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Research article

Self-healing properties of recycled asphalt mixtures containing metal waste: An approach through microwave radiation heating

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ABSTRACT

The concept of self-healing asphalt mixtures by bitumen temperature increase has been used by researchers to create an asphalt mixture with crack-healing properties by microwave or induction heating. Metals, normally steel wool fibers (SWF), are added to asphalt mixtures prepared with virgin materials to absorb and conduct thermal energy. Metal shavings, a waste material from the metal industry, could be used to replace SWF. In addition, reclaimed asphalt pavement (RAP) could be added to these mixtures to make a more sustainable road material. This research aimed to evaluate the effect of adding metal shavings and RAP on the properties of asphalt mixtures with crack-healing capabilities by microwave heating. The research indicates that metal shavings have an irregular shape with widths larger than typical SWF used with asphalt self-healing purposes. The general effect of adding metal shavings was an improvement in the crack-healing of asphalt mixtures, while adding RAP to mixtures with metal shavings reduced the healing. The average surface temperature of the asphalt samples after microwave heating was higher than temperatures obtained by induction heating, indicating that shavings are more efficient when mixtures are heated by microwave radiation. CT scan analysis showed that shavings uniformly distribute in the mixture, and the addition of metal shavings increases the air voids. Overall, it is concluded that asphalt mixtures with RAP and waste metal shavings have the potential of being crack-healed by microwave heating.

1. Introduction

Asphalt is the most common surface material used for pavement construction (Papagiannakis and Masad, 2008). The mass composition of a conventional asphalt mixture is 4–6% bitumen and 94–96% aggregates. Bitumen, an organic product derived from the petroleum refining process, binds the aggregate. The majority of existing asphalt mixtures have been produced with virgin aggregates and bitumen. The construction of an asphalt pavement involves quarrying of aggregates, producing bitumen, operating the asphalt plant, and laying and compacting the asphalt layers, with all the transportation operations associated with these activities. Once constructed, traffic, environment and other external factors deteriorate asphalt pavements; cracking is one of the most common signs of distress and is caused by a number of factors such as fatigue, low temperatures, and bitumen ageing. Although cracks are a problem, since they reduce the structural capacity and increase the permeability, in asphalt pavements cracks can heal by themselves if bitumen reaches a temperature between 30 and 70 °C (Ayar et al., 2016). The crack-healing is caused by the physical characteristics of bitumen that reduce viscosity with temperature increase. When low viscosity is achieved, the bitumen flows through the open micro-cracks, similar to a capillary flow (García, 2012). Cracks heal when the bitumen temperature decreases and viscosity increases. Then, the bitumen that has flown through the micro-cracks binds the two faces of the crack, partially restoring the structural strength of the asphalt mixture.

The principle of self-healing asphalt mixtures by bitumen temperature increase was used to create an asphalt mixture with

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crack-healing properties (Garcia et al., 2010; Liu et al., 2011). In these mixtures, metals, normally steel wool fibers, are added because they absorb and conduct more thermal energy than bitumen and aggregates, improving the electrical conductivity of the mixtures (Menozzi et al., 2015). To artificially heat and heal this type of asphalt mixture, an external electromagnetic field, such as those applied by electromagnetic induction or microwaves, is used to increase the fiber temperature. Later, the fiber heat transfers to the bitumen and aggregates, reducing the bitumen viscosity and repairing open cracks (Gallego et al., 2013; García et al., 2015). Only recently has the effect of adding reclaimed asphalt pavements (RAP) to asphalt mixtures with steel wool fibers and crack-healing properties been evaluated (González et al., 2018), concluding that the addition of steel wool fibers increases the crack-healing of the mixtures, while adding RAP decreases the healing of this type of mixtures, when microwave heating is applied. One disadvantage of adding steel wool fibers is that they tend to cluster in balls and increase the air void content of the mixtures. This increase in porosity is associated with a reduction of the mechanical properties. Other researchers (Franesqui et al., 2017), have only evaluated the effect of adding metallic waste in the heating of asphalt mixtures, without assessing the crack-healing capabilities. Also, a number of waste materials are used in asphalt mixtures without healing purposes, with the aim of replacing virgin materials with waste, or improving other properties of the mixtures (Abreu et al., 2015; Arabani and Tahami, 2017; Calabi-Floody and Thenoux, 2012; Poulikakos et al., 2017; Sun et al., 2017).

Metal shavings, small, irregular tendrils of 5–10 mm length that are a waste from the metal industry, are commonly obtained from metal turnery or machining. Because metal shavings can persist in the environment for a long time before oxidizing and degrading, it is important to find new applications where they can be used to improve the properties of a different material. Since metal shavings are an electrically conductive material similar to steel wool fibers, they could be used to improve the self-healing properties of asphalt mixtures with RAP. In other words, distressed existing asphalt pavements that need restoration could be retrofitted and transformed into sustainable asphalt pavement with crack-healing properties by microwave radiation (Fig. 1). Distressed asphalt can be milled and transported to asphalt plants for storage and later addition to new asphalt mixtures. The mixing process adds metal shavings to the asphalt, and the final mixture with RAP and metal shavings could be healed via microwave external heating.

This research aimed to evaluate the effect of adding metal shavings and RAP on the properties of asphalt mixtures with crack-healing capabilities by microwave radiation heating. This study is part of a long-term research effort in which the effect of adding different metals or other additives in asphalt mixtures with crack-healing properties is explored. The development of these types of mixtures could lead to new, sound asphalt pavements that are environmentally sustainable.

2. Materials and experimental methods

2.1. Aggregates, RAP, and bitumen

The particle size distribution of the aggregates and RAP was selected to prepare dense asphalt mixtures. The aggregates, RAP, and bitumen were sourced from a local construction company based in Santiago, Chile. This company mills and stores RAP used for road construction and other applications in separate piles. The aggregates and RAP were provided in different fractions that were combined to produce four blends of aggregates with RAP contents of 0%, 10%, 20%, and 30%, by mass. The particle size distribution of the four aggregate and RAP blends was very similar (Fig. 2). The penetration grade of the CA24 bitumen used for mixture preparation was 80/100 mm at 25 °C. The bitumen content for all mixtures was 5.2% by volume, which considered the fresh bitumen and the bitumen contained in the RAP fraction of the mixture.

2.2. Metal shavings

Steel shavings (Fig. 3) are formed of ferritic stainless steel with a density of 7.980 g/cm^3. The studied shavings had an average width of 1.310 mm and initial length within the range 3–21 mm; both short and long shavings with different types of geometries were added to the asphalt matrix. Some shavings had helicoidal shape while others were curled long metal particles. The metal shaving contents by total volume of the bitumen were: 0%, 1%, 2%, and 4%.

To determine the morphological characteristics of the metallic waste added to the asphalt mixtures, 120 individual shavings were randomly selected. The length and width of the shavings were determined by using an optical microscope with 35× magnification. The images were analyzed using a specialized software (Schindelin et al., 2012). The morphological variables were presented in frequency histograms with the aim of comparing their length and width distribution. In addition, the detailed morphology of individual shavings was studied using a Scanning Electron Microscope.

2.3. Preparation of asphalt mixture specimens

The sequence for the preparation of asphalt mixtures was the following: 1) heat the aggregates, RAP, bitumen, and bowl in the oven for at least two hours at 150 °C before mixing; 2) place the hot bitumen in the hot metallic bowl; 3) gradually add metal shavings to the bitumen, constantly stirring the bitumen to avoid clusters of shavings; 4) add four small batches of aggregate/RAP blend, starting with the batch with the largest particles. Once each batch of particles was completely coated with fresh bitumen, the next batch with smaller particles was added to the mixture.

Once the four batches of aggregates had been added, and the mixture was homogenous, a sample of approximately 1200 g was placed in a pre-heated Marshall mold. Then the mixture was compacted using a Marshall hammer, giving 75 blows to each face of the specimen. The cylindrical Marshall specimens, 100 mm in diameter and approximately 60 mm in height, were left at room temperature in the laboratory for at least one day. The next step was to produce four semi-circular samples by cutting one Marshall specimen, first through its diameter, and secondly through a plane parallel to the original specimen face using a saw for asphalt. Thus, the dimensions of the semi-circular asphalt samples were 100 mm in diameter and approximately 30 mm thick (Fig. 4). In addition, to guide the cracking of the sample during the three-point bending test, a 10-mm depth, 3 mm thickness notch was cut at the midpoint of the sample base.

2.4. Crack-healing tests by microwave radiation

The simple three-point bending test was conducted on semi-circular samples to calculate the flexural strength of asphalt. These tests have been previously used to assess the healing capabilities of asphalt mixtures (González et al., 2018; Norambuena-Contreras et al., 2016; Norambuena-Contreras and Garcia, 2016). In these tests, the specimen is placed onto two supporting rollers separated by 80 mm (Fig. 4). A third loading roller is positioned at the midpoint of the semi-circular arch of the sample. The test starts by applying a monotonic load that induces tensile stress at the upper tip of the vertical notch located at the bottom of the sample. The notch guides the crack propagation in the upper direction

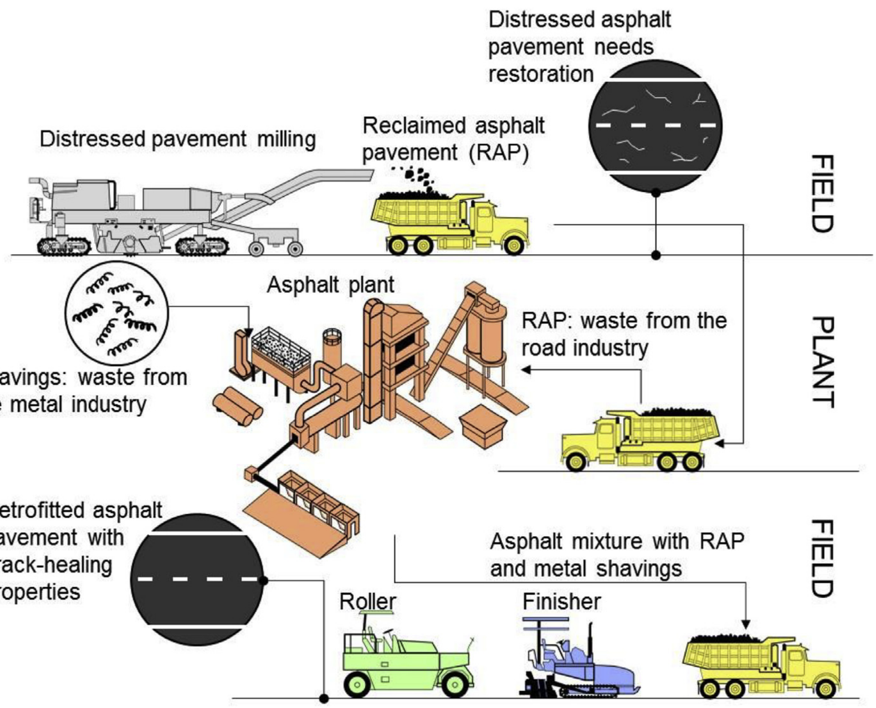

Fig. 1. Conceptual framework of retrofitting conventional, distressed asphalt pavements into a new sustainable asphalt pavement with crack-healing properties.

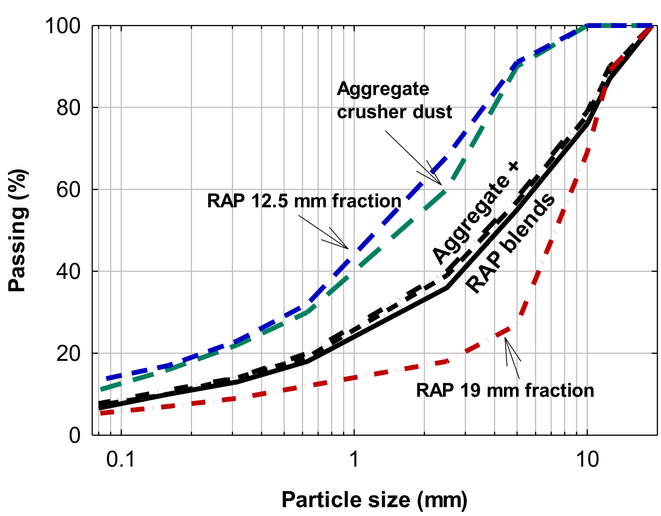

Fig. 2. Particle size distribution of aggregates, RAP, and aggregates/RAP blends.

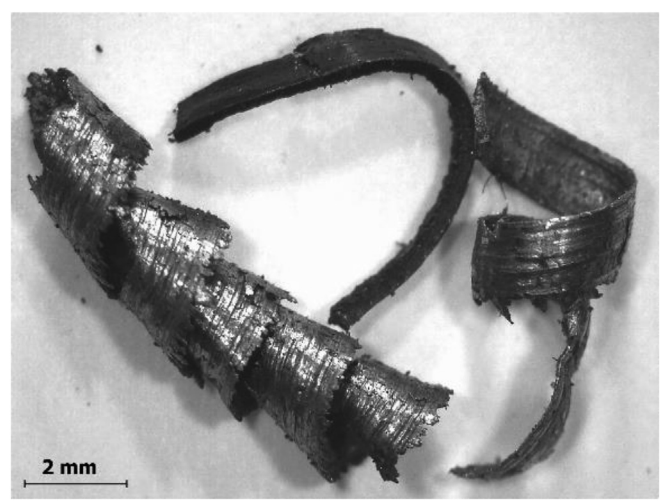

Fig. 3. Optical image of metal shavings used in the study.

during the test. In this study, the three-point bending tests were conducted at −20 °C to achieve brittle behavior of the mixtures and a single crack throughout the sample. The microwave healing of the asphalt mixtures was assessed with the *healing ratio*, i.e., the ratio between the three-point bending strength F_i of the sample after the i_{th} healing cycle, and the initial strength F_0 of the same sample before healing. The monotonic universal testing machine loaded the samples up to failure, recording the peak load. The load speed ratio applied by the machine was set at 0.5 mm/min. Once the bending test finished, cracked asphalt samples were withdrawn from the loading machine and left at room temperature for 3 h until they reached approximately 20 °C. The surface of the samples was examined to verify that the surface moisture resulting from freezing had completely dried. The experimental matrix for the crack-healing tests are presented in Table 1. In the table, the four RAP content levels (0, 10, 20, and 30%) and four shavings content levels (0, 1, 2, and 4%) are shown. Each black dot represents the five semi-circular specimens tested. The average initial strength is F_0, and the average strength measured in the same specimens after i_{th} healing cycle is F_i. The reported healing ratio for the i_{th} healing cycle is the quotient between F_i and F_0.

The semi-circular specimens were healed by microwave heating. Microwaves are electromagnetic waves, similar to X-ray waves, but different in their frequency range from 100 MHz to 100 GHz (Al-Ohaly and Terrel, 1998). Microwave heating has a number of advantages over other heating techniques, for example, heating efficiency, selective energy absorption, and temperature control. The efficiency of a material in absorbing microwaves is described by its dielectric properties (Sun et al., 2018). In this study, microwave

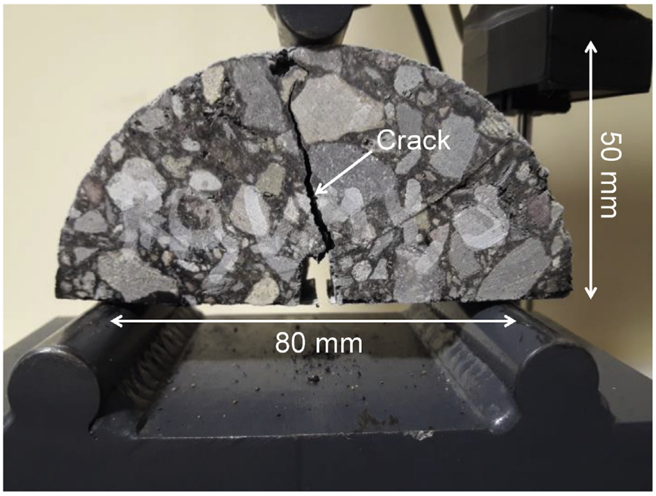

Fig. 4. Cracked semi-circular asphalt sample.

heating was applied for 40 s to the previously cracked semi-circular samples by using a 700 W microwave oven with a work frequency 2.45 GHz, which corresponds to an approximate wavelength of 120 mm. The heating time was found suitable for microwave healing based on previous research results (González et al., 2018; Norambuena-Contreras et al., 2016; Norambuena-Contreras and Gonzalez-Torre, 2017). A total of seven damage-healing cycles were carried out in the test samples.

2.5. Heating by induction radiation

In addition to the healing using microwave radiation, some specimens were heated by induction. Induction heating is the process of heating electrically conductive materials, by electromagnetic induction. In the heating process, an electrical current is applied in a conductive coil, creating an alternating electromagnetic field, with a frequency in the range of kilohertz to megahertz. The electromagnetic field creates a current in the conductive material, such as metal shavings, increasing their temperature by polarization effects (Sun et al., 2018). In this research, specimens were heated for 180 s using a 50 kW, 70 kHz induction machine. The objective of heating cracked samples with a different heating method was to compare the efficiency of heating mixtures with metal shavings under both microwave and induction technologies.

The configuration of the induction heating was different from that of the microwave radiation, as the induction was applied by a flat, horizontal coil. The sample was located below the coil, with its coaxial axis perpendicular to the horizontal plane. The 180 s induction heating was applied only once on samples that had previously been repaired seven times with microwave heating. The heating time was calculated based on previous research (González et al., 2018) where induction and microwave heating was conducted on asphalt samples. The 180 s induction heating is equivalent to the microwave heating time of 40 s. In addition to the induction heating, 40 s microwave heating was conducted on the specimens, with the aim to compare the temperature of specimens using both methods. The specimens selected for the heating study are shown in the experimental matrix (Table 1) below column T°. The specimens that were heated with microwaves only are shown had RAP contents of 0, 10, 20, and 30%, and shaving contents of0, 2, and 4%. This is shown in the experimental matrix (Table 1) where T° indicates the temperature study, and "m" the specimens heated by microwaves.

2.6. Temperature analysis in samples heated by microwave and induction

The temperature of the semi-circular samples was measured on their surface using a 320 × 240 pixels full color thermographic camera during 10 s immediately after microwave heating. In addition, the temperature was measured for 10 s after induction heating, as explained in the previous section. The temperature was recorded for 10 s after heating using the same type and model of camera.

2.7. X-ray computed tomography (CT scan)

Micro-computed tomography was carried out in asphalt mixtures with different RAP and metal shaving contents. For the tests, prismatic samples with dimensions of approximately 30 mm height, 30 mm width, and 50 mm length were cut from the center of the semi-circular samples after the seven healing cycles. The X-ray micro-tomography scans were obtained using a scanner operated at 160 kV and 200 μA. Images were reconstructed at a spatial resolution of 25 μm (voxel side), and the segmentation of the voxels was conducted to identify the different fractions of the mixture components, in particular of the metal shavings. Later, with the reconstitution of a three-dimensional model of the metals in the asphalt samples, it was possible to visualize the shavings

Table 1
Experimental matrix for the crack-healing tests and heating tests.

Shavings content (%)	RAP content (%)																																							
	0										10										20										30									
	F_0	Healing cycles							T°		F_0	Healing cycles							T°		F_0	Healing cycles							T°		F_0	Healing cycles							T°	
		F_1	F_2	F_3	F_4	F_5	F_6	F_7	m	i		F_1	F_2	F_3	F_4	F_5	F_6	F_7	m	i		F_1	F_2	F_3	F_4	F_5	F_6	F_7	m	i		F_1	F_2	F_3	F_4	F_5	F_6	F_7	m	i
0	•	•	•	•	•	•	•	•	◊		•	•	•	•	•	•	•	•	◊		•	•	•	•	•	•	•	•	◊		•	•	•	•	•	•	•	•	◊	
1	•	•	•	•	•	•	•	•			•	•	•	•	•	•	•	•			•	•	•	•	•	•	•	•			•	•	•	•	•	•	•	•		
2	•	•	•	•	•	•	•	•	◊	◊	•	•	•	•	•	•	•	•	◊	◊	•	•	•	•	•	•	•	•	◊	◊	•	•	•	•	•	•	•	•	◊	◊
4	•	•	•	•	•	•	•	•	◊	◊	•	•	•	•	•	•	•	•	◊	◊	•	•	•	•	•	•	•	•	◊	◊	•	•	•	•	•	•	•	•	◊	◊

Note: • = Five semi-circular specimens for three-point bending test; F_0=initial strength before healing; F_i=strength after the i_{th} healing cycle using microwaves; T°=temperature test; m=heating by microwaves in the heating test; mi = heating by microwaves and induction in the heating test, ◊ = specimens for temperature tests.

distribution in the mixtures. Each sample tested in the CT scan had more than 2.4×10^9 voxels.

3. Results and discussion

3.1. Analysis of metal shavings morphology

Frequency histograms for all the morphological data measured using the optical microscope are presented in Fig. 5. The average length of the shavings was 7.181 mm (SD = 3.368 mm), with only a small fraction shorter than 5 mm. The average length is similar to metal fibers that have been previously used in other studies (García, 2012; Norambuena-Contreras and Garcia, 2016), even though the range of the shavings length is larger, between 0.2 and 20 mm. The average width of the shavings was 1.310 mm (SD = 0.877 mm), about 10 times larger than steel wool fibers used in previous studies (González et al., 2018).

Moreover, Fig. 6a and b presents SEM images of individual metal shaving cross sections. Fig. 6a shows the edge irregularities of the metal shavings that have been obtained from steel turnery. The blades used for the machining apply forces on the metal surface in different directions and magnitudes, and the blades used to shape the metal were subjected to different types of vibrations and spinning angular speeds, which produce flaws on the surface of the shavings (Fig. 6b). Additionally, the cross section of the shavings presented different widths. The edge flaws and overall complex geometry of the metal shavings surface observed in SEM images do not favor the bitumen flow during compaction, although these help to increase the adhesion of the metal shavings to the asphalt matrix, reducing the pull-out failures by external mechanical effects.

3.2. Effect of metal shavings and RAP on the crack-healing ratios

A total of 560 semi-circular samples were evaluated for crack-healing properties of asphalt mixtures with metal shavings and RAP by means of three-point bending tests. The average healing ratio of the 560 tests, for all mixtures and cycles, was 0.5215 (SD = 0.1422). Fig. 7 presents the general effects of the metal shavings and RAP contents for the asphalt mixtures. Fig. 7a presents the healing ratio for each metal shaving content, averaging results from the four RAP contents and the seven healing cycles. Fig. 7b shows the healing ratio for each RAP content averaging all the shaving contents and the seven healing cycles. The average healing ratio shown in Fig. 7a for the mixtures without metal shavings was 0.4526 (SD = 0.1773), while the average for the mixtures with metal shavings was 0.5374 (SD = 0.1279), indicating that metal shavings improve the healing of asphalt mixtures. An ANOVA test with a significance level $\alpha = 0.05$ was conducted to further study the effect of RAP, and the effect of fibers. For the RAP, the F-value obtained from the analysis was 24.33, with a p-value<0.001, indicating that RAP has a significant effect in the healing ratio. Similarly, for the fibers the F-value was 26.56, with a p-value<0.001.

Furthermore, the effect of the metal shaving addition was a reduction in the standard deviation of the healing ratios, represented by the error bars (one bar = 2 standard deviations). The general effect of adding 1% of metal shavings was an increase in the healing ratio; however, for 2% and 4% the ratio decreased. The general average for all the mixtures without RAP in Fig. 7b was 0.5968 (SD = 0.1192) and the average healing ratio for all the mixtures with RAP was 0.4872 (SD = 0.1387), indicating that the addition of RAP decreases the healing for a constant microwave heating time of 40 s ($p < 0.001$).

In addition, Fig. 8 shows the detailed healing ratio results for each healing cycle and shavings content. Each column indicates the average of five three-point bending strength values. In some cases, within the five results there were outliers that were eliminated from the analysis, but all the columns show the average of at least four tests. In Fig. 8 the half error bar in the upper direction represents one standard deviation. The general trend for mixtures with and without RAP indicates a decrease in the healing ratio with the number of healing cycles. However, this trend was not clearly observed for most of the mixtures during the first three cycles during which the healing ratio remained constant or showed some increase.

Fig. 8a shows results for the mixtures without RAP with shavings contents from 0% to 4%. The mixtures with 1% metal shavings yielded the highest healing ratios, while the mixture with 4% shavings gave the lowest healing. Fig. 8b shows the detailed results for mixtures with 10% RAP and shavings contents between 0% and 4%. The mixture with 1% metal gave the highest healing ratios, followed by the mixture with 2% shavings. These two mixtures showed a gradual decrease in the healing ratio after the third cycle. The mixtures without shavings and 4% shavings gave healing ratios between 0.33 and 0.50, lower than 1% and 2% shavings. Fig. 8c presents the results for 20% RAP, showing that mixtures without metal gave the lowest healing ratios with an average of 0.3489 (SD = 0.1479) for all healing cycles, while the 2% shavings mixtures yielded an average healing ratio of 0.5712 (SD = 0.0715). In these

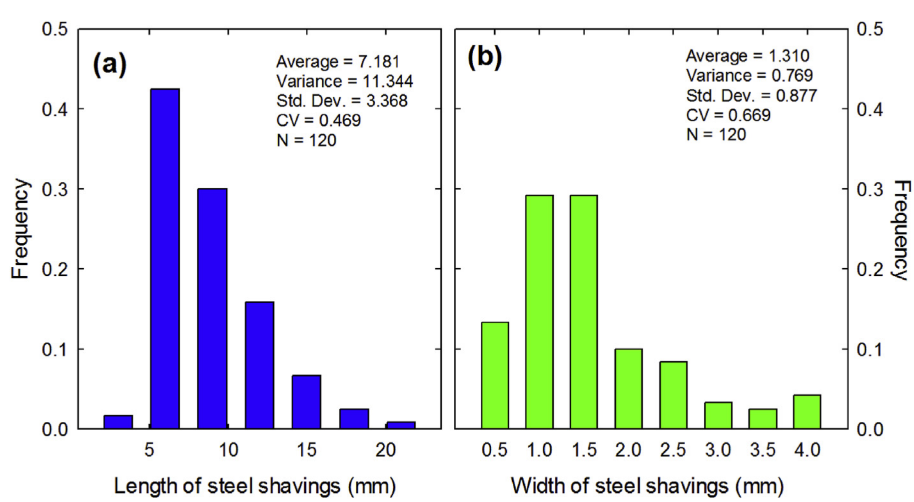

Fig. 5. Frequency histograms for the (a) length and (b) width of the metal shavings.

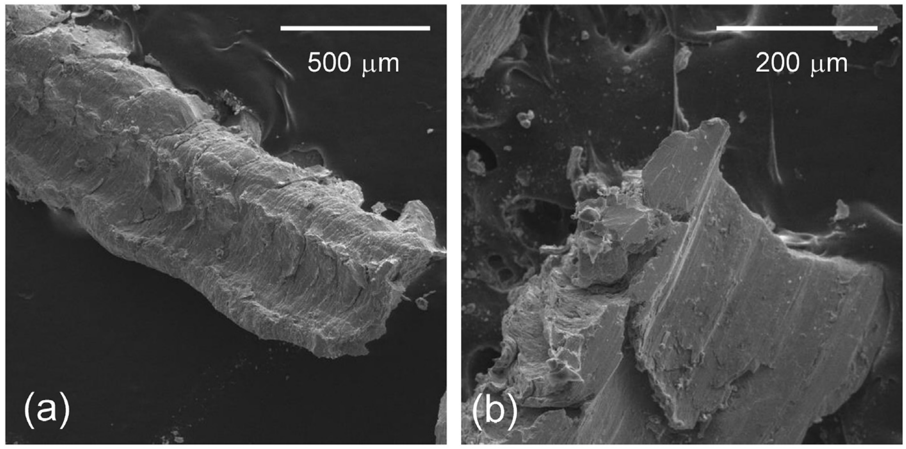

Fig. 6. SEM images of individual metal shavings before mixing and compaction process.

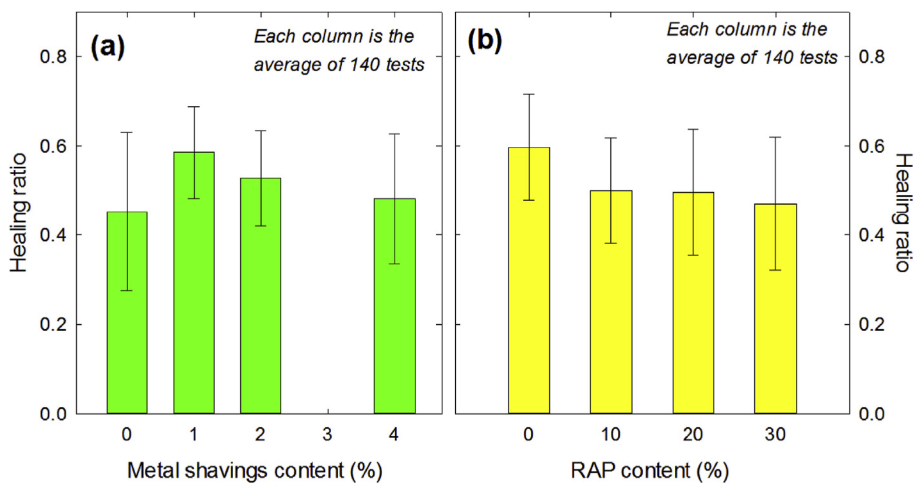

Fig. 7. General effects of (a) metal shavings content and (b) RAP content in mixtures with metal shavings.

mixtures, the healing ratio increased up to the second or third cycle and then gradually started to decrease until the last cycle. Fig. 8d shows the healing ratio results for mixtures with 30% RAP. The mixture with 1% shavings gave the highest healing ratio of 0.6173 (SD = 0.0847), while the average performance for the other mixtures with different shavings content was similar. The healing ratio for most of the mixtures increased up to healing cycle three and then decreased.

3.3. Evaluation of the CT-Scan results

3.3.1. Qualitative analysis of 3D images

Fig. 9a shows the three-dimensional reconstitution of the CT scan on a mixture with 4% metal shavings and 30% RAP content and shows different shape patterns distributed throughout the scanned sample. Helicoidal shavings of different diameters, width, and spatial orientation confirm the heterogeneity of this type of metal. In the scan, it was possible to identify the irregular shape of the shavings edges. Two types of shavings shapes are clearly identified: helicoidal shavings that are stretched in a similar manner to a linear spring, in three dimensions, and shavings that are rolled around one axis, similar to a torsion spring, in two dimensions. The shavings have a thin thickness compared to their length and width, on the order of 0.1 mm. In previous studies (González et al., 2018; Norambuena-Contreras et al., 2016), clustering of metals has been observed in steel wool fibers that agglomerate because they have spontaneous attraction caused by electrostatic currents created by friction with the air or friction between fibers. However, in this study, no apparent clustering of metal shavings was observed in the CT scan images. In addition to shavings, metal powder was found in the aggregates used in this research and is shown in Fig. 9a and b as small, spherical, white spots distributed in the studied volume. Fig. 9b shows the shavings CT scan for a mixture with 2% metal shavings and 30% RAP content. As expected, less metal is observed in the figure, with only a few particles with a linear spring shape. The figure also shows the irregular edges of the shavings and smaller pieces of metals. The spherical spots confirm that the aggregates used in this research contained metal powder; however, these spots may also correspond to metal powder resulting from shredding of metal shavings, or the effect of the mixing and compaction processes.

The different metal distribution observed in Fig. 9 explains the effect of the shavings content on the air voids of the asphalt mixtures (Fig. 10). Figures show that by increasing the shavings contents, the air voids also increase because the shape of the shavings makes the compaction process of specimens more difficult. The bitumen mastic has more difficulty in flowing through the air voids in mixtures with shavings, since the tendrils have a complex

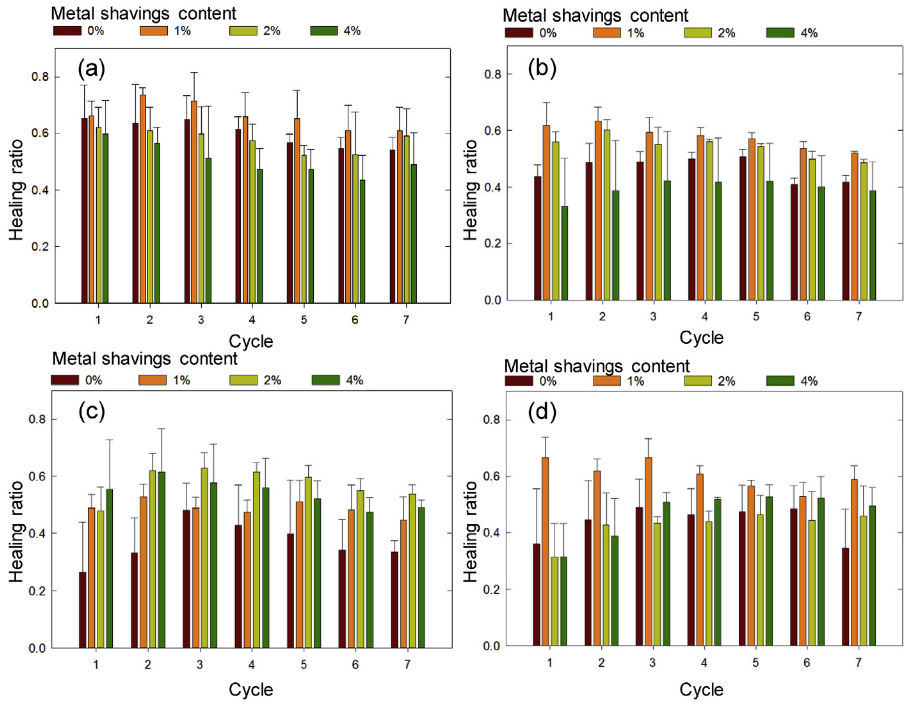

Fig. 8. Healing ratio of samples with (a) 0% RAP, (b) 10% RAP, (c) 20% RAP, and (d) 30% RAP.

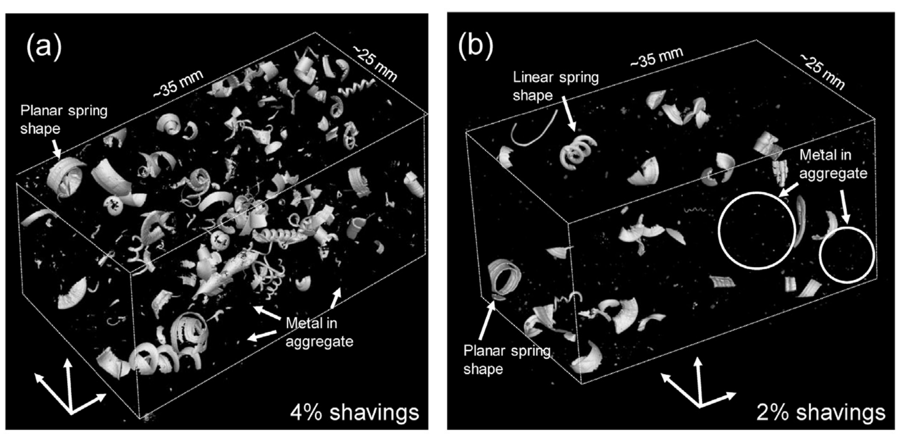

Fig. 9. Three-dimensional images from CT scans for (a) 4% and (b) 2% shavings content.

geometry that leaves voids. In addition, the surface of the shavings (see Fig. 6) has flaws that increase the friction forces between bitumen mastic and shavings, decreasing the flow of the bitumen and increasing the air void content.

3.3.2. *Qualitative analysis of 2D images*

In addition to the three-dimensional reconstitution of images, the two-dimensional (2D) images were available for analysis in Fig. 11. In the Figure, the dark areas are air voids and the white shapes are metal shavings. The aggregate fractions are gray, but the bitumen fraction is hard to distinguish, since its color is between that of the aggregates and air voids. There are some white to light gray spots in the aggregates; these are metal particles detected in the aggregates and that explain the heating of the asphalt mixtures without shavings.

Metal in the aggregates was also detected in another research project reported by the authors in which mixtures with RAP and steel wool fibers were studied (González et al., 2018). In several correlative cross-sections, it was possible to identify air voids in the zone of helicoidal, randomly distributed shavings, confirming that the shape of the metal does not improve the flow of the bitumen mastic to fill air voids.

Fig. 11a shows a crack produced during the three-point bending tests. It was generally observed that cracks follow the mastic, the transition zone, and the mantle of the air voids, which correspond to the weak volume of the mixture. However, in some cases the crack propagated through the aggregate because the −20 °C temperature of the three-point bending tests during breaking made the bitumen a very stiff, brittle, and strong material. Fig. 11b shows a complete cross section of the samples analyzed with CT scanning, hence the scale of the figure is different from Fig. 11a. The vertical, dark line is the approximately 3 mm thickness notch mentioned in Section 2.3. The samples analyzed in CT scans were cut from semi-circular three-point bending samples, and some samples were

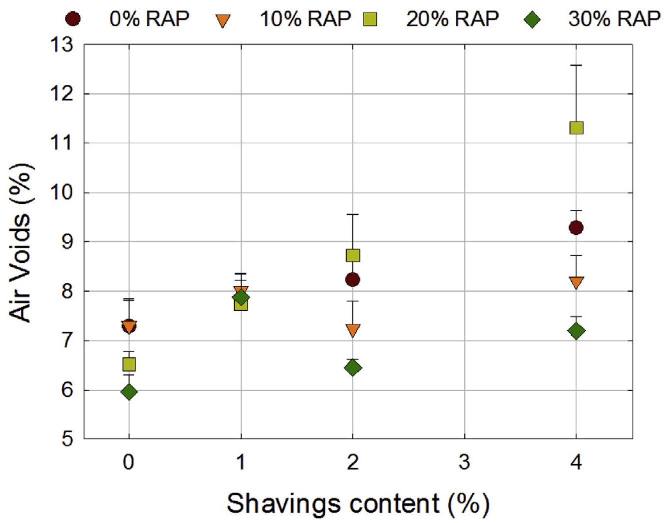

Fig. 10. Air voids versus metal shaving content in asphalt mixtures.

damaged in the weak volumes near the notch (Fig. 11b).

3.4. Temperature analysis of asphalt samples after microwave heating

A total of 43 points were sampled from the surface of the sample for 10–11 s using a specialized temperature software developed by the fabricant of the infrared camera. The location of the points was selected so that they cover the same area of the specimen. The average temperatures during the 10–11s tests ranged from 56.6 to 90.9 °C, with a general average of 71.7 °C. The detailed temperature results for each sample are shown in Fig. 12a. Results show that no significant effect could be established between metal shavings content and surface temperature. Nevertheless, there is evidence ($p = 0.033$) that average temperature in specimens without RAP (64.01 °C, SD = 7.21 °C) was lower than specimens with RAP (71.85 °C, SD = 7.27 °C). Results also show that samples without shavings reached temperatures between 65.2 and 71.9 °C, indicating that metals in the aggregates increased their temperature when heated with microwaves. To verify that aggregates and RAP could be heated without metal shavings, one sample of approximately 100 g of aggregates only, and one sample of RAP only, were heated in the microwave. Each sample was placed in a ceramic bowl that does not heat when microwaved for 40 s. As a result, the temperature of the aggregate and RAP measured with an infrared thermometer was respectively 104.2 °C and 163.9 °C immediately after heating, showing that aggregates and RAP could absorb heat from microwaves, and explaining the temperature achieved by asphalt mixtures without metal shavings.

3.5. Temperature analysis of asphalt samples after induction heating

The results for the induction heating of specimens (Fig. 12b) show that the temperatures of the specimens heated with induction were, on average, lower than those heated with microwaves (Fig. 12a), with an average temperature of 50.85 °C (SD = 12.1 °C). These results were compared with temperatures measured for asphalt samples of mixtures prepared with 2% and 4% steel wool fibers. The average temperature in these specimens was 83.33 °C, which is 63.8% higher than the temperature obtained in samples prepared with metal shavings. The lower temperature measured in samples with metal shavings and heated by induction is explained by electromagnetic theory. The skin effect is a physical phenomenon that describes the nonuniform current distribution within metallic conductors such as fibers and metal shavings when alternating current is applied. The maximum value of the current density will be located on the surface of the conductor; therefore, the current density will decrease from the surface of the conductor towards its center. It has been reported that about the 86% of the current will be concentrated in the surface layer of the conductor (Rapoport and Pleshivseva, 2007). With this in mind, the shapes of the cross-section of an individual fiber and a metal shaving are schematically shown in Fig. 13. The diameter of the fibers used in these asphalt mixtures with crack-healing properties averages 0.13 mm (González et al., 2018). As previously reported in Section 3.1, the average width of the shavings was 1.31 mm. Although the thickness of the shavings was not systematically analyzed in the morphology section of this study, the thickness observed in the SEM images is approximately 0.1 mm. If a metal fiber of length L is assumed the average volume is:

$$V_{fiber} = \pi \left[\frac{D}{2}\right]^2 \cdot L = \pi \left[\frac{0.13}{2}\right]^2 \cdot L\left[mm^2\right] \approx 0.01 \cdot L\left[mm^2\right] \quad (1)$$

The average volume of a metal shaving of width w (1.31 mm), thickness t (0.1 mm), and length L is:

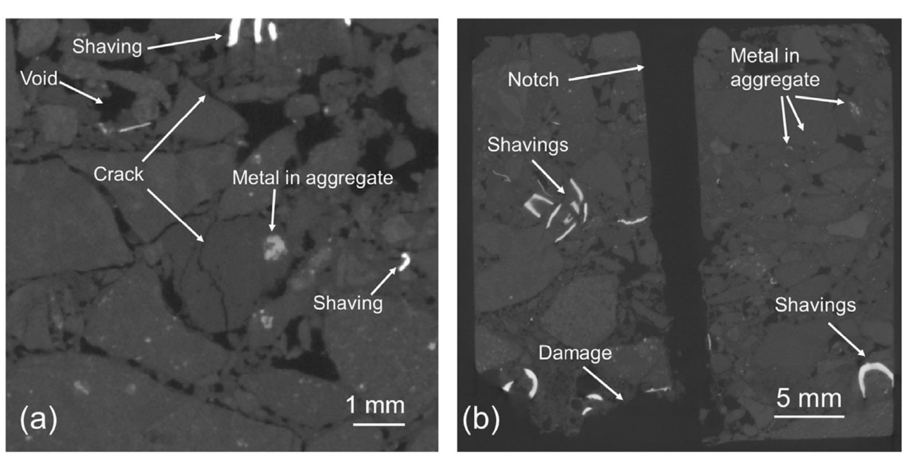

Fig. 11. Top view of asphalt samples: (a) crack through the sample and (b) the sample notch.

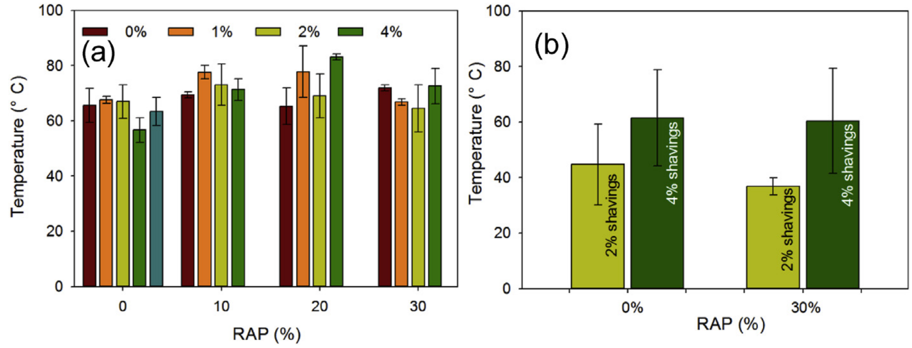

Fig. 12. Average of surface temperatures measured after (a) microwave and (b) induction heating.

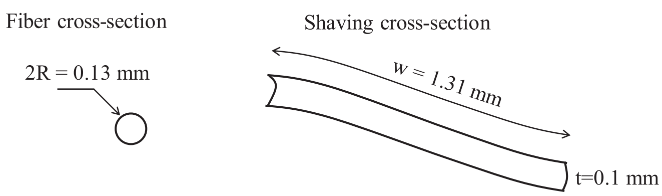

Fig. 13. Comparison of cross-sections between a metal fiber and a metal shaving.

$$V_{shaving} = w \cdot t \cdot L \approx 0.131 \cdot L \left[mm^2\right] \tag{2}$$

Since most of the current is concentrated on the surface, it is relevant to know the relationship between perimeter and volume. For the fibers, this ratio R_{fiber} is:

$$R_{fiber} = \frac{D\pi L}{V_{fiber}} = \frac{0.13\pi L}{0.01 \cdot L} \approx 41 \tag{3}$$

While for the metal shavings, the ratio $R_{shavings}$ is:

$$R_{shavings} = \frac{2(w+t)L}{0.131 \cdot L} = \frac{2.82L}{0.131L} \approx 22 \tag{4}$$

These calculations show that for every unit volume of metal fiber there are approximately 41 units of surface of metal, while for a unit volume of metal shaving there are approximately 22 units of surface metal. In other words, the exposed surface for the fibers almost doubles that of shavings for the same volume of metal added to the mixture, which explains the higher temperature achieved by mixtures with steel wool fibers and heated with induction radiation. Nevertheless, mixtures prepared with metal shavings and heated with *microwaves* achieve a similar temperature to asphalt mixtures fabricated with steel wool fibers.

4. Conclusions

This paper presents the effects of adding metal shavings and RAP on the properties of asphalt mixtures with crack-healing capabilities by microwave radiation heating and induction. Based on the analysis of results, the following conclusions can be drawn from this study:

- Metal waste shavings have an irregular shape with widths larger than steel wool fibers used in other studies for the heating of asphalt mixtures with crack-healing purposes.
- The general effect of the addition of metal shavings was an improvement of the crack-healing properties of asphalt mixtures, while the addition of RAP in mixtures with metal shavings reduced the healing of mixtures.
- The average surface temperature of the asphalt samples after microwave radiation heating was 71.7 °C, while the temperature achieved by induction heating was 50.85 °C, indicating that shavings are more efficient when asphalt mixtures are heated with microwaves.
- CT scan analysis showed that metal shavings are evenly distributed in the mixture. The shavings have different diameters, width, and spatial orientation, confirming the heterogeneity of this type of metal. The addition of shavings increased the air voids of the mixture, which is explained by the complex geometry and rough surface of the shavings observed in SEM analysis.
- Overall, it was concluded that asphalt mixtures with waste materials have the potential of being crack-healed by microwave heating, and hence of potential use for the development of new asphalt pavements that are environmentally sustainable. Nevertheless, in future research, it is necessary to develop a lifecycle cost analysis (LCCA) and a lifecycle assessment (LCA) about this type of heating technology in order to support this conclusion.

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