Crack repair of asphalt concrete with induction energy

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It is well known that the healing rates of asphalt courses increase with the temperature. A new method, induction heating, is used in this paper to increase the lifetime of asphalt concrete pavements. Mastic will be first made electrically conductive by the addition of conductive fibers. Then it will be heated via induction energy. This will repair the damage in the pavement, closing the cracks that could have appeared during its lifetime. Adding too much heat will melt the binder completely and the properties of the material will be lost. In the paper it is shown how this method can be repeated many times for samples that are completely broken and that the evolution of the mechanical resistance of specimens that are broken is limited. It will also be shown how the chemical properties of the bitumen do not change due to heating.

Key words: Induction heating, conductive mastic, steel wool, self healing

1 Introduction

Asphalt concrete is one of the most common types of pavement surface materials used in the world. It is a material that consists of a mixture of asphalt binder, aggregate particles and air voids. This material must resist in good conditions all traffic loads under many different climatic conditions for a long time. In order to maintain these characteristics during its lifetime, asphalt concrete wearing courses should be constantly maintained and repaired. Little cracking on a highway runway can mean the start of large distress. As shown by García et al., 2009, it is theoretically feasible to induction heat mastic through the addition of different types of conductive fibers and fillers. The objective of this research is to investigate how mastic can be heated through the addition of different volumes of electrically conductive particles. The idea is to use this electrically conductive asphalt concrete for healing purposes in the future.

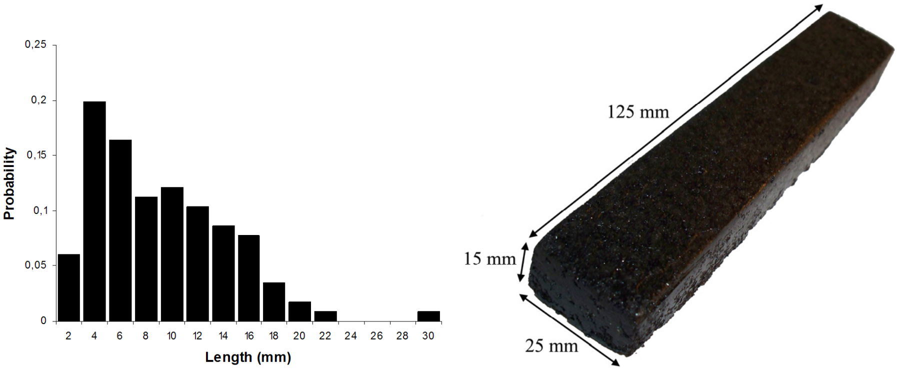
Conductive asphalt concrete may be defined as the mixture of bitumen, aggregates and electrically conductive components which together constitutes high electrical conductivity of the whole material. García et al. (2009) have shown how to make electrically conductive mastic by adding conductive fillers and fibers. In this research (García et al., 2009), it was discovered that it is much more effective to add electrically conductive fibers than to add fillers. In addition, it was observed that there is an optimum volume of fibers for each mixture, bellow which, the conductivity of the material suddenly drops to that of a non conductive material. Adding fibers resumes in mixing difficulties, while the conductivity is hardly increased. In this research it was also demonstrated how this electrically conductive mastic could be heated very fast with induction energy.

If it is possible to heat asphalt concrete on site, self healing rates will increase and cracks will be closed much faster. For that, this research investigates the effect on the induction heating temperatures of mastic with different volumes of electrically conductive particles and sand-bitumen ratios. This research has been performed in mastic, although similar effects could have been obtained in a common asphalt mixture (Liu et al., 2009). To get a better understanding of the ageing effects of heating the mastic with induction, Gel-Permeation Chromatography (GPC) tests are performed.

2 Experimental method

2.1 Materials

Mastic specimens were prepared with different sand-bitumen ratios and volumes of conductive particles. Five different sizes (<0.120, 0.120-0.250, 0.250-0.5, 0.500-1.0, 1.0-2.0 mm) of natural silica mineral, with density 2.67 g/cm3, were mixed to have uniform grading. The virgin bitumen used was 70/100 pen, obtained from Kuwait Petroleum, with density 1.032 g/cm3.



(a) *(b)*

Figure 1: (a) Chopped steel wool sizes distribution. (b) Test samples used in the research.

The electrically conductive particles used were steel wool, of type 000, with diameters between 0.00635 mm and 0.00889 mm and approximate density 7.6 g/cm^3, chopped by hand, always by the same operator. To determine the size, more than 100 fibers were checked by taking photographs under the optical microscope and their length was measured with an image processing program, obtaining the distribution showed in Figure 1 (a).

Finally, the mix proportions for the mastic used to test the healing and the ageing were, by total percentage of weight in the mixture: 74.5 % of sand without filler (aggregates with size less than 0.120 mm were eliminated to enhance the healing effect), 18 % of bitumen and 7.5% of fibers (sand-bitumen, (mass of sand divided by mass of bitumen) (s-b) 1.60 and 5.66 % steel wool).

2.2 *Methods*

Conductive fibers, aggregates and bitumen were blended during 15 minutes at 285 r.p.m. and 150 ºC of temperature. After this, the mass was hand-compacted in silicon-rubber moulds, obtaining specimens with the dimensions shown in Figure 1(b). The electrical resistivity measurements were done at room temperature 20 ºC. The electrodes were made of nickel and placed at both ends of the test sample to measure the electrical volumetric resistance. Dry graphite powder (<20 µm) was used to fill the gaps between the electrodes and the specimens and to ensure a perfect contact between them. The total contact resistance between the electrodes and the graphite was less than 0.1 Ω, which is negligible with respect to the great resistances studied (higher than 20 Ω in the samples). A digital multimeter was used to measure the resistance below 36 10^6 Ω. A resistance tester was used to measure the resistance higher than this value. From the resistance data, the electrical resistivity was obtained from the second Ohm-law:

$$\rho = \frac{RS}{L} \tag{1}$$

Where ρ is the electrical resistivity, L is the internal electrode distance, S is the electrode conductive area and R is the measured resistance. The electric field is assumed constant and the end-effects considered negligible.

The temperature changes were measured with a 320 x 240 pixels, full colour infrared camera. The induction heating experiment was performed by using an induction heating system with a capacity of 50 kW and at a frequency of 70 Hz. Although the system was not fully optimized, it had not influence on the research objectives: demonstrate how mastic can be heated and healed through induction energy.

Besides, Gel-Permeation Chromatography (GPC), a chromatographic method in which particles are separated based on their hydrodynamic volume, was performed to analyze the molecular weight distribution change of induction heated samples at 60, 110, 160 and 200 ºC at a frequency of 70 Hz and a power of 50 kW, so as the original bitumen and a non heated sample. From each one of these specimens, more than 10 tests were performed on material from different positions in the sample. In total, 62 GPC tests were done.

Finally, to prove that mastic could be healed with induction energy, four samples were broken at -20 ºC, while measuring their stress-strain curves. After this, both pieces of the sample were placed in the same moulds where the specimens were originally made, and heated during 2 minutes until its temperature was 120 ºC. Then, the sample was frozen to -20 ºC and broken again while measuring its stress-strain curve.

3 Induction heating

Induction heating is a process which is used to bond, harden or soften metals or other conductive materials. When an alternating electrical current is applied across a conductive coil, an alternating magnetic field with the same frequency as the alternating current causing it is created (Karamuk et al., 1995). According to Faraday's Law, if a magnetically susceptible and electrically material is located within the magnetic field, an electric current (eddy current) will be induced with the same frequency as the magnetic field (Figure 2). Bitumen is not an electrically conductive material, but if conductive closed loops are present in the material eddy currents can be induced, for that reason, electrically conductive particles were added to the mixture. The eddy currents heat up the material according to the well-known Joule effect:

$$P = R \cdot I^2 \cdot t \qquad (2)$$

Where P is the heat generated, R is the material resistance, I the current and t the time of exposure to the magnetic field.

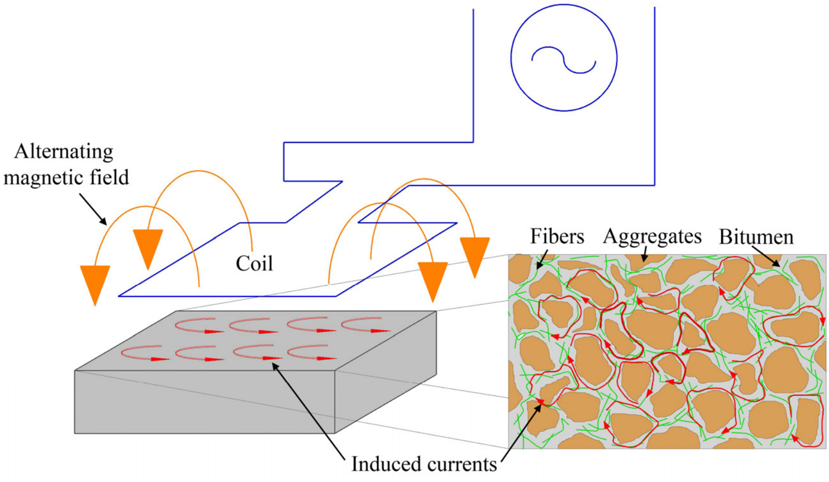


Figure 2: Induction heating scheme.

In Figure 3 the heating curve of the mastic samples used to test the ageing of bitumen through induction heating is shown. In this Figure it can be observed that the curve shape is parabolic. Unfortunately, the resolution of the infrared camera used was not so high to find out the heating mechanism (the pixel size was much higher than the fibers diameter). However, based on the researches by Ahmed et al., 2006, it is possible to elucidate that the predominant mechanism of heating will be the fiber heating, although other mechanisms such as junction heating due to the dielectric hysteresis heating and junction heating due to the contact resistance heating can also happen. In addition, it has been observed how, as the material heats, the viscosity of the sample lowers and a squeeze-out of the bitumen is noticeable.

The amount of heat generated in the specimen is proportional to the power induced on it (Ahmed et al., 2006). The relationship between the source and the power generated in the sample can be expressed as:

$$P = \frac{\left(2\pi f \mu_r H(I) A\right)^2}{R} \tag{3}$$

Where f is the field frequency, μ_r the magnetic permeability of the material studied, $H(I)$ is the magnetic field intensity, which is dependent on the current of the equipment, A the cross-sectional area of the conductive loop in the workpiece and R is the material resistance.

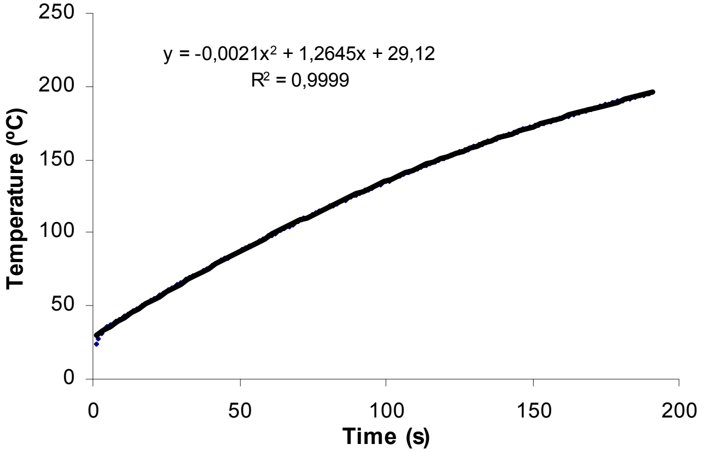


Figure 3: Heating curve for a sample with 5.66 % steel wool (related to the volume of bitumen) and sand-bitumen ratio 1.60

Other fundamental factor in the induction heating of a conductive material is the current frequency. It has been demonstrated that the time to heat a composite to a certain temperature decreases quadratically with the increasing frequency (Rudolf et al., 2000); but the higher the frequency, the lower the heating depth. That is why it would be important to optimize both factors. Nevertheless, for this research, as the purpose was to demonstrate that it is possible to heat conductive mastic with induction energy, these factors were not considered.

4 Results and discussion

4.1 Effect of fiber volume content

Volume resistivities versus fibers content (conductive fibers-bitumen ratio) with a fixed sand-bitumen ratio 2.25 are displayed in Figure 4 (a). As explained by García et al., for small amounts of fibers, the electrical resistivity is very similar to that of a plain mastic, exhibiting insulating behaviour. For the type of fibers and the sand-bitumen ratio used, after more than 6.02 % of fibers have been added, mastic becomes suddenly conductive. Adding more fibers does not improve the electrical conductivity of mastic, but make the mastic difficult to mix and clusters of fibers appear during the mixing process.

In Figure 4 (b) the maximum reachable temperatures at three different heating times for different volumes of fibers are shown. In this Figure it can be seen how the total energy absorbed by the electrically conductive mastic increases with the volume of fibers until a certain point, where the temperature does not increase any more, independently of the volume of fibers added. For example, with approximately 6 % of fibers in the mixture, the maximum temperature reached after 120 s heating is close 150 ºC, but with an 8 % of fibers added, the maximum temperature reached after 120 s heating is also close to 150 ºC. This optimum volume of fibers seems to coincide with the 6.02 % of fibers to create an electrically conductive mastic.

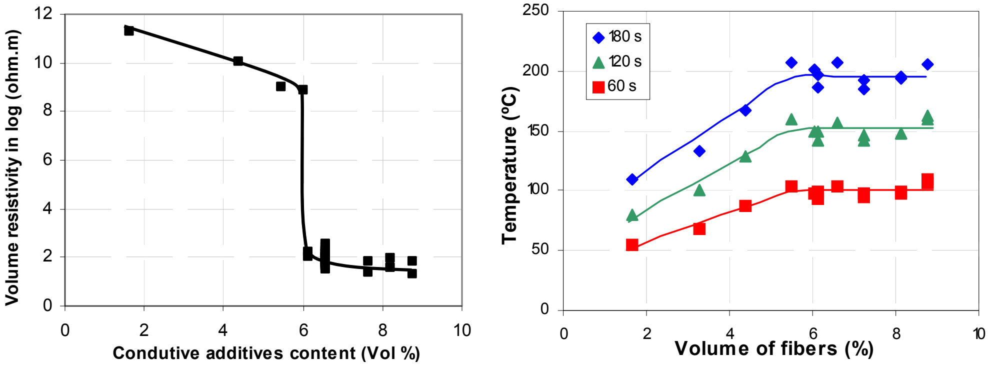
4.2 Analysis and discussion

In Figure 4 it has been proved that it is not necessary to have electrically conductive mastic to increase its temperature via induction heating. Fibers are like small heaters inside the mastic (Figure 2). To be heated with induction energy they need to be connected in small closed-loop circuits. When few fibers are added to the mixture (related to the total amount of bitumen in it), very few circuits will be formed and the increase of temperature will be relatively low. It is also logic to think that when more fibers are added to the mixture, the maximum temperature reached will increase (and the electrical conductivity of the sample). Eventually, there will be so many fibers that all the possible spaces where they could be (they can only be in the volume occupied by bitumen) will be saturated. By increasing their volume further this point, clusters of fibers will appear, there will not be enough bitumen to cover all the fibers and they will be exposed to air (with the consequent oxidation and loss of properties). It was tried to heat the steel wool with induction heating. Its temperature did not almost increased, independently of the heating time, so it can be deduced that the fibers lose the heat very fast into the surrounding environment. Indeed, if they are not completely covered with bitumen, they will not increase the temperature of the mixture. Finally, if their volume is above the optimum of fibers, and clusters are present, the temperature increase will not be uniform.

4.3 Chemical changes analysis

In GPC, the sample components are eluted in order of decreasing molecular weight, an example of a GPC chromatogram is shown in Figure 5 (a). For all the measurements done, the average molecular weight has been studied as a parameter to evaluate ageing (Lu et al., 2002). The average molecular weight is calculated in the following way:

$$M_w = \frac{\sum\left(n_i \cdot M_i^2\right)}{\sum\left(n_i \cdot M_i\right)} \tag{4}$$



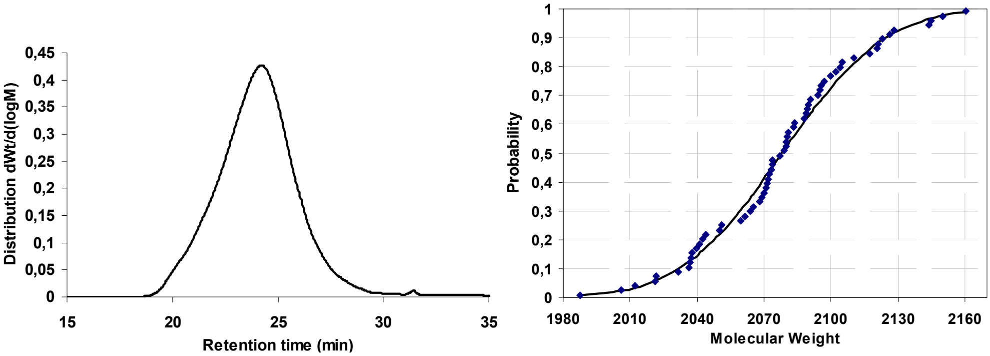
(a) *(b)*

Figure 4: (a) Volume resistivity versus conductive particles content for mastic with sand-bitumen ratio 2.25

(b) Maximum reachable temperatures at three different heating times for different volumes of fibers

Where M_w is the weight-average molecular weight (g/mol), M_i is the molecular weights and n_i are the number of molecules of molecular weight M_i.

To show what happens with this value during the induction heating, in Figure 5 (b), the empirical cumulative distribution function $(i\text{-}0.5)/n$, where i is the position of the value in the series and n is the number of elements in the series, is represented together with the theoretical normal cumulative distribution function. It can be observed how both plots fit quite well, which means that, the molecular weight average does not change due to the induction heating.



(a) *(b)*

Figure 5: (a) Molecular weight distribution plot of an induction-heated bitumen at 110 °C
(b) P-P plot of all the GPC samples, heated at four different temperatures, the original bitumen and the non heated samples

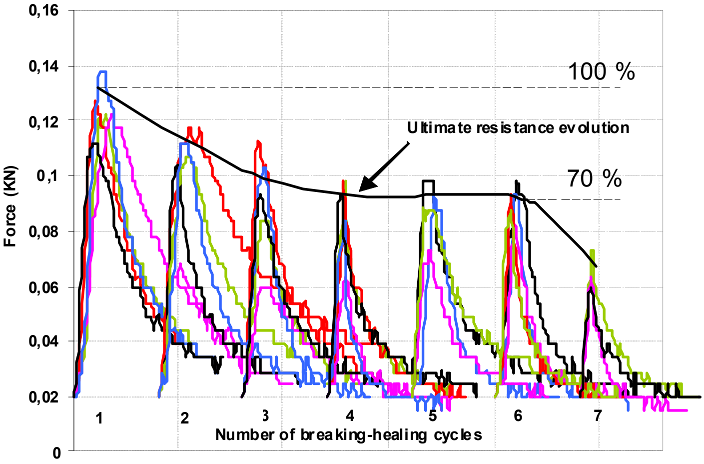


Figure 6: Stress-strain curves for samples with 5.66 % steel wool (related to the volume of bitumen) and sand-bitumen ratio 1.60

García et al., 2009, pointed out that one of the main applications of conductive asphalt is heating it with induction energy to increase its self-healing rates. To have an idea of how does mastic heal with induction energy, in Figure 6, the stress-strain curves of four samples and the stress-strain curves of these samples once healed are shown. As indicated in Section 4.1, these samples were frozen at -20 ºC; so the test specimens failed thorugh brittle fracture. In Figure 6, it can be seen that these samples can be healed almost six times and that the resistance of the samples after the fifth healing is about 70 % of the original resistance.

Although more data are still required to determine the effectivity of the system, this healing cycle is enough to prove that mastic can be healed very fast with induction energy. In addition, the resistance after healing a completely broken sample is relatively high. Future research will focus on the definition of the healing parameters with induction heating, and its application in asphalt concrete, not only in mastic.

5 Conclusions

This paper explains how to heat mastic with induction energy. It has been proved that in order to heat mastic with induction, it is necessary to add electrically conductive fibers. There is an optimum volume of conductive fibers in the mixture, above which the heating speed does not increase any more, the electrical resistivity remains constant or is reduced and clusters of fibers start appearing in the mixture, which makes the heating non uniform. This optimum volume of conductive particles coincides with the volume needed to have the maximum conductivity in the asphalt. Bellow this optimum value, the mastic electrical resistivity drops to that of a non conductive material, but mastic can still be heated due to local conductivity.

Although in García et al., 2009, it was stated that a small increment in the volume of fibers can force an increase in the resistivity, induction heating behaves differently. In the induction heating curve (Figure 4 (b)), the Transition Phase (García et al., 2009) does not exist and, when the volume of fibers is bellow the optimum, the heating rates simply decrease until there are not more fibers in the mixture. To find the optimum volume of conductive particles needed, each mixture should be analyzed separately by increasing the volume of fibers added until the optimum of fibers (percolation threshold) is found.

Finally, the applicability of the system has been demonstrated. First, bitumen is not aged by the induction heating. Second, four samples with the same recipe were broken in two pieces and healed several times. It is concluded that after one cycle of healing, the medium resistance of the samples is about 90 % of the original sample and after fifth cycles of healing the resistance is about 70 % of the original sample. The number of times that a pavement can be healed will depend on the maximum temperature reached, although more research is required to prove this point. Finally, this system would be useful for its application in places with very extreme weather conditions, for example before the winter to close the cracks and avoid the water freezing inside the pavement or to reduce the ravelling in asphalt concrete pavements.

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