Thermal Evaluation of Sustainable Asphalt Pavements with Energy Harvesting Purposes

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ABSTRACT

This paper presents the influence of metallic waste addition on the thermal behaviour of asphalt mixtures and their use as a solar collector. With this purpose, different asphalt mixtures with the same aggregates gradation and bitumen content but with two different types of metallic waste, steel shavings and steel wool fibres, were experimentally analysed. Thermophysical and heating properties of asphalt specimens with, and without, metallic waste were evaluated. Furthermore, thermal behaviour of a solar collector prototype was evaluated under different solar irradiance conditions. The main results showed that the addition of steel fibres improved the thermal conductivity and thermal diffusivity of asphalt mixtures and that steel fibres were more efficient than steel shavings in the heat transfer process through the mixtures. Finally, it was proven that the developed solar collector was able to transfer heat from the pavement surface to the water flowing inside it, and that the water reached a temperature of 53°C under the maximum irradiance conditions. Therefore, it was proven that metallic waste can be potentially used to develop new sustainable asphalt pavements with energy harvesting purposes.

Keywords: Asphalt mixture; Metallic waste; Thermal performance; Solar collector.

1. INTRODUCTION

Recent studies indicate that countries in South America have some of the highest solar radiation levels in the world, with average values of Global Horizontal Irradiance (GHI) over 7 kWh/m^2 and Direct Normal Irradiance (DNI) over 9 kWh/m^2 [1]. In the right conditions, these radiation levels can increase the temperature of asphalt pavements up to 60°C [2]. Thus, the heat absorbed by asphalt pavements can be used with energetic purposes, making them asphalt solar collectors [[3],[4]]. This technology consists on the embedment of pipes inside the pavement with a fluid circulating through them [5], and two of their main applications are: thermal comfort of adjacent buildings and de-icing systems [2].

According to Mallick et al. [3], the performance of asphalt solar collectors is based on the solar radiation absorption capacity of the pavement, which increases its surface temperature. This way, the absorbed heat can be transferred to the circulating flow. In this context, Hassn et al. [6] stated that the pavement surface temperature depends on heat transfer mechanisms, such as: radiation, convection and conduction. However, variables like the porosity of asphalt mixture [7] and the thermal properties of its components can also have influence [8]. From a practical viewpoint, asphalt pavements can be good solar radiation absorbers, because of their black colour and high absorptivity. But they also have high emissivity [4], which can reduce the efficiency of an asphalt solar collector. To solve this, recent studies concluded that the addition of metallic waste in asphalt mixtures can: 1) improve their heating properties [[9],[10]], 2) increase their thermal conductivity counteracting the pavement emissivity [[5],[8]], and 3) reduce the contribution of pavements to the urban heat-island effect [11], efficiently transferring heat from the pavement surface to the fluid in the asphalt solar collector.

The aim of this study was to analyse the influence of the type and content of metallic waste on the thermal behaviour of asphalt mixtures and their use as solar radiation absorbent material. With this purpose, 1) the thermophysical properties of asphalt mixtures with metallic fibres and shavings and 2) the performance of an experimental prototype of asphalt solar collector, were evaluated.

2. MATERIALS AND METHODS

2.1 Materials

A standard dense asphalt mixture was used in the study. The aggregates were classified in three fractions: coarse (size: 5-12.5 mm, density: 2.779 g/cm^3), fine (size: 0.08-5 mm, density: 2.721 g/cm^3) and filler (size <0.08 mm, density: 2.813 g/cm^3). The bitumen used was a CA-24 with a penetration grade of 80/100 mm at 25°C and density 1.039 g/cm^3. Also, steel fibres and shavings were added. Fibres were made of low-carbon steel with density 7.180 g/cm^3, average diameter of 0.157 mm, average aspect ratio of 30 and initial length range 2-8 mm. In contrast, shavings were made of austenitic stainless steel with density 7.980 g/cm^3, average thickness of 0.335 mm and initial length range 1-6 mm. Steel waste (M_w) were added to the mixtures in 4 percentages: 2%, 4%, 6% and 8%, by total volume of bitumen. Finally, 1 reference mixture, 4 mixtures with fibres and 4 mixtures with shavings were manufactured, using the same aggregates gradation and bitumen content.

2.2 Preparation of asphalt specimens

Cylindrical Marshall specimens with 100 mm-diameter and 60 mm-height were manufactured. To prepare the test specimens, the aggregates were previously heated at 150°C for 24 h, while the bitumen and metallic waste were heated at 150°C for 2 h. Then, raw materials were mixed for 3.5 min in a laboratory planetary mixer at a rate of 100 rpm, keeping a constant temperature of 150ºC. They were added in the following order: bitumen and metallic waste, coarse aggregate, fine aggregate and filler. Then, each batch of asphalt mixture was poured into a Marshall mould and compacted with a Marshall hammer applying 75 blows on each face of the specimen. A total of 32 specimens with metallic waste and 4 reference specimens were manufactured.

2.3 Bulk density and air void content

Bulk density of each specimen was calculated as the ratio between the dry mass and the real volume obtained as the water-submerged mass. In addition, the Air Void Content (*AVC*) was determined using the previous calculation of the bulk density and the theoretical maximum density according to Eq. (1).

$$AVC(\%) = (\rho_{mt} - \rho_a)/\rho_{mt} \quad (1)$$

Where ρ_a and ρ_{mt} are the bulk density and the theoretical maximum density of each mixture in g/cm^3, respectively. Representative values of ρ_a and AVC for each mixture were calculated as the average value of 3 measurements.

2.4 Thermophysical properties of asphalt mixtures

To evaluate the influence of the type and content of metallic waste on the thermophysical properties of the asphalt specimens with and without metallic waste, thermal conductivity (λ), specific heat (C_p) and thermal diffusivity (β) were determined. First, λ was measured using the KD2-Pro thermal properties analyser (Decagon Devices) formed of a handheld controller and a needle stainless steel RK-1 sensor (length of 60mm and diameter of 3.9mm), with a measurement range of 0.1-6.0 $Wm^{-1}K^{-1}$. All the measurements were made based on the transient linear heat source theory [12]. Additionally, C_p was calculated according to Eq. (2). Where m_T is the total mass of each asphalt specimen in kg; m_{Ag}, m_M and $m_{M.W}$, and C_{Ag}, C_M and $C_{M.W}$, are the mass in kg and the specific heat in J/kgK of aggregates, bitumen and and metallic waste, respectively. $C_{M.W}$ was differentiated as C_f or C_s in the case of fibres and shavings, respectively. C_{Ag} [7], C_M, C_f [8] and C_s [13] values were 908 J/kgK, 1900 J/kgK, 482 J/kgK and 450 J/kgK, respectively.

$$C_p = \left(m_{Ag} * C_{Ag} + m_M * C_M + m_{M.W} * C_{M.W}\right)/m_T \quad (2)$$

$$\beta = \lambda/(\rho_a * C_p) \quad (3)$$

Finally, β was calculated according to Eq. (3). Where λ was measured in W/mK, ρ_a in g/cm^3 and C_p of each mixture in J/kgK.

2.5 Solar irradiance simulation in laboratory

To simulate solar irradiance in laboratory conditions, radiation data in the city of Concepción (Chile), between 2001 and 2013 were statistically analysed. The maximum and minimum average solar irradiance conditions were determined from the analysis, being respectively 898.57 W/m^2 in December (summer season), and 289.38 W/m^2 in June (winter season). Then, those values were used as input parameters on the solar model developed by Norambuena-Contreras et al. [14], to estimate the needed height at what a 250W infrared radiation source should be placed to simulate a specific solar irradiance. Consequently, the calculated distances between the radiation source and the asphalt specimen to simulate the conditions of maximum and minimum solar irradiance were 0.4 m and 0.9 m, respectively.

2.6 Thermal behaviour of asphalt mixtures and solar collector under infrared radiation

To evaluate the thermal behaviour of asphalt mixtures, each specimen was exposed to a 250W infrared radiation source that simulated the conditions of maximum and minimum irradiance estimated in section 2.5. To do this, temperature was measured in steady-state conditions during 24 h, and in transient-state conditions during 12 h-heating and 12 h-cooling. Furthermore, to evaluate the thermal behaviour of an asphalt solar collector prototype, one specimen with metallic waste was selected, and a 12 mm-diameter copper pipe was installed inside it, with a water storage capacity of 20 cm^3, see Figure. 1(a). The prototype was also exposed to the 250 W infrared radiation source simulating the maximum and minimum solar irradiance. The temperature in the solar collector was measured in transient-state conditions during 12 h heating and 12 h cooling, thus simulating a day-night cycle. Both in the cases of asphalt specimens and the solar collector, the temperature distribution was registered using 3 K-type thermocouples, and the surface temperature was registered using an infrared camera Optris PI160, Figure, 1(b) and (b).

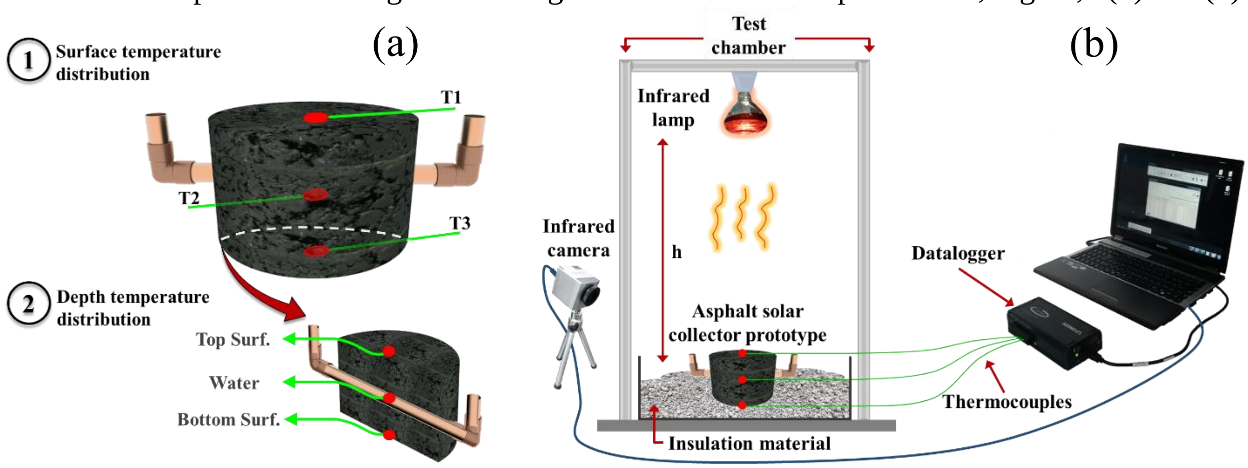

FIGURE 1 Scheme of (a) asphalt solar collector and thermocouples distribution, and (b) heating test in asphalt mixtures and solar collector via infrared radiation.

3. RESULTS AND DISCUSSION

3.1 Influence of metallic waste on the thermophysical properties of asphalt mixtures

Table 1 presents the average results of the thermophysical properties of asphalt mixtures with, and without, metallic waste. It can be observed that the addition of metallic waste reduced the bulk density of the mixtures, compared to mixtures without waste, which was due to the increase of their porosity. Likewise, an increase on the porosity of asphalt mixtures can affect their thermophysical properties and the collector efficiency. Specifically, an increase of λ in asphalt mixtures can allow the collector to transfer more energy to the fluid inside it. However, results showed a reduction of this property with the increase of the amount of metallic waste, which was attributed to the increase of mixtures porosity, see Table 1. Moreover, λ values were higher in mixtures with fibres than in those with shavings, because of 2 reasons: 1) the high aspect ratio of the fibres that generate more contact points between them, and 2) the different value of λ for each metallic waste [15].

TABLE 1 Average results of thermophysical properties in asphalt mixtures.

	Steel wool fibres					Steel shavings				
M_w	ρ_a (g/cm^3)	AVC (%)	λ (W/mK)	C_p (J/kgK)	β (x10^{-7}) (m^2/s)	ρ_a (g/cm^3)	AVC (%)	λ (W/mK)	C_p (J/kgK)	β (x10^{-7}) (m^2/s)
2%	2.347	6.86	1.343	954.67	5.994	2.362	6.26	1.187	954.01	5.268
4%	2.313	9.05	1.385	951.45	6.293	2.338	8.05	1.246	950.16	5.609
6%	2.342	8.24	1.379	948.27	6.209	2.316	9.27	1.257	946.36	5.735
8%	2.310	10.21	1.369	945.13	6.270	2.285	11.22	1.252	942.62	5.813
0%	2.356	5.83	1.406	957.93	6.230	2.356	5.83	1.406	957.93	6.230

Besides, the addition of metallic waste in asphalt mixtures slightly reduced C_p values (see Table 1), consequently decreasing the amount of energy needed to increase their temperature. Furthermore, the addition of metallic fibres mainly increased β with respect to a reference mixture, thus increasing the heat transfer rate inside asphalt mixtures. This was attributed to the fibres morphology. While the reduction of β in asphalt mixtures with shavings was associated with the increase on the porosity of the mixtures. Finally, due to the fact that: 1) higher values of λ increase the amount of heat transfer to low thermal energy zones [11], 2) lower values of C_p increase the heating rates of asphalt mixtures, and 3) higher values of β increase the heating rate through asphalt mixtures, the results indicated that asphalt mixtures with 4% of metallic fibres can be potentially used to develop an asphalt solar collector prototype.

3.2 Heating properties of asphalt mixtures and solar collector under infrared radiation

The heating results under steady-state conditions on asphalt mixtures with, and without, addition of fibres, see Figure. 2(a), and shavings, see Figure. 2(b), showed that there is no direct relationship between the temperature reached by the mixtures and the amount of metallic waste. This was attributed to the heterogeneous distribution of metallic waste inside the asphalt mixtures and to the increase of their porosity. In addition, Figure. 2 presents the results of heating rate between the 2nd and 3rd hours of exposition to infrared radiation, showing that the heating rate in mixtures with fibres was higher than that in mixtures with shavings. Hence, the morphology and distribution of steel wool fibres together with the improvement on the thermophysical properties of mixtures with fibres were the most influential variables during the first hours of heating.

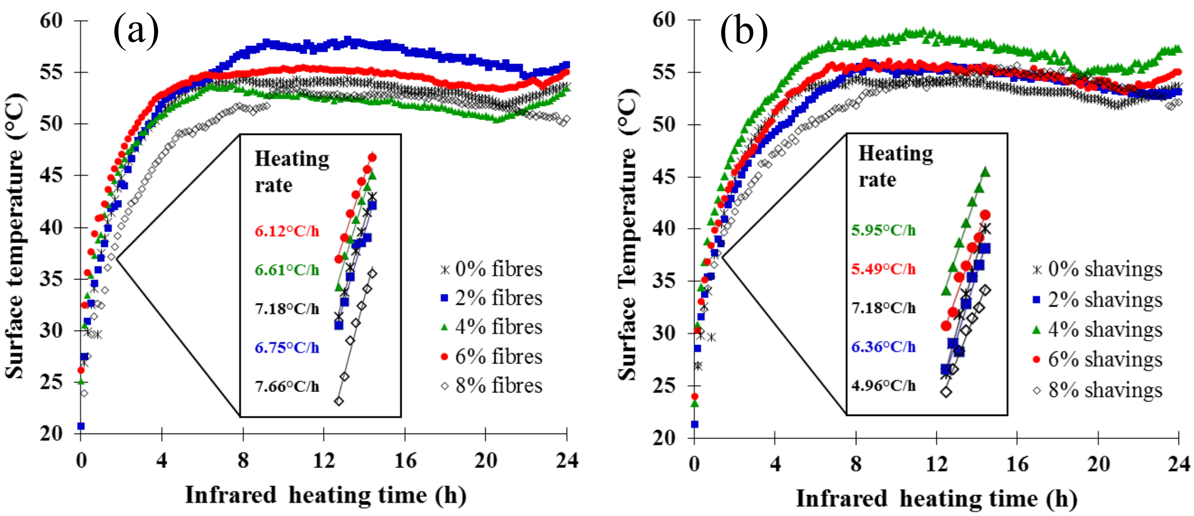

FIGURE 2 Temperature evolution under steady-state conditions in asphalt mixtures with: (a) steel fibres and (b) steel shavings.

Moreover, as shown in Figure. 2, the temperature of asphalt specimens after 12 h of heating kept constant reaching a steady state. However, the addition of metallic waste to asphalt mixtures did not contribute to improve this thermal balance, compared to a reference mixture without waste. In addition, Figure. 3(a) presents the heating rate on the top surface, inside and under the bottom surface of all asphalt mixtures after 1 h-heating and 1 h-cooling. In particular, a high heating rate can allow the fluid to reach higher temperatures in a specific time. While lower cooling rates allow the fluid to keep longer the reached temperature, thus increasing its efficiency. In this context, Figure. 3(a) shows that the amount of metallic waste added to the mixtures and the heating-cooling rate were no directly related. However, asphalt mixtures with 4% of steel fibres increased their heating rates and decreased their cooling rates with respect to mixtures without metallic waste.

Furthermore, Figure. 3(b) shows the heating results of an asphalt solar collector prototype made using an asphalt specimen with 4% of metallic fibres, under maximum and minimum irradiance conditions. It can be observed that there is a fast increase of temperature during the first 4 h of heating, and that the collector reached the thermal balance after 6 h. However, the reached temperature was more stable in the minimum irradiance condition. This was attributed to the fact that the collector absorbed less thermal energy under the minimum irradiance conditions, thus reducing the effect of the fibres and the copper pipe on the heat transfer process through the mixture. Finally, after 12 h of heating, the water inside the collector reached temperatures of 33°C and 53°C, under the minimum and maximum solar irradiance conditions, respectively, which represented a temperature reduction of 3.32% and 10.23% with respect to that reached on the top surface of the collector.

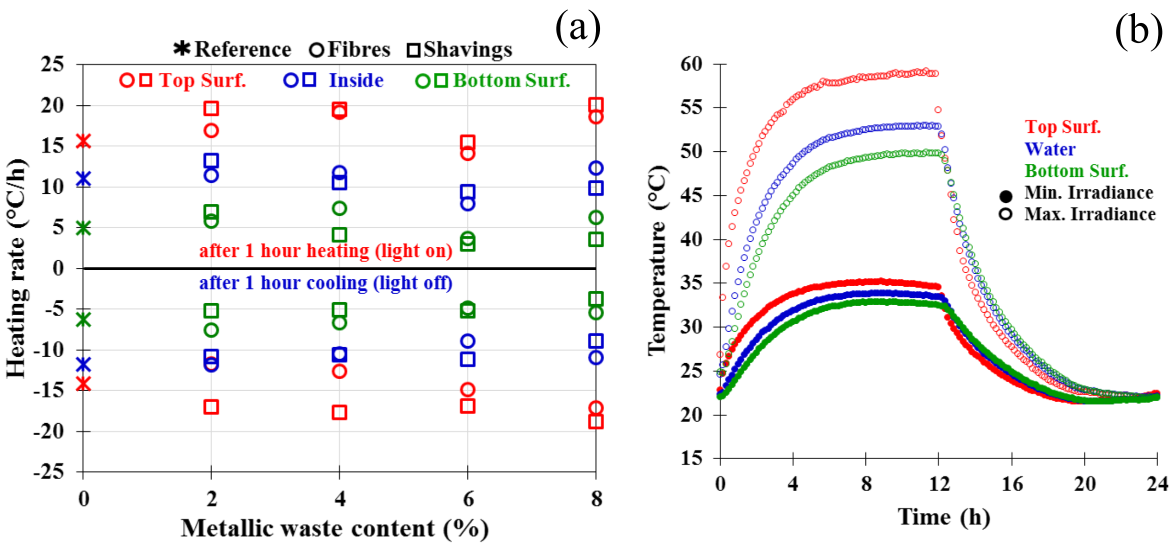

FIGURE 3 Temperature evolution under transient-state conditions in: (a) reinforced asphalt mixtures and (b) asphalt solar collector prototype.

4. CONCLUSIONS

- Density of asphalt mixtures with metallic waste reduced with the air voids content increase, that was mainly attributed to the total volume variation of each asphalt specimen, rather than the variation of the mass.
- Thermal conductivity and specific heat of asphalt mixtures were reduced with the addition of metallic waste. However, the incorporation of steel wool fibres in asphalt mixtures caused an increase on their thermal diffusivity, consequently decreasing the influence of air voids on the heat transfer through the mixtures.
- In addition, under steady-state heating, asphalt mixtures with fibres increased their heating rate during the first hours of exposition to infrared solar radiation. In contrast, under transient-state heating, just in the case of asphalt mixtures with 4% of fibres an increase on the heating rate and a decrease on the cooling rate was registered.
- Finally, it was proven that the asphalt solar collector with 4% fibres was able to transfer heat from the pavement surface to the water flowing inside it, and that the water reached a temperature of 53°C under the maximum irradiance conditions.

5. ACKNOWLEDGMENTS

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