Crack-healing variability of asphalt mixtures with RAP and steel wool fibers by the action of external microwave heating

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ABSTRACT

Microwave heating of asphalt pavement containing steel wool fibers is an auspicious technology for asphalt pavement rehabilitation. These types of mixtures have the ability to self-heal their cracks when external microwave heating is applied. The assessment of crack-healing has mainly been conducted in mixtures prepared with virgin aggregate materials. This paper studies the variability of the crack-healing in asphalt mixtures prepared with reclaimed asphalt pavement (RAP) and steel wool fibers. The healing ratio was calculated using three-point bending strength of semi-circular asphalt specimens. The average of seven healing cycles applied on the asphalt specimens showed that the general effect of RAP content was an increase in the variability of the crack-healing of the mixtures. Low fibers contents of 1% and 2% reduced the variability of the crack-healing capabilities of asphalt mixtures. It was observed that the number of healing cycles reduce the variability of the healing capabilities of asphalt mixtures. Overall, it is concluded that small contents of fibers and RAP do not increase the variability in the crack-healing of this type of mixtures.

Keywords: crack-healing, variability, microwave, steel wool fibers, asphalt mixtures.

1. INTRODUCTION

Despite their excellent characteristics as a road material, asphalt mixtures deteriorate with traffic and environmental factors. One of the most common and first distress observed in asphalt pavements, during their service life, is cracking. The main causes of asphalt cracking are: i) mechanical fatigue, caused by the cyclic loading applied by traffic [1], ii) bitumen aging, mainly caused by oxidation and high asphalt temperatures [2], and iii) temperature variation, caused by large temperature gradients in short periods of time [3]. To keep a good service level of the road, cracks must be repaired during their initial formation or early stage, i.e., when they are narrow and cover only a small area of the pavement surface. Otherwise, there is a risk of a rapid progression that could lead to more severe cracking, loss of pavement strength, and finally, a reduction of pavement durability, particularly when exposed to water that can penetrate into the asphalt and underlying pavement layers [4]. It is well known, however, that asphalt mixtures have the capability of self-heal their cracks when exposed to high temperatures. If the bitumen is not too aged, i.e., during the early life of the pavement, asphalt mixtures can close, seal, or heal the cracks independently [5] because the thermoplastic characteristic of bitumen. This means that the temperature increase reduces bitumen viscosity; hence, bitumen can flow through the cracks and restore the structural capacity of the pavement material [6].

Researchers used the concept of crack-healing asphalt mixtures by increasing bitumen temperature to create an asphalt mixture with self-healing properties by means of external heating, using magnetic induction [7] or microwaves [8]. Small contents of steel wool fibers

(2-6% of the bitumen volume) increase the absorption and conductivity of thermal energy, as well as the electrical conductivity [9] of this type of mixtures. To heat the asphalt mixtures, an external electromagnetic field, such as those applied by a microwaves oven, increases the steel wool fibers temperature. The heat of the fibers transfers to the bitumen and aggregates, which are not good heat conductors. However, the heat transferred to the bitumen reduces its viscosity, and the bitumen flows through the open cracks and repairs the asphalt mixture [6],[10].

Previous studies have shown that microwave heating has the potential to crack-heal asphalt mixtures reinforced with steel wool fibers [11]. However, most of the work conducted on the healing of asphalt mixtures by microwave heating has only considered the average effect of using virgin aggregates and bitumen. Only recently has metallic waste been added to asphalt mixtures to absorb and conduct heating energy in order to achieve asphalt mixtures with healing purposes using microwave heating [12],[13]. Nevertheless, the addition of fibers and RAP could increase the variability in the crack-healing of asphalt, which could also increase the variability in the performance of this type of mixtures in the field. Hence, this article reports the variability of the crack-healing in asphalt mixtures prepared with RAP and steel wool fibers using microwave heating.

2. MATERIALS AND METHODS

2.1 Materials

This research considered the use of dense asphalt mixtures, a standard pavement material used in Chilean roads. The aggregates, supplied by a road construction company, were separated in different size fractions. The RAP, was obtained from the milling of distressed asphalt roads, was also separated in different fractions by size. Finally, the virgin aggregates and RAP were blended to achieve the particle size distribution of a dense mixture recommended by the Chilean Highway Manual [14]. The content of RAP in the mixture was 0%, 10%, 20%, and 30%, by mass. Although different RAP contents were added to the aggregate/RAP blend, the final particle size distribution of the blend was similar (Figure 1a). The mixtures were prepared with a CA24, penetration grade 80/100 (25ºC) bitumen commonly used in Chile. A constant total bitumen content of 5.2% by volume, equivalent to a total bitumen content of 57 g, was targeted for all the asphalt mixtures. This content included the bitumen of the RAP fraction (Figure 1b) and the new, virgin aggregate added to the mixtures.

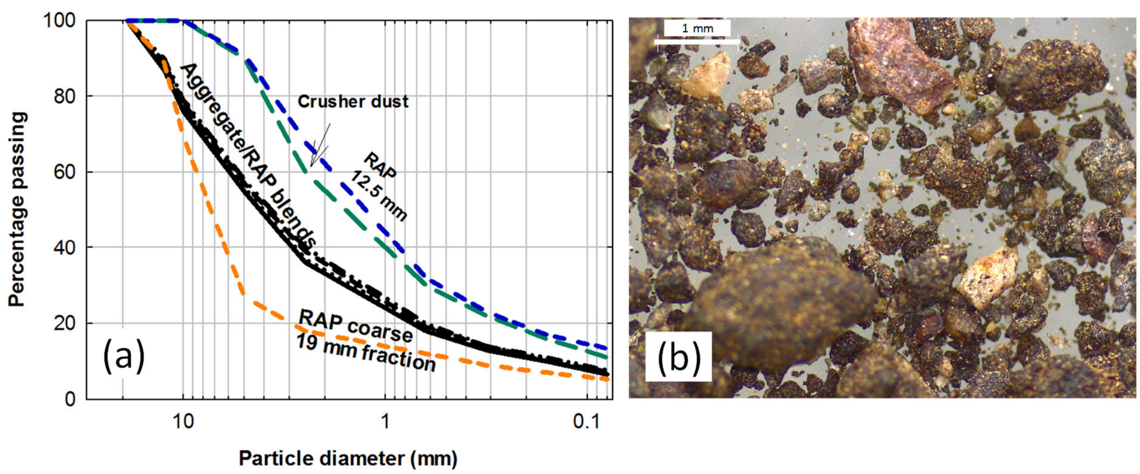

FIGURE 1 (a) Particle size distribution of aggregates, RAP, and aggregates/RAP blends (b) optical view of RAP fine fraction

Steel wool fibers (Figure 2a), composed of low-carbon steel with a density of 7.180 g/cm^3 were added in small proportions to the mixtures. The metal fibers had an average diameter of 0.133 mm (Figure 2b), with an average initial length range of 2-14 mm. The fiber content by total volume of the bitumen were: 0%, 1%, 2%, and 4%.

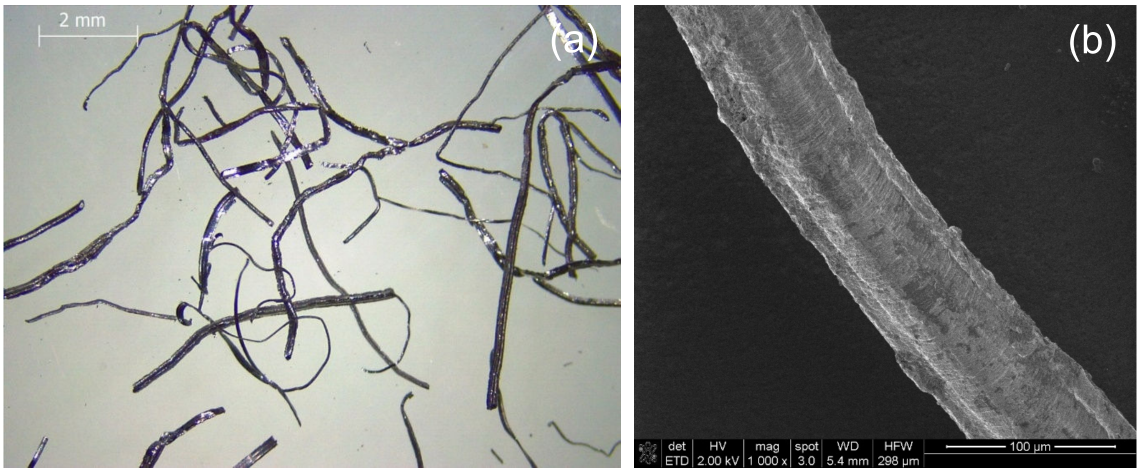

FIGURE 2 (a) Optical and (b) SEM image of steel wool fibers used in the study.

2.2 Preparation of asphalt specimens

The bitumen, aggregates and fibers were heated for at least two hours before mixing. The adopted mixing sequence for specimens with fibers has been published somewhere else [13]. Cylindrical Marshall specimens, 100 mm diameter and 60 mm height, contained a total bitumen content of 5.2%. Once compacted, the specimens were sawed in two planes to produce semi-circular samples, dimensions 50 mm in radius and approximately 30 mm thick. A 10-mm depth notch with a thickness of 3 mm was cut at the midpoint of the semi-circular samples (Figure 3a).

2.3 Three-point bending tests on semi-circular specimens

The microwave healing of asphalt mixtures was measured testing the semi-circular specimens with three-point bending tests. In these tests, a monotonic load was applied to the semi-circular samples up to maximum load or failure. Only the peak force applied in the test was recorded and considered for the analysis of results. The semi-circular samples were placed on two supporting rollers, separated by 80 mm. A third loading roller was positioned at the midpoint of the semi-circular arch of the specimen (Figure 3a). The load was applied by a multispeed testing machine, with a load cell of 50 kN and controlled by a computer. The load speed was set to 0.5 mm/min, and specimens were preconditioned at -20ºC during 24 h before the test, to achieve a brittle failure. Once the bending test finished, cracked asphalt samples were carefully taken from the loading machine, and left at room temperature (20-25° C).

2.4 Crack-healing of specimens using microwave radiation

Microwave heating was applied to the previously cracked semi-circular samples by using a 700 W, 2.45 GHz microwave oven. The heating time was set to 40 s for all samples, this time has been found suitable as reported on previous research results [11].

The healing ratio (HR) is the parameter used in this research to assess the healing capability of asphalt mixtures. HR was defined as the relationship between maximum force measured in the test sample after the healing (F_i), and the maximum force of the test sample initially tested (F_0) being "i" the number of times the sample has been healed in the microwave:

$$Healing\ ratio = \frac{F_i}{F_0} \tag{1}$$

A total of seven damage-healing cycles were carried out on the test samples (Figure 3b). A total of 520 tests were analyzed for this study on the variability of the healing rafio asphalt mixtures.

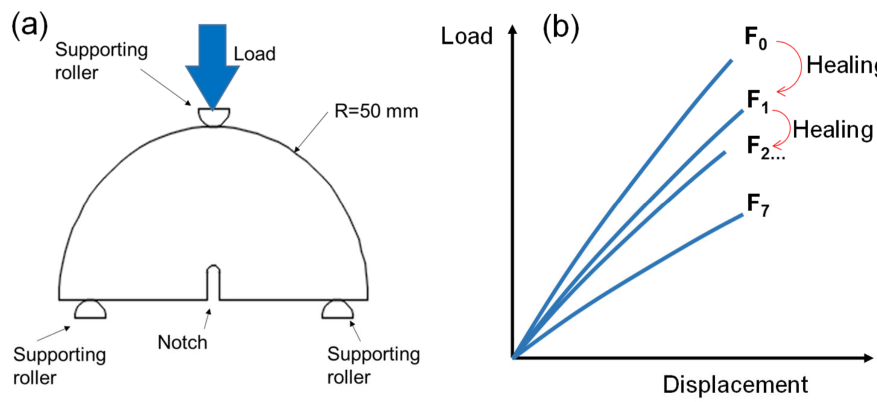

FIGURE 3 (a) Configuration of the semi-circular bending test, and (b) representative load versus displacement curves for different healing cycles on the same specimen.

3. RESULTS AND DISCUSSION

3.1 Effect of RAP on the variability of the healing ratio

Figure 4 presents the histograms of all the healing ratios and healing cycles for the mixtures with different RAP contents. The horizontal axis of each plot is the healing ratio, while the vertical axis is the frequency of the observed healing ratio grouped in 0.025 intervals. Figure 4 shows that an increase in the RAP content increases the healing ratio variability of the mixtures (i.e., standard deviation or SD) from SD≈0.10-0.11 to SD≈0.13. This is explained by the nature of the RAP material that is obtained from the milling of asphalt roads that have been in service for many years, and have been exposed to different loads and environmental factors. It is therefore expected that RAP increases the variability in the performance of the mixtures.

In addition, when the asphalt mixture with different contents of RAP was produced in the laboratory, the aged bitumen is blended with virgin bitumen. It is likely that aged bitumen, with a higher viscosity, is not totally mixed with new bitumen, and therefore this effect increases the variability of the bitumen flow during the microwave heating. Moreover, RAP increases the aggregates heterogeneity of the mixture, since aggregates from different sources are added. Although standard deviations are important, yielding coefficient of variations between 20% and 30%, the large number of tests performed and showed in Figure 4 give strength to the analysis conducted. To verify the significance of the RAP effect, an analysis of variance (ANOVA) was conducted, yielding a p-value lower than 0.001.This result indicates that the RAP content has a significant effect on the healing ratio.

3.2 Effect of fibers on the variability of the healing ratio

Figure 5 presents the histograms of all the healing ratios and healing cycles for mixtures with 0%, 1%, 2%, and 4% fiber content. The highest measured means were obtained for 1% and 2% fiber content. The variability for the mixtures without fibers and 4% fibers were the highest. For 1% and 2% fiber content the variability was lower than the other mixtures. Clusters of fibers have been observed in mixtures with high contents of fibers by means of computer tomography [13],[14]. Clusters of fibers therefore, might increase the variability in the crack-healing ratio of the mixtures. Conversely, the effect of adding fibers to the mixtures is an increase in the healing ratio. The coefficient of variations calculated is in the range 18-25%. The number of tests are shown in Figure 5. To verify the significance of the RAP effect, the p-value obtained from the ANOVA, yielded a p-value of 0.05, showing that the fiber has a clear effect in the healing ratio, although is less significant than the RAP content.

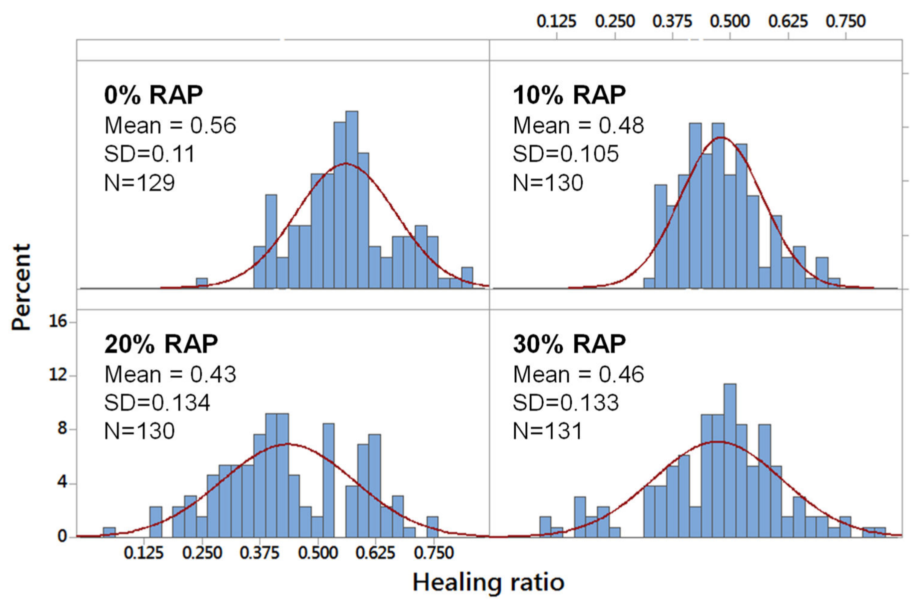

FIGURE 4 Histogram of healing ratios for different RAP contents.

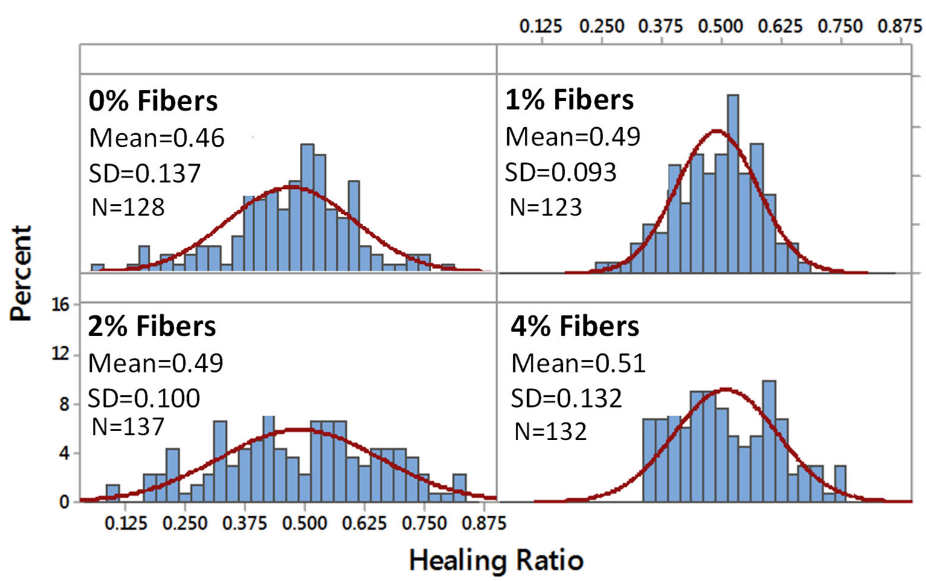

FIGURE 5 Histogram of healing ratios for different fiber contents.

3.3 Effect of the number of healing cycles on the variability of the healing ratio

Figure 6 presents the histogram of the healing ratio for all the mixtures, for the seven healing cycles. The 0.17 standard deviation for the first healing cycle was higher than all the other healing cycles (coefficient of variation = 36%). The second highest variability was measured in the second healing cycle (coefficient of variation = 27%). Then, the standard deviation plateaus approximately in SD≈0.12-0.13 for the rest of the healing cycles. The lower variability in higher order healing cycles could be explained by the crack propagation during the bending tests. During the first cycles it was observed fractured aggregates in the free, cracked surfaces of the bitumen, which have also been detected by means of computer tomography when specimens are tested at low temperatures [13]. This type of fracture introduces variability in the breaking results and also reduced the healing ratio during the first healing cycles. Although it was not demonstrated in this research, it is believed that after several healing cycles the bitumen flows through the aggregate crack, improving the healing. The p-value obtained from the ANOVA, yielded a p-value of 0.005, indicating that the number of healing cycles have an effect in the healing ratio.

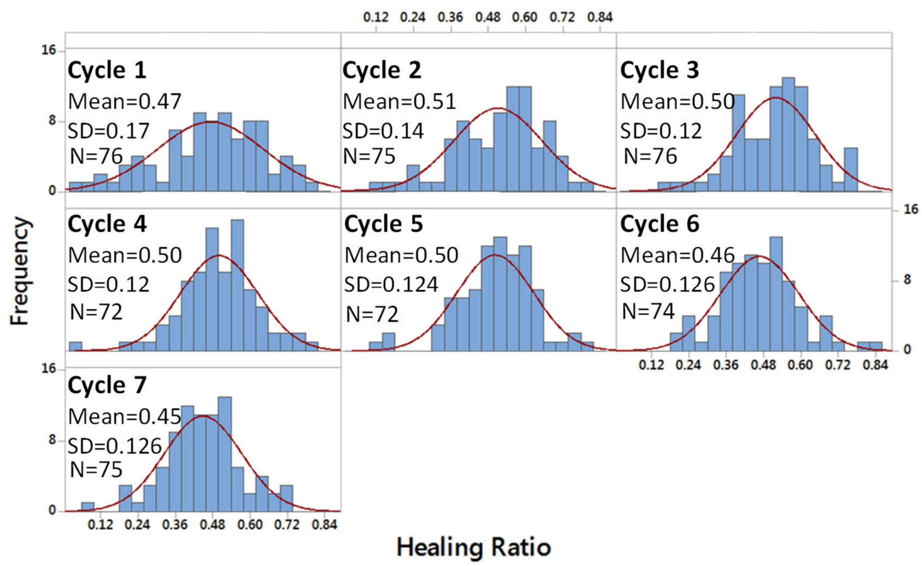

FIGURE 6 Histogram of healing ratios for different healing cycles.

4. CONCLUSIONS

This paper has explained the effect of adding RAP and metal fibers on the variability of the crack-healing capabilities of asphalt mixtures, gained by microwave radiation heating. Based on the analysis of results, the following conclusions can be drawn:

- Asphalt mixtures without RAP, or low RAP content of 10%, show low variability in the healing capabilities of asphalt mixtures. When the RAP content is in the order of 20-30% the variability increases.
- Low fiber contents of 1% and 2% reduce the variability of the healing capabilities of asphalt mixtures, compared to mixtures without fibers and with 4% fibers.
- The number of healing cycles reduces the variability of the healing capabilities of asphalt mixtures.
- Overall, results suggest that the variability obtained in asphalt mixtures with crack-healing capabilities remains within an acceptable range.

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