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

J. Norambuena-Contreras [a],*, A. Gonzalez [b], J.L. Concha [a], I. Gonzalez-Torre [a], E. Schlangen [c]

[a] LabMAT, Department of Civil and Environmental Engineering, University of Bío-Bío, Concepción, Chile
[b] Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile
[c] Microlab, Faculty of Civil Engineering and Geosciences, Delft University of Technology (TU Delft), Delft 2628 CN, The Netherlands

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.

ARTICLE INFO

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.

© 2018 Elsevier Ltd. All rights reserved.

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

* Corresponding author.
 E-mail address: jnorambuena@ubiobio.cl (J. Norambuena-Contreras).

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