Journal of Environmental Management 214 (2018) 242–251

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

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

A. González [a, b, *], J. Norambuena-Contreras [c], L. Storey [d], E. Schlangen [e]

[a] Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Catolica de Chile, Santiago, Chile
[b] Faculty of Engineering, Universidad del Desarrollo (UDD), Santiago, Chile
[c] LabMAT, Department of Civil and Environmental Engineering, University of Bío-Bío (UBB), Concepción, Chile
[d] Department of Civil Engineering, University Federico Santa María (UTFSM), Valparaíso, Chile
[e] Microlab, Faculty of Civil Engineering and Geosciences, Delft University of Technology (TU Delft), Delft, 2628 CN, The Netherlands

ARTICLE INFO

Article history:
Received 28 November 2017
Received in revised form
14 February 2018
Accepted 1 March 2018

Keywords:
Asphalt mixture
Waste
Metal shavings
Crack-healing
RAP
Microwave heating
Induction heating
X-ray microtomography

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

* Corresponding author. Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Catolica de Chile, Santiago, Chile.
E-mail address: algonzav@ing.puc.c (A. González).

https://doi.org/10.1016/j.jenvman.2018.03.001

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