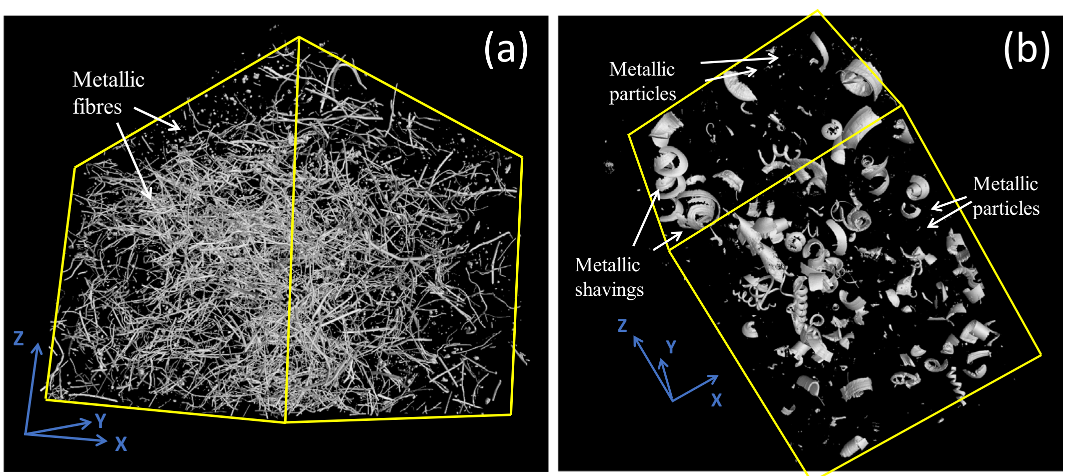

Fig. 7. Three-dimensional images of X-ray micro computed tomography on asphalt mixtures with (a) 4% metallic fibres, and (b) 4% metallic shavings. Bounding box dimensions are 20 × 20 × 50 mm approximately.

$\times$ 10^8 Ωm, 1.56 × 10^8 Ωm, 4.05 × 10^7 Ωm and 2.04 × 10^7 Ωm, respectively. Results show that samples with fibres showed an electrically conductive behaviour, different from samples with shavings, which showed electrically conductive behaviour similar to the reference mixtures without waste. Additionally, it was found that the average electrical resistivity decreased with increase of the fibre content (Fig. 8a), thus increasing the electrical conductivity of the asphalt mixtures.

To better understand results from Fig. 8a–e show a schematic representation on the effect of the type and content of metallic waste on the electrical resistivity of asphalt mixtures. Fig. 8b presents the reference mixture without fibres; however, in Fig. 8c and d fibres behave as electrically conductive channels. Therefore, the higher the fibre content, the greater the probability of electrical contact between fibres, increasing the electrical conductivity of the material. This reaffirms the percolation theory on electrically conductive composite materials [29], which establishes that conductivity of a composite material increases if the content of the electrically conductive fraction increases, until a percolation point, where the electrical conductivity remains constant. Based on this theory, it would be possible to identify three phases associated with the fibre behaviour in asphalt mixtures (blue columns in Fig. 8a):

(i) *Isolation or non-conductive phase*: where fibres are dispersed in the mixture, and its electrical behaviour is similar to that of a reference mixture (Fig. 8b and c). Phase i corresponds to samples with a fibre content up to 4%.
(ii) *Transition phase*: where the electrical resistivity is significantly lower than the reference and the asphalt mixture starts to show an electrically conductive behaviour (Fig. 8d). Phase ii corresponds to samples with a fibre content between 6% and 8%.
(iii) *Conductive phase*: where the fibres define an electrically conductive channel, and the effect of an increase in the fibre content on the electrical resistivity is not significant. This value is known as the percolation point; however, with the range of fibre contents used in this study, the percolation point was not observed (Fig. 8a).

Fig. 8a shows that asphalt mixtures with shavings have similar electrical resistivity to reference or control mixtures without shavings (3.27 × 10^8 Ωm), indicating that shavings have no effect on the reduction of electrical resistivity. The average electrical resistivity obtained from samples with shavings, listed from highest to lowest, were: 6.5 × 10^8 Ωm, 5.5 × 10^8 Ωm, 4.9 × 10^8 Ωm, and 3.5 × 10^8 Ωm with contents of 6%, 4%, 2%, and 8%, respectively.

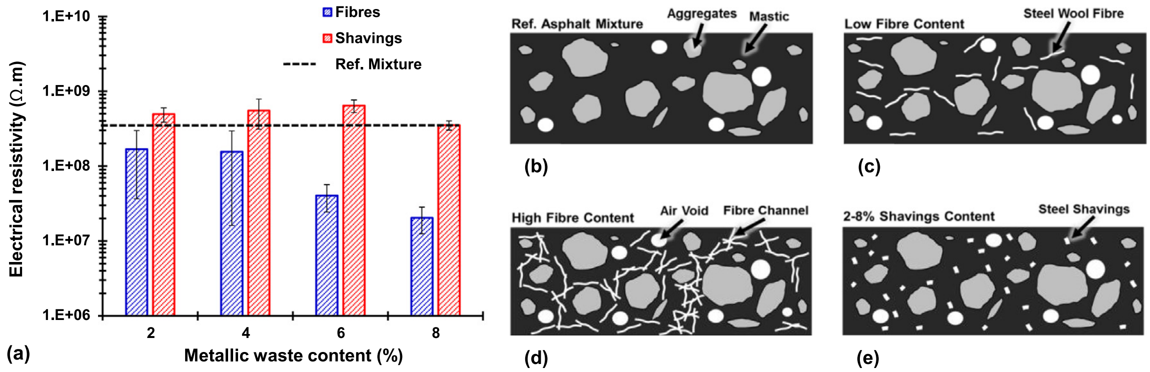

Fig. 8. (a) Average electrical resistivity of the samples depending on the type and content of metallic waste, and (b-e) effect of the metallic waste inside the asphalt mixtures: (b) reference mixture without waste, (c) mixture with a low fibre content, (d) mixture with a high fibre content, and (e) mixtures with shavings. Image based on Wang et al. [17].

This result is explained by the hypothesis that a fraction of the shavings were crushed during the mixing and compaction processes, behaving like particles and not as fibres with higher aspect ratio, as observed in CT-Scan results (Fig. 7) and in previous works published by Gonzalez et al. [22]. In summary, the crushed shavings do not favour the formation of conductive channels inside the asphalt mixtures, thus making them unable to behave like electrically conductive elements. This behaviour is also explained by the austenitic stainless steel shavings, composed of nickel and chrome. These elements provide higher electrical resistivity to steel than the low-carbon steel contained in the case of the steel wool fibres [30] and hence, asphalt test samples with steel shavings have a lower capacity to transfer the electricity through them (Fig. 8a).

The lowest electrical resistivity was obtained for mixtures with 8% fibres, 2.04×10^7 Ωm. Thus, the electrical resistivity to reach the percolation threshold was not observed in this study, although mixtures with 6% and 8% of fibres showed an electrical transition behaviour. Therefore, in future research, mixtures with fibres could be potentially used to develop conductive roads that behave as piezoelectric materials. In these pavements, the application of traffic loads would produce a variation in their electrical resistivity, making it possible to self-monitor possible damages with the help of sensors [31].

3.3. Effect of the metallic waste on the thermophysical properties of asphalt mixtures

Table 2 presents the average results of the thermophysical properties (thermal conductivity, specific heat capacity and thermal diffusivity) obtained from the asphalt test samples with different types and contents of metallic waste. Table 2 shows that the addition of metallic waste decreases the average thermal conductivity with respect to the reference mixture. This result is explained by previous studies [32] that relate the AVC increase with the addition of metallic waste to the mixtures (Fig. 5). The increase of AVC reduced the heat transmission of the mixtures, as a result of the higher heat dissipation through the air voids. The reference mixtures showed the highest average thermal conductivity ($1.406\ \mathrm{W\,m^{-1}\,K^{-1}}$); however, mixtures with fibres showed higher thermal conductivity than mixtures with shavings, regardless of the waste content (Table 2). This is explained by the shape and spatial distribution of fibres and shavings in the asphalt matrix as shown in the X-ray three-dimensional (3D) images (Fig. 7). Shavings (Fig. 7b), have helicoidal and spring shapes, with different diameters, width and spatial orientation. The shavings have a thin thickness compared to their length and width, of the order of 0.1 mm. The thickness of shavings is larger than fibre diameter, hence, the exposed area of the shaving surface per volume of metal is lower than in fibres (Fig. 7a). This means that fibre metal is distributed homogeneously throughout the mixture, while metal shavings are more concentrated only in some points of the asphalt. This behaviour, together with the increase of AVC, caused the higher susceptibility of mixtures with shavings to reduce their thermophysical properties. Therefore, metallic fibres enhanced the internal heat flux to low temperature zones of the samples, indicating that the influence of the fibre content was more important than the AVC in this type of mixtures. Another reason to explain the difference between thermal conductivity in samples with fibres and shavings is the composition of the waste steel. Chagas et al. [33] found that the austenitic steel of the shavings used in this research has a lower thermal conductivity than the low-carbon steel of the fibres [32], resulting in the lower ability to transfer heat in mixtures with shavings, compared to mixtures with steel fibres.

In addition, Table 2 shows that the specific heat capacity of the samples decreased with the increase in the metallic waste content. This is explained by the increase in the total mass of the samples with the increase of the waste content; hence, the highest specific heat capacity was measured in the reference mixture ($957.93\ \mathrm{J\,kg^{-1}\,K^{-1}}$). Besides, the specific heat capacity of samples with fibres

Table 2
Average thermophysical properties of the asphalt test samples with and without metallic waste.

Metallic waste content	Steel wool fibres			Steel shavings		
	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)	Thermal diffusivity ($\times 10^{-7}$) (m^2/s)	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)	Thermal diffusivity ($\times 10^{-7}$) (m^2/s)
2%	1.343	954.67	6.017	1.187	954.01	5.286
4%	1.385	951.45	6.192	1.246	950.16	5.621
6%	1.379	948.27	6.223	1.257	946.36	5.662
8%	1.369	945.13	6.209	1.252	942.62	5.691
Ref. 0%	1.406	957.93	6.185	1.406	957.93	6.185

was similar to that of reference mixture samples, ranging from 954.67 J kg^{-1} K^{-1} to 945.13 J kg^{-1} K^{-1} with 2% and 8% of fibres, respectively. However, the specific heat capacity of samples with shavings was slightly lower than the reference mixtures, ranging from 954.01 J kg^{-1} K^{-1} to 942.62 J kg^{-1} K^{-1} with 2% and 8% of shavings, respectively. This is explained because of two reasons: i) the higher density of the shavings compared to the fibres, which increased the total mass used in Eq. (5), and ii) the specific heat capacity values of the metallic waste considered in Eq. (5), which was slightly lower in shavings than in fibres.

Similarly, Table 2 presents the thermal diffusivity of the mixtures with fibres. For a 4% metal content, the thermal diffusivity was higher than that for the reference mixtures. The highest thermal diffusivity was measured in samples with 6% of fibres (6.223 $\times 10^{-7}$ m^2/s), followed by samples with 8% and 4% with 6.209 $\times 10^{-7}$ m^2/s and 6.192 $\times 10^{-7}$ m^2/s, respectively. These results are explained by the reductions of bulk density and specific heat capacity of these asphalt mixtures that were higher than their reduction in their average thermal conductivity (Table 2). In contrast, the shavings addition produced a reduction of the thermal diffusivity of asphalt mixtures compared to the reference mixture.

3.4. Effect of the metallic waste on the heating and crack-healing properties of asphalt mixtures

Table 3 presents the results of temperatures reached by the asphalt mixtures with metallic waste after 30 s and 40 s of microwave heating. The temperature was collected at 7 points of the sample surface. The Table shows that, in general, the temperature of the mixtures increases with the increase in the metallic content up to 6%. However, a lower temperature was measured in samples with 8% of metal content, attributed to their AVC increase (Fig. 5), which enhanced the ability of the mixtures to dissipate heat. As result of the temperature distribution reached by the semi-circular samples, Fig. 9 presents a matrix of representative thermographic images of the asphalt samples with different types and content of metallic waste, seconds after being heated using microwave radiation. The figure shows that samples with fibres reached a more homogeneous surface heating, while samples with shavings presented localised heating zones, explained by the spatial distribution of this waste in the samples. Fibres are more equally distributed in the mixture (Fig. 7a), while shavings are more concentrated in some points of the sample (Fig. 7b). Likewise, it

Table 3
Results of temperatures reached by the asphalt mixtures after microwave heating for 30 s and 40 s.

Metallic waste content	Average ± Std.Dev.of maximum temperature (°C)			
	Steel wool fibres		Steel shavings	
	30 s	40 s	30 s	40 s
2%	76.4 ± 4.3	89.9 ± 14.7	75.0 ± 2.6	80.2 ± 4.9
4%	89.1 ± 7.7	91.8 ± 15.5	76.8 ± 18.3	86.6 ± 3.8
6%	93.9 ± 9.8	106.3 ± 12.6	83.6 ± 17.3	78.0 ± 14.5
8%	73.7 ± 21.2	99.0 ± 2.7	83.1 ± 9.9	99.3 ± 8.9

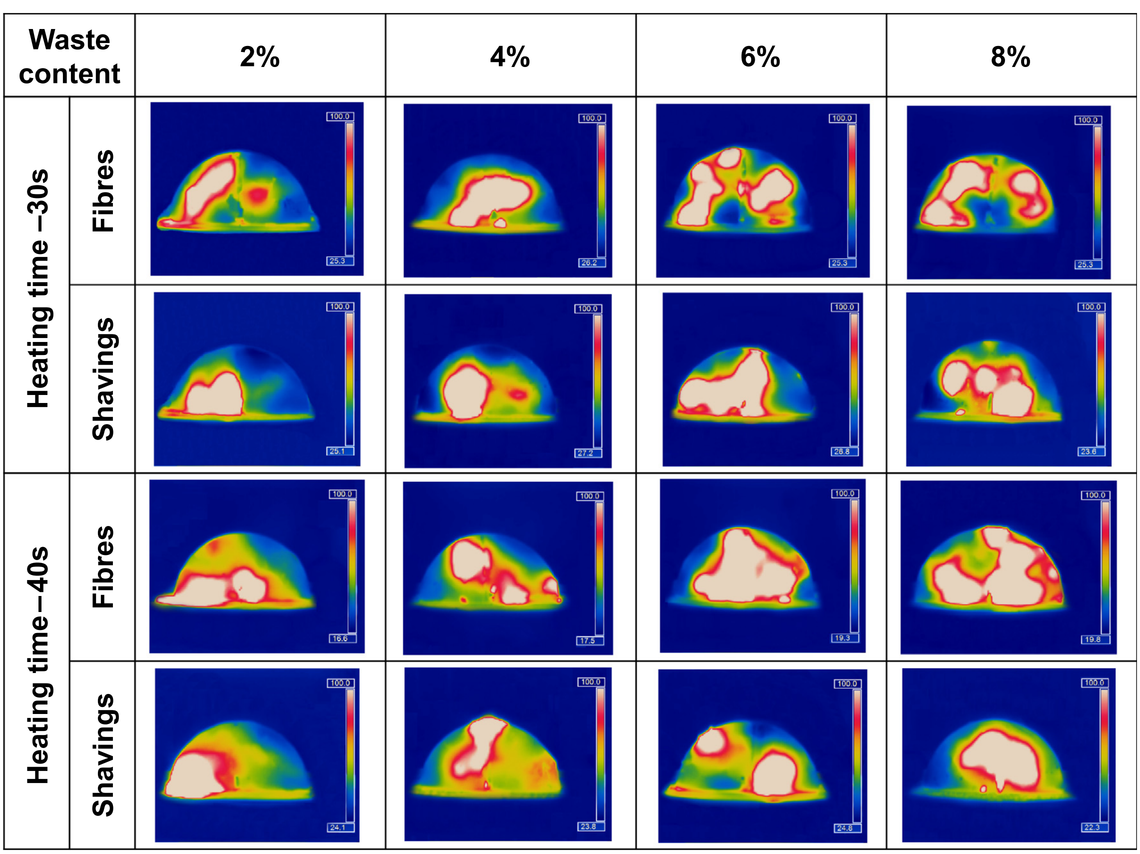

Fig. 9. Thermographic images of the asphalt test samples with fibres and shavings after microwave heating.

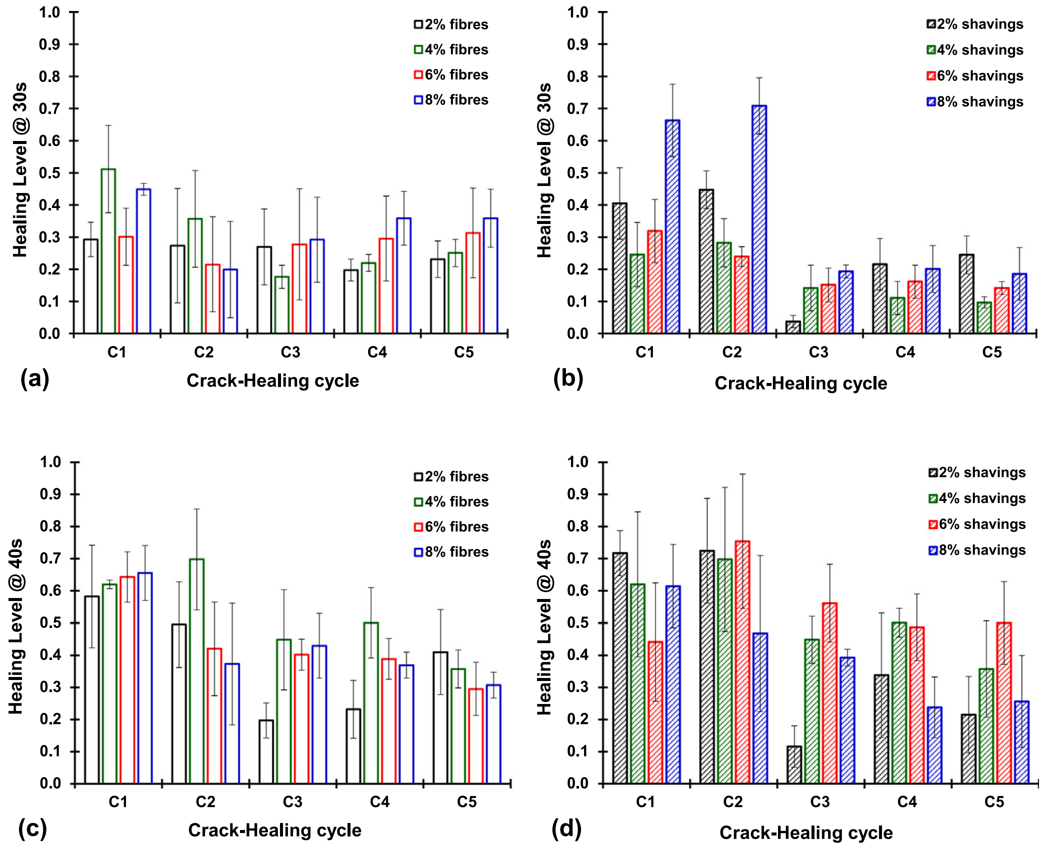

Fig. 10. Healing levels reached by asphalt mixtures with different type and content of metallic waste, and microwave heating time: (a) mixtures with fibres heated for 30 s, (b) mixtures with shavings heated for 30 s, (c) mixtures with fibres heated for 40 s and (d) mixtures with shavings heated for 40 s.

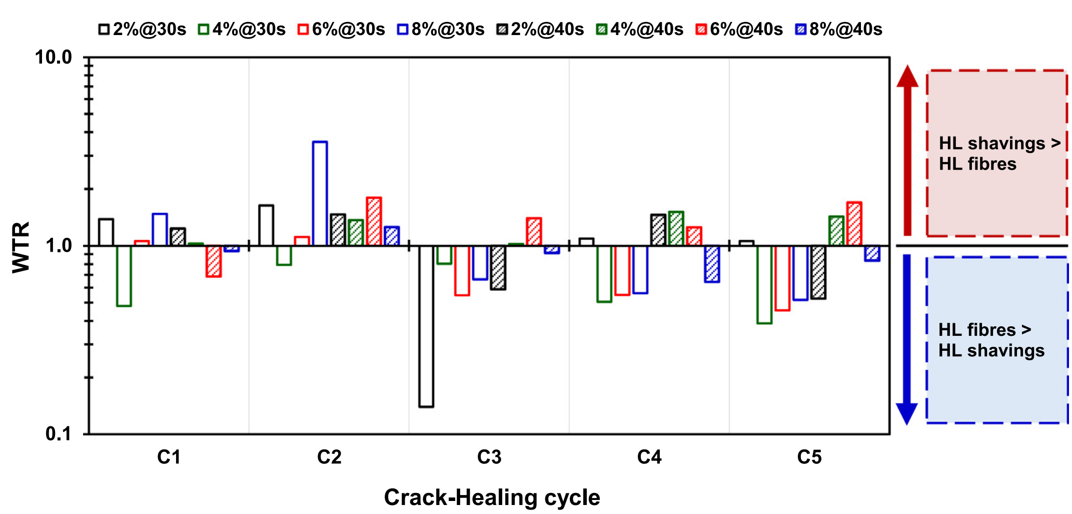

Fig. 11. Waste Type Ratio (WTR) obtained for the different contents during the 5 crack-healing cycles.

was observed that samples heated for 40 s reached higher maximum temperatures than samples heated for 30 s, which can imply higher crack-healing levels [15].

Fig. 10 presents the average Healing Levels (*HL*) results and their standard deviation (error bars) measured in the samples with fibres and shavings during the 5 crack-healing cycles, after the 30 s and 40 s heating times. The figure shows that the *HL* reached by the samples heated for 40 s, are higher than the *HL* reached by the samples heated for 30 s, for asphalt mixtures with fibres and shavings. This result is attributed to the higher temperatures of the samples heated for 40 s (Table 3 and Fig. 9) that reduce bitumen viscosity, facilitating the bitumen flow through the open cracks, and sealing them [13]. For example, for the first healing cycle the average *HL* values in samples with 2%, 4%, 6%, and 8% of fibres heated for 30 s were 29.3%, 51.2%, 30.1% and 44.9%, respectively. The *HL* values reached by the equivalent samples after 40 s heating were 58.2%, 60.3%, 64.3%, and 65.6%. In contrast, samples with 2%, 4%, 6%, and 8% of shavings heated for 30 s reached average

HL values of 40.5%, 24.6%, 31.9%, and 66.3%, respectively. The *HL* reached by the equivalent samples after 40 s heating were 71.7%, 62%, 44.1%, and 61.4%.

Additionally, Fig. 10 shows that, in general, increasing the number of crack-healing cycles decreases the *HL*, regardless of the content of metallic waste, although there are differences for the two heating times applied (Fig. 10). For instance, the average reductions of *HL* for the samples with fibres and shavings heated for 30 s, between the first and last crack-healing cycle (C1-C5) were 10.3% and 24%, respectively. Conversely, samples with fibres and shavings heated for 40 s presented higher average reductions of 30.5% and 28%, respectively. This reduction was also observed in previous research studies [13–15], and is attributed to the high temperatures reached by the asphalt mixtures that produce damage in the bitumen and in the samples, varying their microstructure, increasing the porosity, and reducing their mechanical strength [13].

Additionally, regarding the differences between the samples with fibres and with shavings, Fig. 10 shows that samples with shavings reached higher average *HL* values than samples with fibres, when heated for 40 s. However, results present an important scattering, described by the error bars. Therefore, t-Tests, with a significance level $\alpha = 0.05$, were conducted to study the statistical differences in the healing of samples with fibres and shavings. For the heating times of 30 s and 40 s, p-values of 0.258 and 0.137 were obtained, respectively. This means (p-values >0.05) that the registered differences are not statistically significant. Regarding the effect of the metallic waste content on the *HL*, samples with 2%– 8% gave similar *HL* values in samples heated for 30 s. Exceptionally, it was observed that the *HL* of mixtures with 8% of shavings in cycles C1 and C2 (Fig. 10b), stand above the rest of results. This is explained by the spatial distribution of the shavings and the high temperatures reached because of that distribution (Fig. 7b). Nevertheless, samples heated for 40 s, with 4% of fibres and 6% of shavings content achieve the highest*HL*. To do a better comparison of the *HL* obtained in samples with fibres and shavings (Fig. 10), Fig. 11 presents the results of the Waste Type Ratio (WTR), defined by Eq. (8):

$$WTR = \frac{HL_s}{HL_f} \tag{8}$$

where HL_s is the average *HL* reached by the samples with shavings, with a specific waste content, cycle number and heating time; and HL_f is the average *HL* reached by the samples with fibres with the same waste content, cycle number and heating time. *WTR* is an indicator of the type of waste that yields the highest *HL* for each mixture type and heating time applied. $WTR > 1$ means that samples with shavings have higher *HL* than samples with fibres in the equivalent conditions. In contrast, values of $WTR < 1$ mean that samples with fibres have higher *HL* than samples with shavings. The closer the WTR value to 1, the lower the difference of *HL* between the samples with fibres and with shavings.

As can be observed in Fig. 11, the samples with fibres heated for 30 s, showed, in general, higher values of *HL* than those with shavings ($WTR < 1$). In contrast, samples with shavings heated for 40 s, showed higher *HL* ($WTR > 1$). Nevertheless, the influence of the metallic waste type or the crack-healing cycle on the healing behaviour of asphalt mixtures was not clearly observed. In view of the above, Fig. 12 shows the relationship between the healing levels (*HL*) of samples with fibres and shavings heated for 30 s and 40 s, regardless of the waste content in the mixture and the crack-healing cycle. In this Figure, an equality line (slope 1:1) was included with the aim of determining the difference between the *HL* reached by the samples with fibres and the samples with shavings. The HL dots of the figure, aligned to the equality line,

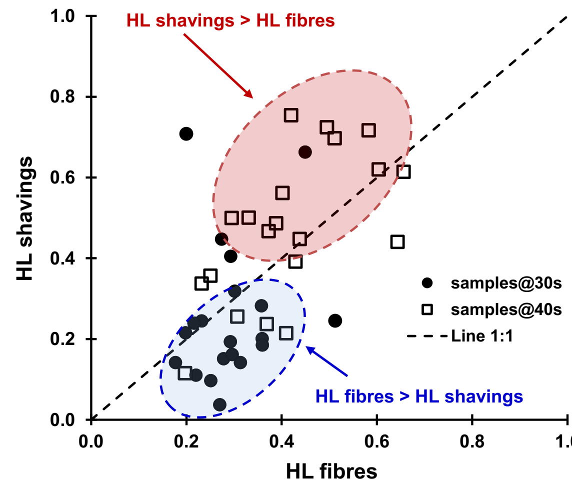

Fig. 12. Relationship between the Healing Levels reached by the asphalt mixtures with fibres and shavings.

represent similar *HL* values for fibre and shavings mixtures. Dots located over the equality line indicate higher *HL* measured in samples with shavings, and vice versa. However, the dots are not aligned, indicating different *HL* values, as discussed in Fig. 11.

Additionally, in Fig. 12 the majority of the dots located under the line 1:1 are samples heated for 30 s (see blue cluster of dots in Fig. 12), indicating that healing of samples with fibres is more effective with 30 s of heating time. However, samples with shavings heated for 40 s in general have higher *HL* values (see red cluster of dots in Fig. 12), and therefore higher healing efficiency levels. In this context, Fig. 13 presents the Healing Efficiency Level (*HEL*) calculated for the test samples with fibres and shavings for all the crack-healing cycles evaluated. This Efficiency Level represents the *HL* variation in asphalt mixtures when heated for 30 s and 40 s. The *HEL* is calculated using the following Equation:

$$HEL = \left[\frac{HL_{40s}}{HL_{30s}}\right]_{w\%,c} \tag{9}$$

where HL_{40s} is the *HL* obtained ine samples heated for 40 s; and HL_{30s} is the *HL* obtained in their equivalent samples heated for 30 s for the same type and metallic waste content. In other words, this ratio quantifies the efficiency of increasing the microwave heating time of the test samples in 10 s.

In Fig. 13, it can be observed that *HEL* is higher than 1 in most cases, which means that the *HL* with a 40 s heating time is always

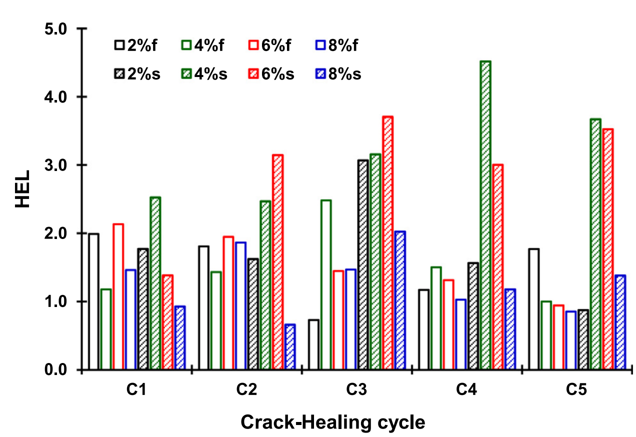

Fig. 13. Healing Efficiency Level (HEL) of asphalt mixtures with different type and content of metallic waste (f = fibres, s = shavings).

higher than that with a 30 s heating. In addition, in general the *HL* after a heating time of 40 s, was twice the *HL* of samples heated for 30 s. Moreover, the *HEL* obtained in asphalt mixtures with shavings were higher than in mixtures with fibres, implying that an increase of 10 s in the heating time is more effective in samples with shavings. Finally, it was observed that samples with 4% and 6% shavings presented the highest *HEL*, while samples with fibres presented similar values of *HEL* regardless of the waste content and the number of crack-healing cycles. Therefore, asphalt mixtures containing 4% and 6% metallic waste content could be potentially used to build long-life roads with crack-healing properties through microwave radiation heating.

4. Conclusions

In this paper, the effect of the metallic waste addition on the electrical, thermophysical and microwave crack-healing properties of asphalt mixtures has been evaluated. Based on the results analysis, the following conclusions were obtained:

- Asphalt mixtures containing metallic waste reduced their bulk density with respect to mixtures without waste, and the bulk density of the mixtures with waste slightly reduced with the increase of the waste content.
- The air void content in asphalt mixtures containing metallic waste increased with the increase of waste content. Overall, mixtures with steel shavings presented lower air void contents than mixtures with steel wool fibres.
- CT-Scan results proved that the metallic waste spatial distribution inside the asphalt mixture samples was not uniform. It was observed that a fraction of the steel shavings were crushed during the mixing and compaction processes, thus fracturing into smaller particles which makes them concentrate only in some points of the asphalt mixture. In contrast, fibres maintain their initial morphology, being homogeneously distributed throughout the mixture.
- The electrical resistivity of the asphalt mixtures decreased with the increase of the fibre content. This was explained by the good connectivity of fibres in the asphalt mixture. In contrast, the electrical resistivity did not decrease with the increase of shavings content, registering constant values higher than that of the reference mixture. This was due to the type of steel that composes the shavings and to their poor connectivity inside the asphalt mixtures.
- It was proven that the asphalt mixtures containing metallic waste reduced their thermal conductivity and their specific heat capacity. However, steel wool fibre contents up to 4% produced an increase in the thermal diffusivity. In contrast, metallic shavings decreased the thermal diffusivity of asphalt mixtures regardless of their content.
- Finally, it was found that both the heating time and the metallic waste type had an influence on the crack-healing behaviour of asphalt mixtures. Thus, heating times of 40 s achieve *HL* values twice those with heating times of 30 s, and the increase of 10 s on the heating time had a greater influence on samples with shavings. Moreover, it was proven that the addition of fibres was more effective to seal the cracks when applying shorter heating times (30 s), while the presence of shavings in asphalt mixtures reached higher *HL* values when applying longer heating times (40 s).

This preliminary study indicates that the addition of metallic waste from industry can modify the electrical, thermophysical and crack-healing properties of the asphalt mixtures. As a result, metallic waste combined with microwave heating, has the potential for the future development of a new self-healing asphalt technology.

Conflict of interest

None.

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