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Microwave Healing Performance of Asphalt Mixture Containing Electric Arc Furnace (EAF) Slag and Graphene Nanoplatelets (GNPs)

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Abstract: Pavement preventive maintenance is an important tool for extending the service life of the road pavements. Microwave heating seems to be a promising technology for this application, as bituminous materials have the potential to self-repair above a certain temperature. As ordinary asphalt mixture has low microwave absorbing properties, some additives should be used to improve the heating efficiency. In this paper, the effect of adding Electric Arc Furnace (EAF) slag and Graphene Nanoplatelets (GNPs) on the microwave heating and healing efficiency of asphalt mixtures was evaluated. Microwave heating efficiency was assessed by heating the specimens using several heating times. In addition, the electrical resistivity of the mixtures was measured to understand its possible relationship with the microwave heating process. Furthermore, the healing rates of the asphalt mixtures were assessed by repeated Indirect Tensile Strength (ITS) tests. The results obtained indicate that the additions of graphene and EAF slag can allow important savings, up to 50%, on the energy required to perform a good healing process.

Keywords: graphene nanoplatelets (GNPs); EAF steel slag; asphalt mixtures; microwave heating; self-healing

1. Introduction

Cracking is one of the most common signs of asphalt pavement deterioration, producing a reduction of the mechanical strength and durability of the road pavement over time [1] affecting driving comfort and safety [2].

Generally, the cracks observed at the pavement surface can be caused by two major mechanisms, the bottom-up cracks and the top-down cracks. The bottom-up cracks are initiated by tensile strains at the bottom of the asphalt layer and the top-down cracks are initiated by surface tensile and shear stresses, environmental effects and ageing [3]. Fortunately, the asphalt mixture is a self-healing material, and if enough energy is applied, original mechanical properties can be partially or nearly totally restored. Such technology can enable an important reduction in the consumption of natural resources, saving aggregates and bitumen that would be used in reconstruction or repair/maintenance actions in the road network. By extending the service life of the current pavement, it may occur an overall reduction of the maintenance interventions, thus saving the corresponding costs and CO_2 emissions, as well as minimizing the traffic disruptions caused by such actions [4].

From a molecular point of view, the self-healing phenomenon is due to the wetting and interdiffusion of material between the two faces of a microcrack to achieve properties of the original material [5]. Sun et al. developed a healing function of asphalt material based on molecular diffusion theory [6]. Healing activation energy was found to be a promising parameter for evaluating self-healing ability as if appreciable energy equal to or greater than the healing activation energy exists at the damage faces, the self-healing reaction will start. Molecular diffusion models can only be used for describing the microcracks healing, as in the case of macrocracks, the molecular interdiffusion cannot occur due to a wider gap between the faces. In this case, the capillary flow healing model can be used to describe the self-healing phenomenon. Garcia explained that above a specific temperature, the bitumen behaves as a Newtonian fluid, and can fill the cracks in a sort of capillarity flow [7]. Different types of bitumen exhibit different threshold temperatures for flow, depending on their rheological properties, usually ranging from 30 °C to 70 °C. The flow behavior index of the bitumen was found to be appropriate to characterize the threshold for the initial self-healing temperature of the bitumen [8–10].

The healing capability of asphalt mixtures depends on several internal and external factors [11]. As for the internal factors, bitumen properties have a strong influence on healing capability. Bitumen with lower flow behavior index not only need less energy for starting healing, but also produce better healing levels [10]. At the microscale level, chemical composition has a strong influence on the healing properties of asphalt [12,13]. Cheng et al. demonstrated the influence of the surface energy on the healing capability of bitumen [14]. According to the findings of these authors, the most efficient healers should have relatively lower Lifshitz–van der Waals components and higher acid–base components of surface energy. The amount of bitumen content in the mixture increases the healing capability of asphalt pavement [15]. Some volumetric properties also influence the self-healing properties [16], as well as the type of mixture. Garcia et al. found that porous asphalt mixtures heal faster than the dense mixture, and provide better healing levels [10]. Between the external factors, rest time, temperature and damage degree are the most influential [9,17]. Many researchers have focused on finding the optimal temperature to maximize the healing effect. If the temperature is too low, bitumen cannot flow through the cracks. However, if the temperature is too high, the healing level decreases, probably due to the expansion of the asphalt mixture, which could cause structural defects in the pavement [17–20].

In the field, due to the continuous traffic flow, usually, the rest periods are not long enough to allow the self-healing to occur, and the pavement temperature rarely reaches the temperature needed for flowing. For this reason, in the last years, researchers have studied several technologies to promote the self-healing process. An example is the capsule healing, in which capsules containing rejuvenator oil are mixed with the asphalt materials [21,22]. When crack damage appears next to the capsules, they open and release the oil. The bitumen will be rejuvenated and the life of the asphalt mixture extended [23]. Another type of technology consists of heating the pavement, through induction or microwave heating, in order to reduce the viscosity of the bitumen and heal the cracks.

In the case of induction heating, electrical currents are induced by adding conductive particles in the composition of the mixture, and the heat is generated by the Joule effect [24–26]. Several additives and respective dosages were studied in order to maximize the conductivity of the mixture, such as steel wool, steel fibers, graphite, carbon black and carbon fibers [24,27–30]. Another heating technique is microwave heating, that was found to be more effective than induction heating to heal cracks in asphalt roads [19]. Microwaves are electromagnetic waves with frequencies ranging from 300 MHz to 300 GHz, and wavelengths from 1 m to 1 mm. In industrial applications, the frequencies 915 MHz and 2.45 GHz are the most commonly used, but for special applications, the frequency 5.8 GHz is increasingly used [31]. When microwave radiation is applied, the polar molecules of the asphalt mixture attempt to line up (polarization) with the alternating electromagnetic field. The inability of this polarization to follow the extremely rapid reversals of the electromagnetic field generates random motion and inter-molecular friction that produces heat [32,33]. Microwave heating basically depends on the strength and the frequency of electromagnetic field, the dielectric properties of the matter, which represents the efficiency of material in absorbing microwave energy, the conductivity losses and some thermal properties [34].

Several authors studied the dielectric properties of asphalt mixture for different applications, such as deicing [35], density measurement [36], recycling [33], and maintenance purposes [34,37]. Since the microwave susceptibility of conventional asphalt mixture is low, some authors have added microwave absorbing additives to the mixture for healing purposes [38], such as steel wool fibers [1,19,39,40], steel slag [2,37,41], steel shaving [42], ferrite [17,18] and carbon nanotubes [43]. Trigos et al. proposed a classification of different aggregates frequently used for pavements construction in terms of microwave heating efficiency [44].

Steel slag is a byproduct of the steel production process and is widely used in road pavements, due to his excellent mechanical properties, in terms of roughness, shape, angularity, hardness, polishing and wear resistance [45]. From the environmental point of view, the use of steel slag allows to reduce the amount of material to dispose of, and therefore, the incorporation in asphalt mixtures permits to convert a waste material into a resource. Additionally, the inclusion of slag does not imply any additional cost because the cost of the slag is similar to the prices of natural aggregates [38]. However, only a few studies focused on its microwave absorbing properties and its use for healing purposes in asphalt mixtures. Liu et al. proposed a method to increase the content of ferric oxide of steel slag particles, improving the microwave heating efficiency of asphalt mixture [37]. Li et al. studied the influence of steel slag filler on the self-healing properties of the asphalt mixture using a fatigue-healing-fatigue test. The results show an enhancement in the healing properties of the mixture containing steel slag [2]. Phan et al. used coarse steel slag and steel wool fibers in the asphalt mixture and evaluated the healing rate through three-point bending test [41]. The main result was that the addition of 30% steel slag increased the healing properties of the asphalt mixture.

Recently, with the advent of nanotechnology, some nanomaterials were used in asphalt mixtures. Several mechanical properties can be improved by adding some nanomaterials, such as nanosilica, nanoclay and nanoiron [46]. Recently, carbon and graphene family nanomaterials have been used for asphalt modification [47], such as graphene nanoplatelets (GNPs). The addition of GNP in the mixture leads to an improvement in flexural strength at low temperatures, better performance at high temperatures [48] and easier compaction [49]. However, only a few studies focused on the microwave heating and healing efficiency of asphalt mixture containing graphene nanomaterials. Li et al. used graphene to improve the microwave heating and healing properties of bitumen [8]. The results showed that graphene provides benefits in terms of heating and healing performance.

The objective of this paper is to evaluate the effect of adding Electric Arc Furnace (EAF) slag and Graphene Nanoplatelets (GNPs) on the microwave heating and healing efficiency of asphalt mixtures. This research is the continuation of the study carried out by Gallego et al. [50], where preliminary results of the heating efficiency of these additives were obtained. The graphene nanoplatelets were incorporated as a binder additive, while the EAF slag was added as partial replacement of the natural aggregates. The asphalt mixtures heating efficiency was evaluated using the ratio °C/kWh/kg and, in addition, the electrical resistivity was measured to understand the effect of conductivity losses in the heat generation process. The healing efficiency was studied by applying microwave energy to damaged specimens and evaluating the healing recovery using the Indirect Tensile Strength (ITS) test.

2. Materials and Methods

2.1. Materials

A conventional dense asphalt mixture AC20 35/50 (EN 13108-1:2007) was the mixture type selected to conduct the experimental study. The mixture particle size distribution is presented in Table 1. Limestone aggregates, limestone filler, and 35/50 conventional bitumen were the materials chosen for the production of the mixtures. According to the bitumen specification, the temperatures of 165 °C and 155 °C were adopted for the asphalt mixture production and compaction, respectively. The bitumen content, 4.7% by total weight of the mixture, was previously determined using the Marshall method. The mixing process was conducted using a laboratory mixer (EN 12697-35:2016). Cylindrical specimens of 100 mm in diameter and approximately 63.5 mm in height were compacted using a Marshall hammer (EN 12697-30:2004) applying 75 blows on each side of the specimen.

Table 1. Grading curve of the asphalt mixtures.

Sieve (mm)	% Passing
22	100
16	83
8	56
4	42
2	34
0.5	19
0.063	5

Six types of asphalt mixtures were produced in this study: one conventional reference mixture (with no additives), two mixtures with graphene (with 1% and 2% dosage by mass of modified binder) and three mixtures with EAF slag (with 3%, 6% and 9% of aggregate replacement).

Graphene nanoplatelets, commercially designated as GRAPHENIT-XL, were used to make the asphalt mixtures susceptible to microwaves. Regarding its chemical composition, graphene is essentially carbon (96.41%) with traces of other elements, such as oxygen (1.05%), sulphur (0.48%), nitrogen (0.48%), hydrogen (0.07%) and others. The graphene presents a bulk density of 0.04 g/cm^3. Similarly to other nanomaterials, the nanoscale of the graphene platelets enables a high specific surface area, thus occupying considerably more volume than conventional macroscopic particles. Figure 1 presents a sample of 2.50 g of graphene nanoplatelets and, by the left side, for comparison, 2.50 g of conventional limestone filler (fraction passing sieve 0.063 mm).

Figure 1. Mass of 2.50 g of limestone filler under 0.063 mm (**left**) and graphene nanoplatelets (**right**).

The Graphene nanoplatelets were dispersed in the bitumen matrix by adding the nanomaterial to the bitumen heated at 160 °C and applying high-speed mechanical stirring (2000 rpm) during 60 min. Additional details about the mixing process can be found elsewhere [51]. After each bitumen modification (with 1% and 2% graphene), the asphalt mixtures were produced and compacted as described for the conventional mixture.

The EAF slag used in this study is produced in Spain, and its chemical composition is reported in Table 2. After the hydration process carried out by the producer, the free calcium oxide becomes almost zero. This procedure prevents expansion problems associated with the presence of CaO. Two fractions of slag were used as a replacement of limestone aggregates, 0.5/2 mm and 0.063/0.5 mm. Figure 2 presents a sample of 50 g of both fractions. Although many investigations report that the substitution of coarse aggregates improves the mechanical properties of the mixture [45], in this research only fine aggregates were replaced, because this provides more homogeneous heating throughout the mixture, as reported by other authors [52]. Volumetric replacement principle was used in order to take into account the different bulk density of slag and natural aggregates [45].

Table 2. Chemical composition of EAF slag.

Chemical Composition	%
Al_2O_3	8.81
CaO	24.28
Fe_2O_3	40.49
MgO	3.02
MnO	4.72
SiO_2	12.60
P_2O_5	0.36
Other substances	5.72

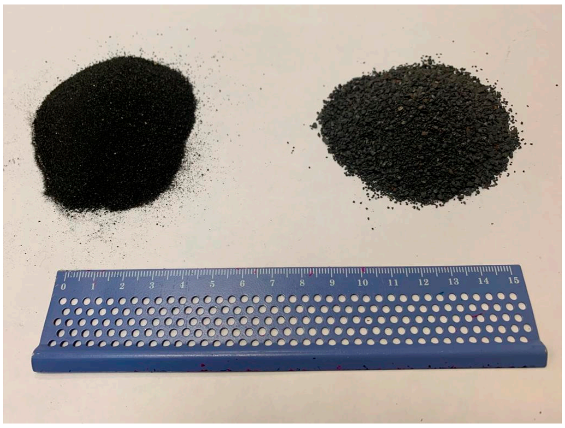

Figure 2. Mass of 50 g of slag, fraction 0.063/0.5 (**left**) and 0.5/2 mm (**right**).

2.2. Bulk Density of the Asphalt Mixtures

Bulk density of the asphalt mixtures (EN 12697-6:2012) was calculated in order to evaluate the physical properties of the mixtures with and without the addition of slag or graphene. Saturated surface dry (SSD) procedure was applied, in which the specimen is first saturated with water, and then its surface is blotted dry with a towel. The bulk density ρ_{bssd} is calculated as:

$$\rho_{bssd} = \frac{m_1}{m_3 - m_2} \times \rho_w \quad (1)$$

where m_1 is the mass of the dry specimen in g; m_2 is the mass of the specimen in water in g; m_3 is the mass of the saturated surface-dried specimen in g and ρ_w is the density of the water at the test temperature.

2.3. Indirect Tensile Strength (ITS) Test

The effect of additives on the mechanical properties of the mixtures was evaluated with the Indirect Tensile Strength (ITS) test (EN 12697-23:2018). The selected test temperature was 15 °C. In the ITS test, a diametrical load was applied at a constant deformation rate of 50 ± 2 mm/min till the rupture of the specimen. Such loading produces tensile stress through the vertical diametral plane, as shown in Figure 3. To prevent excessive deformation of the specimens, the test was interrupted when the measured load dropped by 20% after the peak load. The Indirect Tensile Strength (ITS), in MPa, was calculated as:

$$\text{ITS} = \frac{2 \cdot P_{max}}{\pi \cdot d \cdot h} \quad (2)$$

where P_{max} is the peak load, in KN, d is the diameter of the specimen in mm and h is the height of the specimen, in mm.

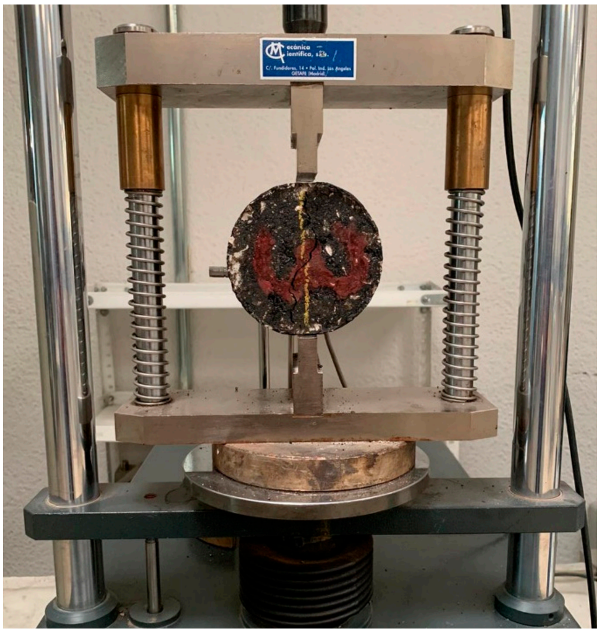

Figure 3. Indirect Tensile Strength (ITS) test.

2.4. Microwave Heating

To heat the samples of asphalt mixture, a conventional microwave oven (with maximum power of 700 W and a frequency of 2.45 GHz) was used. In this study, the medium power level (350 W) was selected and used through all of the study. The heating efficiency of the mixtures was calculated as follows. The cylindrical specimens were cut into two pieces and then were conditioned at 25 °C for 2 h. Then, both pieces were placed in the microwave oven and heated for five heating times: 30 s, 60 s, 90 s, 120 s and 150 s. After each heating time, the two halves of the specimen were separated and an infrared thermometer was used to measure the internal temperature, as the average of eight randomly measurements, as shown in Figure 4. Additionally, the energy consumption during heating was measured with an electricity meter. Linear regression analysis was used to model the relationship between the internal temperature (°C) of the asphalt mixtures and the total energy consumption during the heating process (kWh/Kg).

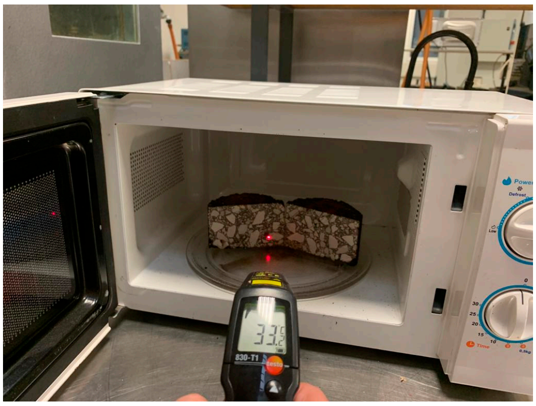

Figure 4. Internal temperature measurement.

2.5. Electrical Resistivity Measurement

The electrical resistance of the asphalt mixture was measured with the two-probe method, by using a megohmmeter with 5 ranges (50 V–1000 V).

The asphalt specimen, with a height of about 4 cm, was placed between two copper plate electrodes with dimensions of 15 × 15 cm connected with the megohmmeter, as shown in Figure 5. In order to ensure perfect contact, graphene powder was used to fill the gaps between the plate electrodes and the specimens. The electrical resistivity was calculated applying the second Ohm's law:

$$\rho = \frac{R \cdot S}{l} \quad (3)$$

where R is the electrical resistance of each specimen in Ω, S is the electrode-specimen contact area measured in m^2 and l is the thickness of the asphalt sample in m.

Figure 5. Electrical resistivity measurement.

2.6. Self-healing Test Procedure

The self-healing performance of the asphalt mixtures was evaluated as follow. First, each cylindrical specimen was tested under the Indirect Tensile Strength (ITS) test, according to Section 2.3. Then, the specimens were left at room temperature until they reached a temperature of 25 °C, and elastic rubber bands were used to tight the specimens before the heating treatment, as shown in Figure 6. A similar approach was used by other authors [53], which used a plastic collar to tight the specimen.

Figure 6. Simulation of in situ confining conditions of the asphalt pavements.

Preliminary tests conducted in the laboratory showed that the absence of the confining elastic rubber bands produces an enlargement of the crack during the heating process, due to the collapse of the mixture, that makes impossible the healing process. In situ, this cannot occur due to the lateral confinement of the asphalt mixture in the pavement. This phenomenon can be observed in Figure 7, where the broken specimen (Figure 7a) was heated without the inclusion of the rubber bands, causing an enlargement of the crack (Figure 7b).

Figure 7. The broken specimen before heating (**a**), and the enlargement of the crack after the heating without rubber bands (**b**).

The rubber bands were, therefore, used to approximately simulate the in situ confining conditions of the asphalt mixture in the pavement, and to obtain a more realistic measurement of the healing performances. Then, microwave radiation was applied. In order to evaluate the effect of temperature on the healing efficiency, the specimens were heated at different internal temperatures, 40 °C, 60 °C, 80 °C, 100 °C. Times required to reach these internal temperatures were found using the linear models obtained as described in Section 2.4. After the heating process, the specimens rested at 25 °C for 24 h, and then, after removing the rubber bands, Indirect Tensile Strength (ITS) test at 15 °C was repeated in order to evaluate the Healing Rate (HR):

$$HR(\%) = \frac{(ITS_{fin})}{(ITS_{in})} \cdot 100 \tag{4}$$

where ITS_{fin} is the Indirect Tensile Strength of the sample after the healing process and ITS_{in} is the Indirect Tensile Strength of the sample initially tested.

The schematic representation of the methodology is reported in Figure 8.

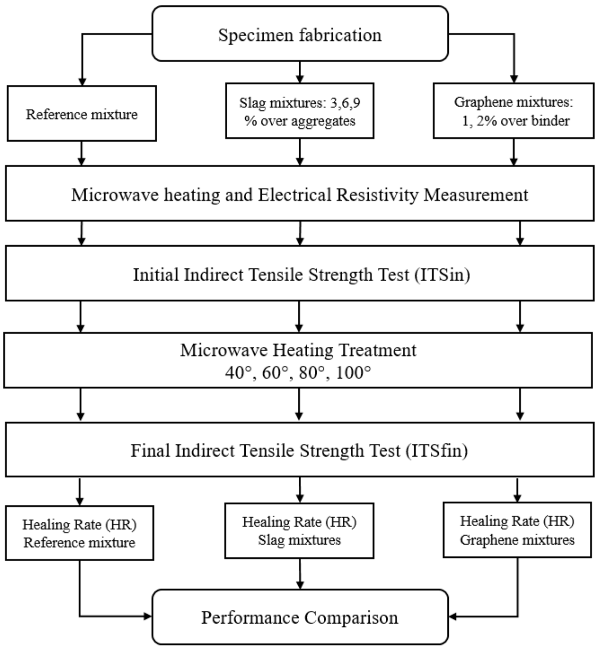

Figure 8. Flow chart of the healing process.

Furthermore, the analysis of variance (ANOVA) was performed to evaluate the effect of the temperature and the additive content on the healing rates of the asphalt mixtures.

3. Results

3.1. Influence of Slag and Graphene on the Physical and Mechanical Properties of the Asphalt Mixtures

The effect of additives on the bulk density of the asphalt mixtures is shown in Figure 9. The values are the average of 12 specimens, and the error bars represent the standard deviation. The reference mixture, without additives, has a bulk density of 2.452 g/cm^3. It can be observed that by adding slag to the mixture, the bulk density increases, until 2.481 g/cm^3, 2.503 g/cm^3 and 2.526 g/cm^3 for mixtures with 3%, 6% and 9% of slag, respectively. This trend is due to the higher specific gravity of the slag respect to natural aggregate, as reported also by other authors [45,54,55]. In contrast, graphene addition has the effect of decreasing the bulk density of the mixtures, until 2.429 g/cm^3 and 2.412 g/cm^3 for mixtures with 1% and 2% of graphene, respectively. This effect was probably due to the presence of graphene that increased the viscosity of the bitumen, as any powdered filler incorporated in the bitumen. Therefore, as the mixing and compaction temperatures were kept constant regardless of the content of graphene, for comparative purposes, the compaction was less effective when incorporating graphene.

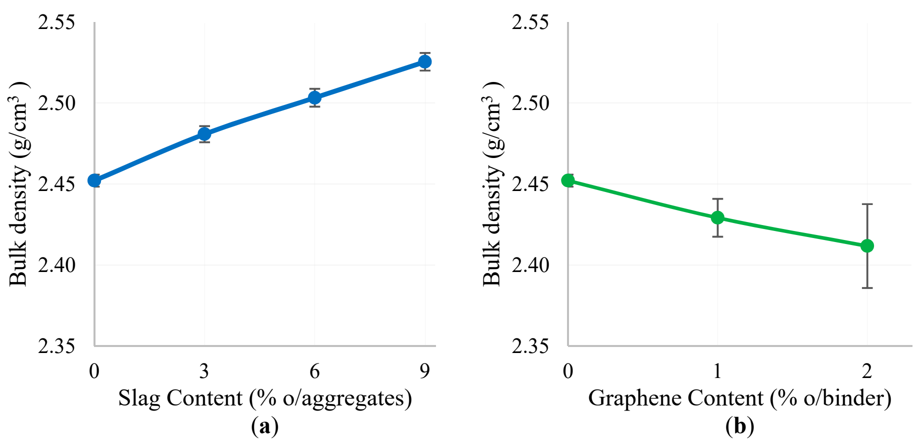

Figure 9. Effect of slag (**a**) and graphene (**b**) on the bulk density.

The effect of additives on the initial Indirect Tensile Strength (ITS_{in}) of the mixtures is shown in Figure 10. The values are the average of 12 specimens, and the error bars represent the standard deviation. It can be observed that the addition of slag or graphene has no important effect on the ITS_{in} of the mixtures.

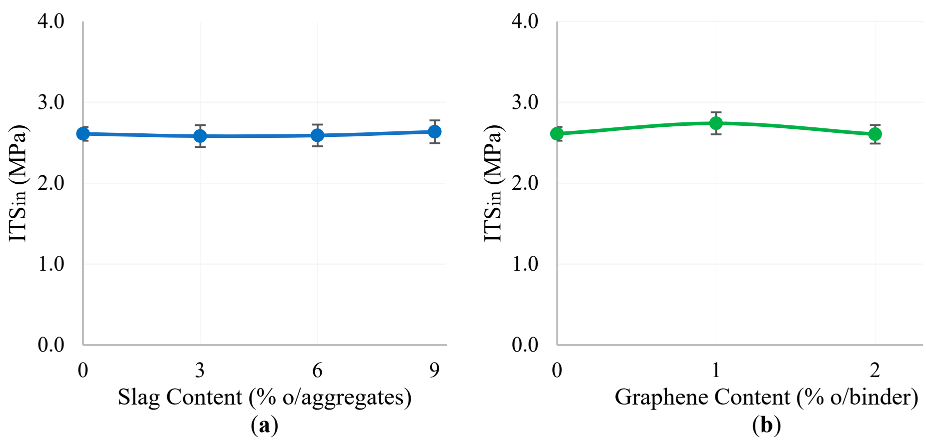

Figure 10. Effect of slag (**a**) and graphene (**b**) on the Indirect Tensile Strength ITS_{in}.

3.2. Influence of Slag and Graphene on the Heating Efficiency of the Asphalt Mixtures

The effect of adding slag or graphene to the mixture is an increase in the heating rates, as shown in Figure 11. The higher the amount of additive, the faster the temperature increase with energy. Even the mixture without additives can be heated by microwaves, although more energy, and consequently more heating time, must be applied to reach the same temperature. This means that microwave heating technique can also be used for existing pavements without additives, as also reported by other authors [56]. It can be observed in Figure 11 and Table 3 that the lineal models fit well the data, in terms of R^2. Nevertheless, it is interesting to analyze the effect of adding slag or graphene in terms of energy saving. The addition of 3 %, 6 % and 9 % (o/aggregates) of slag allows to save, respectively, 29%, 37% and 45% of the heating energy, respect to the ordinary asphalt mixture, while the addition of 1% and 2% (o/binder) of graphene allows to save 29% and 50% of the heating energy. This improvement of energy efficiency can produce several benefits in terms of CO_2 emissions and maintenance costs.

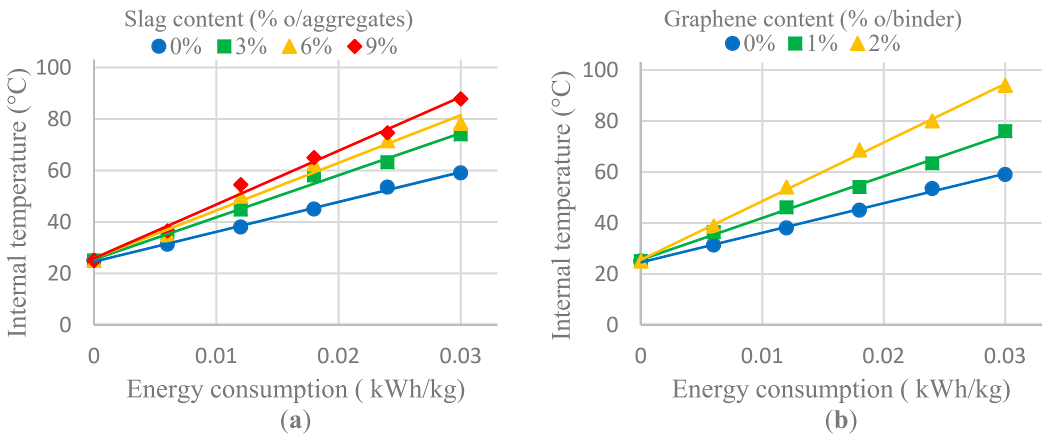

Figure 11. Effect of slag (**a**) and graphene (**b**) on the microwave heating consumption.

Table 3. Output of the linear regression models.

Additive	Content (%)	Linear Regression Equation	R^2	°C/ kWh/kg	°C/s
-	0	y = 1160x + 24.57	0.998	1160	0.232
Slag (% o/aggregates)	3	y = 1634x + 25.48	0.993	1634	0.327
	6	y = 1850x + 25.98	0.987	1850	0.370
	9	y = 2089x + 25.89	0.992	2089	0.418
Graphene (%o/binder)	1	y = 1638x + 25.60	0.996	1638	0.328
	2	y = 2301x + 25.58	0.998	2301	0.460

3.3. Influence of Slag and Graphene on the Electrical Resistivity of the Asphalt Mixtures

According to other studies [27–30], the electrical resistivity of the mixture slightly decreases with the additive content, until a critical value, called percolation threshold, where resistivity sharply decreases. The effect of adding slag or graphene on the electrical resistivity of the mixture is shown in Figure 12. In the case of slag addition, the percolation threshold is reached approximately between 6% and 9% of slag, when the electrical resistivity passes from 1.5×10^8 Ω·m to 1.7×10^6 Ω·m, corresponding to a reduction of 99%. Nevertheless, in the case of graphene, higher contents should be added to reach the percolation threshold. Comparing these results with the heating models (Figure 11), the contribution of the conductivity to the microwave heating can be analyzed. If the conductivity influenced the microwave heating, the sudden reduction of electrical resistivity (percolation threshold) would have led to a drastic increase in the heating rates. However, observing the heating curves of slag mixtures (Figure 11), the increase of the heating rate (°C/ kWh/kg) with the slag content is almost linear. This result can be referred to the fact that at microwaves frequencies, ranging from 300 MHz to 300 GHz, the conductivity contribution to heating is very low, and the heat is produced mostly by dipolar polarization rather than by the current created and the resulting Joule's effect. In this sense, the dielectric and thermal properties of the mixtures should be analyzed in future researches, in order to better understand the microwave heating phenomenon of asphalt mixtures and optimize the heating process.

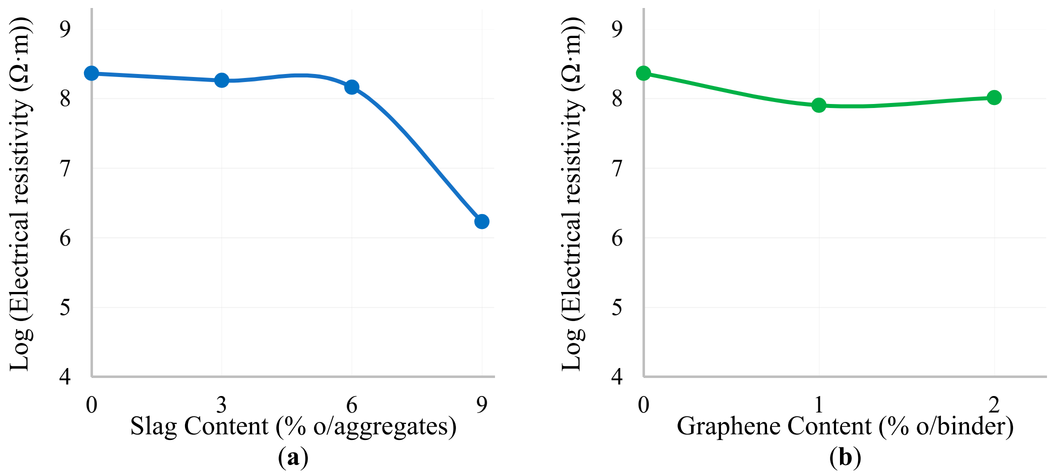

Figure 12. Effect of slag (**a**) and graphene (**b**) on the electrical resistivity.

3.4. *Influence of Slag and Graphene on the Healing Properties of the Asphalt Mixtures*

The results of the healing test are shown in Figure 13. The values represent the average Healing Rate (HR) of 3 samples, and the error bars represent the standard deviation. A one-way analysis of variance (ANOVA) was performed to evaluate the effect of the temperature on the healing rate of the asphalt mixtures. Normality and homogeneity of variances assumptions were checked. The analysis showed that the effect of the temperature was significant, $F(3,68) = 46.96$, p-value = 0.000. Post hoc comparisons using the Tukey HSD test indicated that all the means were significantly different from each other (p-value < 0.05). Therefore, the effect of the temperature was an increment in the healing rate of the asphalt mixtures. In fact, as described in Section 1, by increasing the temperature, the bitumen reduces its viscosity and flows through the open cracks easier, healing them. At 100 °C, for all the mixtures under study, the average HR is 67% (SD = 3.9), while the average HR for the mixtures heated at 40 °C is 44% (SD = 2.9). These results are consistent with those obtained by other authors [20,40,42].

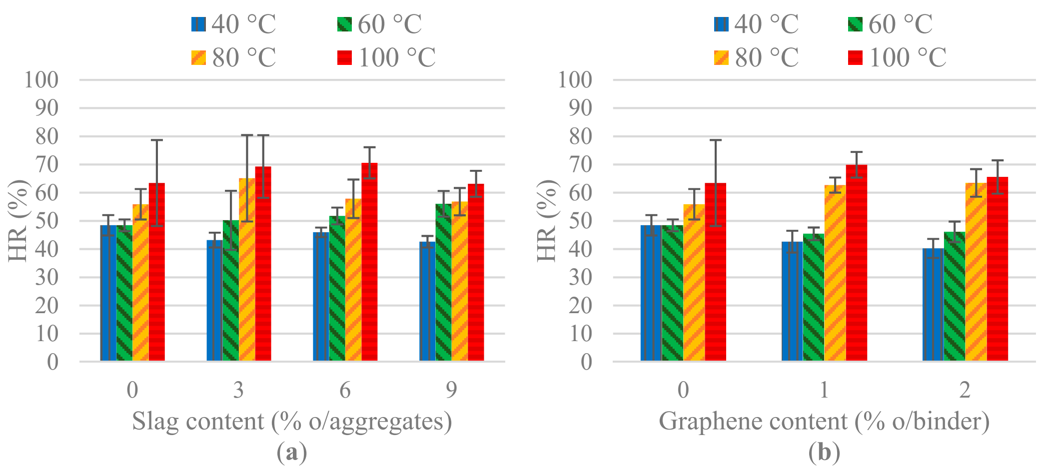

Figure 13. Effect of slag (**a**) and graphene (**b**) on the Healing Rate (HR)

A one-way analysis of variance (ANOVA) was performed to evaluate the effect of the additive content on the healing rates of the asphalt mixtures. Normality and homogeneity of variances assumptions were checked. The analysis showed that the effect of the additive content was not significant, $F(5,66) = 0.15$, p-value = 0.98. Therefore, the addition of slag or graphene did not produce substantial benefits in terms of the healing rate of the asphalt mixtures. However, the benefits in terms of energy savings are important. In this sense, Figure 14 shows the relationship between the total energy consumption during the heating and the healing rate of the mixtures. These curves should be interpreted as an indicator of the healing efficiency of the energy consumed by the microwave heating technique. The greater the slope of the curves, the higher the healing efficiency. In the case of slag, considerable benefits can be obtained even with the addition of 3% (o/aggregates), while with higher contents, no improvements are achieved. Similarly, in the case of graphene, the improvement of the healing efficiency is obtained with the addition of 2% (o/binder). For example, in order to obtain HR = 60%, the healing efficiency of the mixtures with 3% of slag and 2% of graphene is about double compared to the reference mixture. In this way, approximately half of the energy for pavements maintenance operations would be saved.

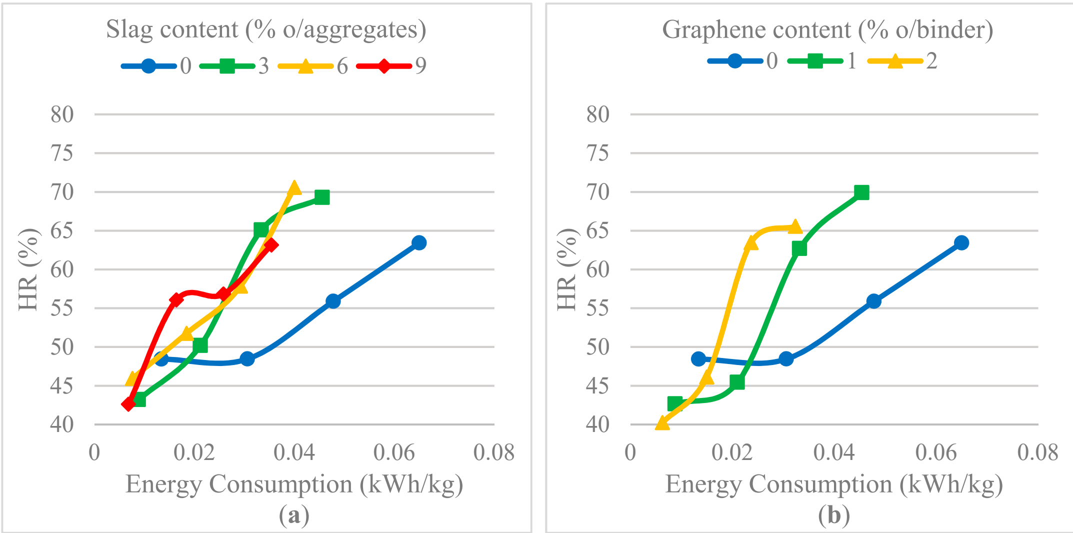

Figure 14. Effect of slag (**a**) and graphene (**b**) on the Healing Efficiency

4. Conclusions

In this paper, the effect of adding Electric Arc Furnace (EAF) slag or Graphene Nanoplatelets (GNPs) on the microwave heating and healing efficiency of asphalt mixtures was evaluated. The following conclusions can be drawn:

- It was found that the higher temperatures enhanced the healing performances of the asphalt mixtures, with and without the addition of slag or graphene.
- Although the asphalt mixture without additives can be heated with microwaves, both the slag and graphene allow saving approximately 50% of the energy during the heating process.
- The addition of slag or graphene does not seem to enhance the healing rates of the mixture. However, for the same healing rate, the addition of slag or graphene can halve the energy consumption during pavements maintenance operations. In accordance with the laboratory findings, the addition of 3% of slag (o/aggregates) or 2% of graphene (o/binder) is sufficient to obtain these savings of energy.
- Finally, it was observed that apparently, the contribution of the electrical conductivity to the microwave heating is low. Therefore, microwave heat generation could be attributed mostly to the

oscillating electromagnetic fields that excite molecules rather than to eventual electrical currents generated in the mixture and the resulting Joule's effect.

The use of GNPs in the asphalt mixtures is an innovative field, and the results of this work can be a starting point for further investigations in this area. In future research, other types of nanomaterials and the optimum dosage can be analyzed and compared with other traditional materials used in asphalt pavements, such as EAF slag.

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