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ORIGINAL ARTICLE

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Healing response of cold recycled asphalt mixtures with electric arc furnace slag under microwave heating and re-compaction

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Abstract The objective of the present paper is the assessment of the healing efficiency of a thermo-mechanical treatment (microwave heating and re-compaction) on cold recycled asphalt mixtures. The asphalt mixture specimens were fabricated with different electric arc furnace slag (EAFS) contents to improve the mixtures' microwave susceptibility. The healing response was then assessed in terms of recovery of their initial indirect tensile strength. Furthermore, statistical analysis was conducted by means of a three-way analysis of variance to determine the influence of temperature, re-compaction energy, and EAFS content on the healing capability of the mixtures. Although re-compaction and heating in the ranges studied do not themselves cause healing, the combination of both produced excellent healing performance. The optimal content of EAFS was established at 5% of EAFS over the weight of the asphalt mixture.

Keywords Cold recycled asphalt mixture · Electric arc furnace slag · Thermomechanical treatment · Healing rate

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1 Introduction

In recent years, great interest has been paid to recycling technologies in the sector of asphalt pavements, to reduce the consumption of natural resources and fossil fuels, pollutant emissions, energy and the costs associated with reconstruction operations [1]. According to the mixing temperature, recycling technologies can be divided into hot recycling (HR) technologies, warm recycling [2] and cold recycling (CR) technologies [3]. However, compared to the hot recycling method, CR methods offer superior economic, environmental, and construction benefits [4]. Furthermore, according to the recycling process, CR can be sub-classified in cold in-place recycling (CIR), and cold central-plant recycling (CCPR). The employment of CIR technology permits using 100% of Reclaimed Asphalt Pavement (RAP) generated during maintenance and reconstruction of existing roads and saving costs for transportation operations [5, 6].

Few studies have been conducted assessing the field performance of CIR technologies using 100% of RAP. Filho et al. [7] realized a trial section in Brazil with a base course made of a cold recycled asphalt mix using 100% RAP with an emulsified asphalt-recycling agent. The study reported good structural capacities in terms of stiffness and International Roughness Index (IRI). In another field experience, Wu et al. [8] utilized a 100% RAP cold mix for both surface and base layers on a low-volume road in Florida, US. After 22 months, the primary distresses observed in the 100% RAP cold-mix field project were weathering and ravelling, with no cracking and rutting reported. Hugener et al. [9] evaluated the field performance of different rejuvenators in a 100% RAP mixture in Switzerland, and no significant damage was reported during the test.

However, despite the environmental and economic benefits, CIR processes have not been widely implemented on a large scale, mainly due to the lower mechanical performance and durability of Cold Recycled Asphalt Mixtures (CRAMs) compared with conventional hot asphalt mixtures [10].

In this context, it is believed that the employment of emerging maintenance technologies, such as the microwave (MW) assisted self-healing technique, can be used for extending the service life of CRAMs pavements and therefore promoting CIR technologies. This technology consists of triggering the self-healing response of asphalt mixtures through an external stimulus (e.g., microwave heating). The healing phenomenon relies on molecular wetting and interdiffusion between the two surfaces of a microcrack to restore the properties of the original material. While this process is slow at low temperatures, it has been observed that elevating the material's temperature enhances molecular activity, thereby promoting both diffusion and the healing process [11, 12]. By applying microwave (MW) energy, the heat causes the damaged asphalt pavement's bitumen to lower its viscosity, allowing it to flow into the cracks and effectively repair the pavement [13]. The MW treatment can be applied various times during the pavement's lifespan [14]; hence its development would reduce the requirement for natural resources, energy consumption, CO_2 emissions during maintenance operations, and the traffic disruptions caused by such actions. It has been reported that this technology can result in a 16% reduction in emissions and a 32% decrease in costs over the entire lifecycle of the pavement [15]. During the last decade, researchers worldwide investigated the MW-assisted self-healing performance at laboratory scale [16, 17], and different prototypes and full-scale tests have been realized to evaluate the technical viability of this technology [18, 19]. Maliszewski et al. [18] installed a MW generator on a trailer and conducted a full-scale test to assess the in-situ effectiveness of MW-assisted self-healing technology. The results were promising, demonstrating satisfactory crack closure performance with MW treatment. In another full-scale experiment, Sun et al. [20] designed a microwave maintenance vehicle for road applications to evaluate the feasibility of microwave heating technology. The authors demonstrated that incorporating steel fibers into the asphalt mixture allowed for a heating rate of 26 °C/min, and the application of MW treatment exhibited high crack-healing effectiveness.

One of the primary challenges to address is the enhancement of the dielectric properties of asphalt mixtures, as they are the primary factors responsible for generating microwave (MW) heat [21]. While conventional asphalt mixtures can be heated using microwaves, their limited dielectric properties result in a slow and inefficient heating process. To tackle this shortcoming, some MW absorbers can be added to the asphalt mixtures, increasing the dielectric properties and improving the efficiency of microwave heating. Typical additives used for this purpose include steel slag [22–25], metallic fibres [26–28] and carbon nanomaterials [29, 30]. Electrical arc furnace slag (EAFS) is an excellent solution for MW heating applications, thanks to its high amount of Fe_2O_3, which increase the dielectric properties of asphalt mixtures and therefore improve the efficiency of the MW heating process [21, 31]. Gulisano et al. [30] found that adding 9% of EAFS by volume of aggregates allowed to save 45% of the energy needed for heating the asphalt mixtures. EAFS exhibited favourable mechanical and physical properties and its price closely aligns with that of natural aggregates [32], which supports its utilization as an aggregate in asphalt mixtures [33]. Additionally, its usage as a waste material contributes to the principles of the circular economy.

Although microwave heating is an interesting solution for assisted self-healing operations, the initial mechanical properties of the asphalt mixtures cannot be totally restored with only heating treatment. Various research conducted at laboratory scale obtained recovery rates between 60 and 90% [13, 23, 27, 34, 35]. To enhance the performance of microwave healing treatment, Gallego et al. [36, 37] proposed using a thermomechanical treatment, consisting of the application of microwave heating and further re-compaction of the asphalt mixture. The kneading action during re-compaction facilitates the diffusion and randomization of bitumen molecules, contributing to the restoration of strength [37]. The thermomechanical treatment was found to strongly increase the healing performance, and the original mechanical properties of asphalt mixtures are even exceeded with this treatment. Furthermore, this technique allows healing HMA mixtures at a relatively low temperature (60 °C), with obvious benefits in terms of energy savings. The thermomechanical treatment was also effective for healing half-warm asphalt mixtures [38]. However, no studies on the healing capability of CRAMs with thermomechanical treatment have been found in the literature.

For this purpose, the objective of the present paper is the assessment of the healing performance of the thermomechanical treatment (i.e., microwave heating + re-compaction) on cold recycled asphalt mixtures (CRAMs). For this, asphalt mixture specimens were fabricated with different EAFS content to improve the mixtures' microwave susceptibility. The specimens were broken and then subjected to thermomechanical treatment. The healing performance was then assessed in terms of recovery of their initial indirect tensile strength. Furthermore, statistical analysis was conducted to determine the influence of temperature, re-compaction energy, and EAFS content on the healing capability of the mixtures.

2 Materials

The Cold Recycled Asphalt Mixtures (CRAMs) were fabricated using Reclaimed Asphalt Pavement (RAP), premix water, bituminous emulsion, and Portland cement (strength class 32.5 N), (Fig. 1). The RAP had a specific gravity (EN 12697–5) of 2.44 g/cm^3 and a bitumen content (EN 12697–1) of 4.89%. The recovered bitumen had a penetration (EN 1426) of 11•10^{-1} mm and a softening point (EN 1427) of 80.3 °C. The granulometry of the RAP, including the aged binder, was the RE2 band, recommended by Spanish regulation PG4 is presented in Table 1. In accordance with the Spanish specifications [39]. The emulsion consisted of a cationic slow setting (B5) bitumen emulsion, produced with rejuvenating agents and 60% of residual bitumen (C60B5 REC REJUV).

Furthermore, EAFS with a specific gravity of 3.65 g/cm^3 was utilized in the fractions 8/0.5 mm.

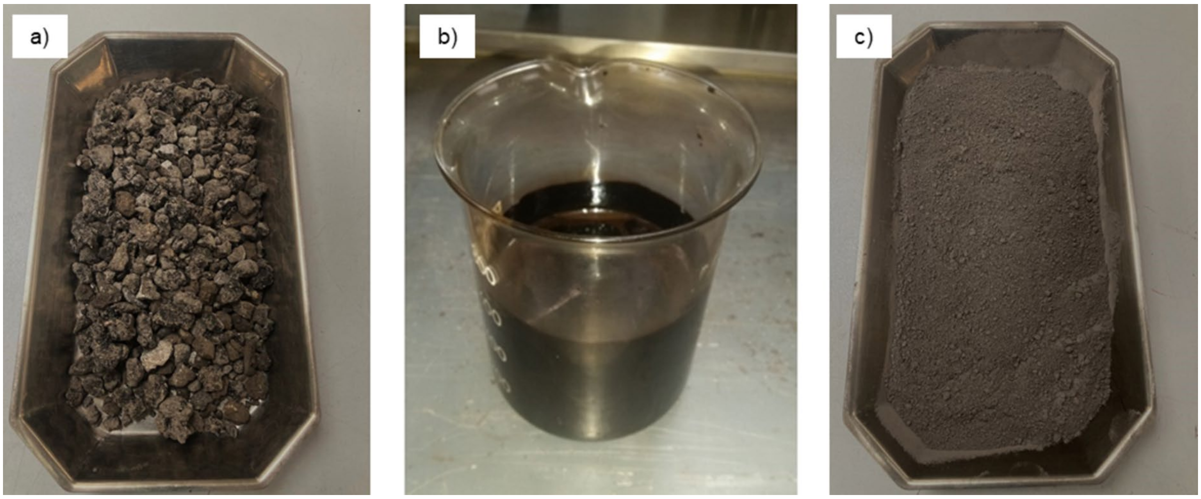

Fig. 1 Materials used for the mixture, **a** RAP, **b** bituminous emulsion and **c** cement

Table 1 RAP gradation (% passing)

Size # (mm)	20	12.5	8	4	2	0.5	0.25	0.063
Gradation curve	100.0	75.0	63.0	44.0	27.0	10.2	6.6	2.7
Minimum RE2	80.0	62.0	49.0	31.0	19.0	2.0	0.0	0.0
Maximum RE2	100.0	89.0	77.0	58.0	42.0	20.0	10.0	3.0

The producer conducted a prior hydration process of the EAFS to mitigate potential expansion issues resulting from its elevated CaO and MgO content. It is noteworthy that the final price of the EAFS, including the hydration process, was very similar to that of natural aggregates, ensuring the economic viability of this solution.

3 Methodology

3.1 Composition of the cold recycled asphalt mixtures

To assess the effect of EAFS on the MW-absorbing properties, three kinds of CRAMs were fabricated, the difference of which lay in the EAFS content, 0% (Reference), 5%, and 10% by volume of the aggregates. A volumetric substitution was conducted to consider the different specific gravity of the EAFS and the RAP. In addition, the higher absorption properties of EAFS with respect to the RAP led to the modification of the emulsion content to obtain comparable content of effective bitumen emulsion in each mixture. Based on the results of existing literature on EAFS mixtures [40, 41], it was chosen to increase the bituminous emulsion by 0.1% and 0.2% for the EAFS 5% and EAFS 10% mixture. The volumetric composition of the three mixtures is shown in Table 2.

3.2 Preparation of the specimens

The materials were blended using a laboratory mixer. Initially, the RAP and EAFS were introduced into the container and mixed with 30 g of water for one minute. Subsequently, the emulsion was incorporated and mixed for another minute, followed by the addition of cement and further mixing for one minute and 30 s. Cylindrical specimens measuring 100 mm in diameter and approximately 63 mm in height were compacted using a gyratory compactor (EN 12697–31) applying 100 gyrations. After compaction, a curing process was applied, according to previous laboratory tests [4]. For this purpose, the specimens were wrapped in plastic film leaving the upper face exposed, as depicted in Fig. 2. This approach was adopted because, under actual construction conditions, evaporation and water loss would primarily occur through the upper or exposed surface. The specimens were maintained in these conditions for 5 days and subsequently placed in an oven at 50 °C until constant weight, which was achieved after 3 days.

3.3 Mechanical characterization

The Indirect Tensile Strength (ITS) test was performed to characterize the mechanical properties of CRAMs with RAP and EAFS. The test was conducted at 15 °C. During the test, a diametrical load was applied at a consistent deformation rate of 50 ± 2 mm/min until the specimen ruptured. The Indirect Tensile Strength (ITS) in megapascals (MPa) was then obtained using the Eq. 1:

$$ITS = \frac{2 \cdot P_{max}}{\pi \cdot d \cdot h} \quad (1)$$

Table 2 Volumetric composition of the cold recycled mixtures

Type	Size # (mm)	EAFS 0% (reference)	EAFS 5%	EAFS 10%
RAP	20/12.5	25	25	25
RAP	12.5/8	12	12	12
RAP	8/4	19	17.5	16
RAP	4/0	42	38.5	35
Cement	–	2	2	2
EAFS	8/4	–	1.5	3
EAFS	4/2	–	1.4	2.8
EAFS	2/0.5	–	2.1	4.2
Emulsion	-	4	4.1	4.2

Fig. 2 Curing of cylindrical specimens

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

A total of 81 specimens were tested, with 27 specimens for each type of mixture.

3.4 Microwave heating test

MW heating test was performed to assess the MW-absorbing properties of the CRAMs and the effect of EAFS content on the heating efficiency. The test consisted of exposing the samples to microwave radiation and evaluating the temperature increase. A conventional microwave oven (power 700 W and a frequency of 2.45 GHz) was used. Three samples for each type of mixture were tested to verify data repeatability. The samples were first cut into two pieces, as shown in Fig. 3. This procedure, according to previous laboratory tests, enables a more accurate assessment of the impact of various EAFS contents.

The samples had an initial temperature of 25 °C. Then, the two pieces of each sample were put together and introduced into the microwave oven. The microwave radiations were then applied for periods of 30 s up to 120 s. The reference mixture, which needed more time to reach high temperatures, was heated for periods of 60 s up to 240 s. Between each two consecutive periods, the oven was opened, the two halves of the sample were put apart, and the temperature of both cutting faces of the sample was recorded with a thermographic camera, as shown in Fig. 4. It can be observed that, despite an overall homogeneity in sample heating, singular hot points are evident due to the presence of EAFS. The average temperature was measured with thermographic analysis software, which allows obtaining the thermal map of the specimen and extracts the average temperature. The energy consumed during the test was also recorded with an electricity meter.

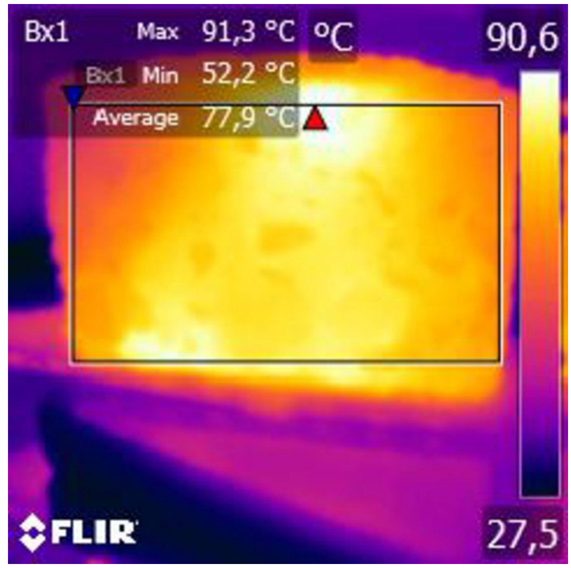

Fig. 4 Thermographic camera image

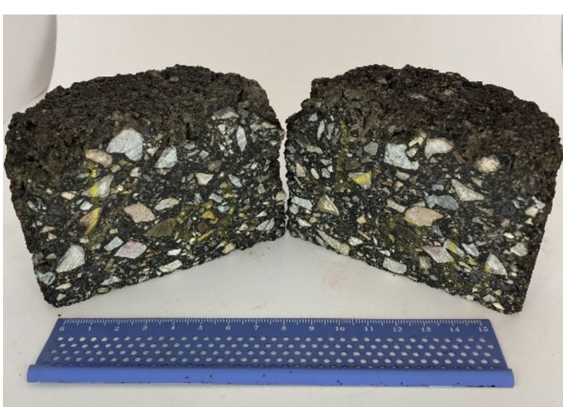

Fig. 3 Specimens for the microwave heating test

Once the temperature data were collected, temperature vs. the microwave energy consumption was plotted. As the samples had a mass of 1 kg approximately, the energy consumption can be expressed in kWh/kg. Linear regression analysis was then performed to model the relationship between the energy consumption and the temperature of the asphalt mixture. The slope of each line (e.g., heating rate) is an indicator of the MW susceptibility of the mixtures, as a high slope ensures a rapid and efficient heating process.

3.5 Microwave-assisted self-healing test

To assess the performance of the microwave heating treatment for the assisted self-healing of CRAMs, a healing test was performed. As reported in Sect. 1, the microwave heating treatment can only partially recover the initial mechanical properties of asphalt mixtures. An additional re-compaction of the mixtures can provide several benefits in terms of healing performance. For this, a thermomechanical treatment, consisting of microwave heating + re-compaction energy, was applied to evaluate the performance of this kind of treatment on CRAMs.

A schematic illustration of the microwave-assisted self-healing test is shown in Fig. 5.

After the fabrication and curing periods, the cylindrical specimens were left to rest for 24 h at ambient temperature, approximately 25 °C. They were then stored at 15 °C for 4 h, and the Indirect Tensile Strength (ITS) test was conducted, according to EN 12697–23:2018 (Fig. 5a), determining the initial resistance as R_0.

Then, the thermomechanical treatment, consisting in a combination of MW heating and re-compaction, was applied (Fig. 5b). The broken specimen was introduced into the microwave oven, and the radiation was applied until it reached the desired internal temperature. The needed energy for reaching a certain temperature was calculated through the heating lines equations obtained as indicated in Sect. 3.4 and showed in Sect. 4.2. After the heating treatment, the specimen was subjected to the re-compaction treatment at different energy levels in terms of the number of gyrations. An ad-hoc re-compaction mold, which can be longitudinally opened, was used in this phase. The hot specimen was put into the slightly opened mold (at the selected temperature), and then the mold was tightened again. This procedure is crucial because it allows, on the one hand, the simulation of in-situ lateral confinement of the mixture, and on the other hand, it enables the introduction of hot specimens without exerting force on them. This is necessary as the diameter of the mixture slightly increases during the previous Indirect Tensile Strength test. More details of the tailored re-compaction mold can be found in Refs. [36, 37].

After the re-compaction, the specimen was left for 24 h at ambient temperature, approximately 25 °C. Then, the specimens were kept at 15 °C for 4 h, and the indirect tensile strength (ITS) test was repeated to obtain the final resistance (R_f) (Fig. 5c). Finally, the healing rate (HR) was calculated as (Eq. 2):

$$HR\ (\%) = \frac{R_f}{R_0} \cdot 100 \qquad (2)$$

HR is an indicator of the healing response of the thermomechanical treatment, representing the

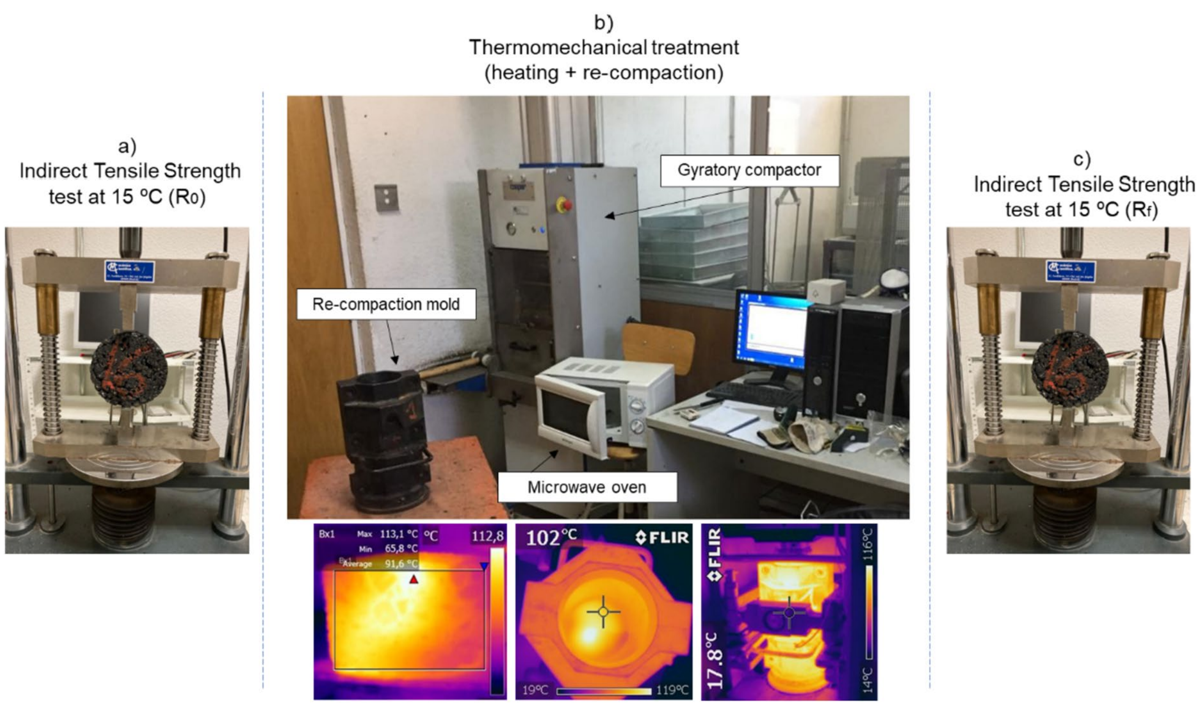

Fig. 5 Microwave-assisted self-healing test

recovery rate of the original mechanical properties of the CRAMs subjected to the treatment.

To evaluate the effect of the internal temperature of the specimens on the HR, the specimens were heated at three different temperatures, 20 °C (no heating), 50 °C, and 80 °C. For the same reason, three re-compaction energy levels were tested, 0 gyrations (no re-compaction), 25 gyrations, and 50 gyrations. The healing test was conducted on specimens with different amounts of EAFS, 0, 5, and 10%, hence the effect of EAFS content on the healing performance was also evaluated.

To assess the effect of the three factors, temperature, re-compaction energy, and EAFS content, on the healing performance, a three-way analysis of variance (ANOVA) was conducted and the significance level was fixed at $\alpha = 0.01$ was conducted. This kind of analysis permits estimating the main effect of the three factors and the interaction effect between them in the final healing response. Previous research [36] showed that the interaction effects could not be ignored and represent an essential element to take into consideration in the investigation of the healing response of asphalt mixtures. Levene's test was employed to verify the homoscedasticity assumption. Homoscedasticity would be verified if the p-value > 0.01. Moreover, a Tukey HSD Post hoc test was executed to identify the levels of the factors that exhibited significant differences from one another.

4 Results

4.1 Mechanical characterization of cold recycled asphalt mixtures

Figure 6 shows the result of the ITS test. The results represent the average of 27 specimens for each EAFS content, and the error bars represent the standard deviations The average ITS was 0.90, 0.76, and 0.85 MPa for the CRAMs with 0, 5, and 10% of EAFS, respectively. The results showed that the incorporation of EAFS seems to slightly reduce the ITS of asphalt mixtures, which is in line with the results obtained by other authors [4, 6] with a cold mix with 100% RAP, and with half-warm asphalt mixes with EAFS and RAP [38]. As indicated in Sect. 3.1, the dosage of the bituminous emulsion was determined based on the findings from existing literature on EAFS. The

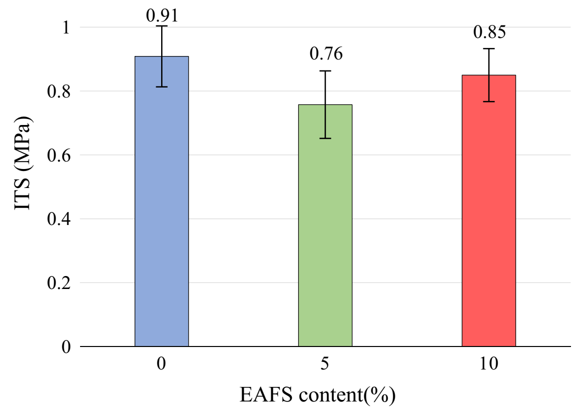

Fig. 6 Effect of EAFS on the ITS

literature suggested an increase in the binder content to account for the higher absorption properties of EAFS compared to Recycled Asphalt Pavement (RAP). However, it is possible that the emulsion contents in the present paper were not sufficient, resulting in an inadequate binder distribution among the aggregate particles and a reduction in the Indirect Tensile Strength (ITS) of the mixture. Further investigation would be necessary in order to quantify the effective bitumen content on EAFS asphalt mixtures.

4.2 Thermographic analysis

Figure 7 presents the result of the thermographic analysis. It can be observed that the coefficients of determination (R^2) for the models were higher than 0.94, indicating a linear relationship between the temperature and the energy consumed during the heating process. The addition of EAFS had the effect of increasing the microwave susceptibility of the CRAMs. The trend of the temperature of the mixtures highlights the effect of adding EAFS on the microwave susceptibility of the CRAMs. The higher the EAFS content, the greater the microwave susceptibility of the mixture. The heating equations reported in Fig. 7 allowed to obtain the energy needed to reach a specific temperature. For example, to heat the CRAMs until a fixed internal temperature of 80 °C, the energy required is 0.039, 0.025, and 0.023 kWh/kg for the mixture with 0, 5, and 10% of EAFS, respectively. In other words, adding 5 and 10% of EAFS saves 36% and 41% of the necessary energy for heating the CRAMs. The results are in line with those obtained by Gulisano et al. [30]

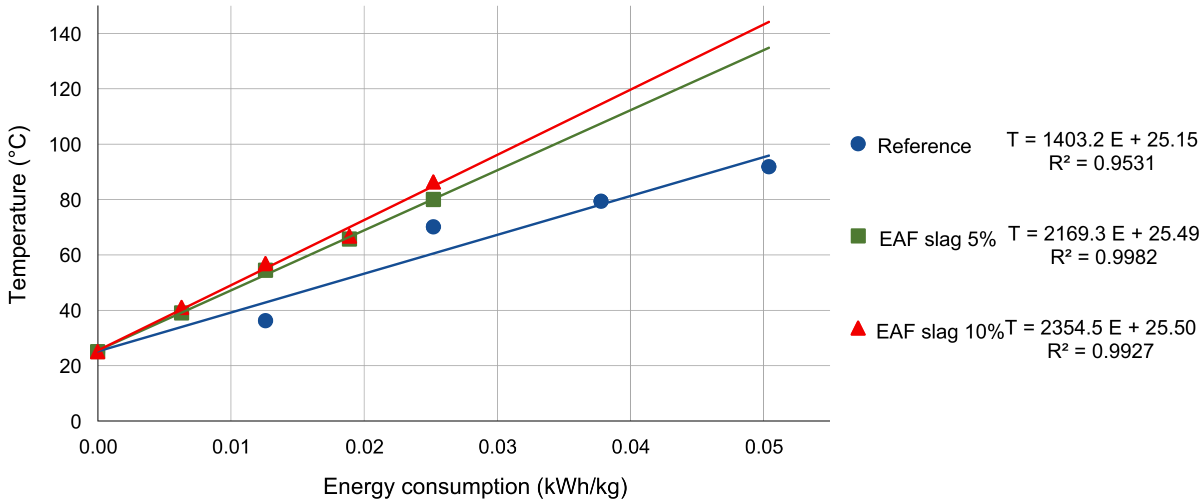

Fig.7 Microwave heating test

with hot asphalt mixtures and proved that the microwave heating technique could be used for heating CRAMs.

4.3 Combined effect of temperature and re-compaction on the healing capability

The results of the healing test are reported in Fig. 8, which show the combined effect of temperature (°C) and re-compaction energy (N, number of gyrations by the gyratory compactor) on the healing rate (HR) of the CRAMs.

The result of the three-way ANOVA is presented in Table 3. The homoscedasticity assumption of the model was verified, as Levene's test showed equal variances for all groups, $F(26, 53) = 1.48$, p-value $= 0.112$.

Both temperature and re-compaction significantly increased the healing performance of CRAMs. In addition, post hoc Tukey HSD tests revealed significant differences at any levels of temperature and re-compaction.

Furthermore, the interaction effect between temperature and re-compaction was significant (p-value < 0.001), highlighting the importance of the synergic combination of both treatments for healing the mixtures. When no re-compaction was applied, the HR of all the mixtures was very limited at each temperature, and the best results were obtained at 80 °C, with HR values of approximately 70%. Likewise, the application of the re-compaction energy at a temperature of 20 °C did not produce any benefits in terms of HR, and approximately 60% of the initial mechanical properties can be restored.

However, the combination of both heating and re-compaction produced excellent healing performance, and the initial mechanical properties of the CRAMs were exceeded by far. The highest results were obtained for the maximum temperature of 80 °C and the maximum re-compaction level of 50 gyrations. In contrast, previous studies conducted on hot asphalt mixtures [36, 37] have revealed that beyond a certain level of re-compaction, no further improvements were observed, regardless of an increase in temperature.

The average initial resistances R_0 of the specimens with 0%, 5%, and 10% were 0.87, 0.67, and 0.78 MPa, respectively, coherent with typical resistance values obtained with CRAMs [6]. After the thermomechanical treatment (80 °C and 50 gyrations), the average final resistances R_f of the same specimens were 2.92, 2.45, and 2.24 MPa, corresponding to HR of 335, 366, and 287%. Comparing these results with those obtained in previous research, where the thermomechanical treatment was applied on hot asphalt mixtures [36, 37], the HR of Cold Recycled Asphalt Mixtures (CRAMs) was enormously higher. In the case of hot asphalt mixtures, the HR obtained was between 100 and 110%. However, one possible explication for this behavior lies in the compaction performance of cold recycled and hot asphalt mixtures, as

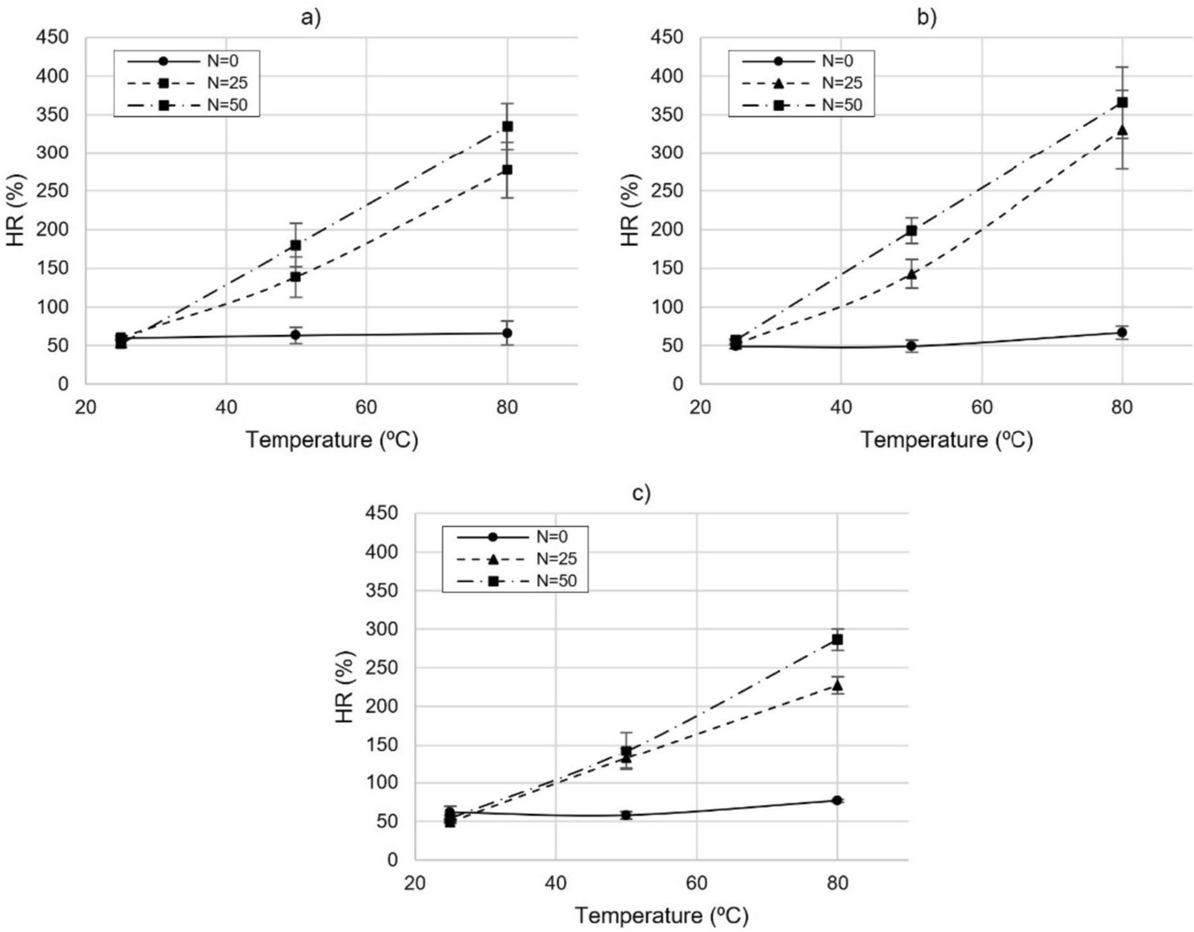

Fig. 8 Healing results of cold recycled asphalt mixtures (CRAMs) with **a** 0%, **b** 5%, and **c** 10% EAFS

Table 3 Output of the ANOVA analysis

Source	SSQ	*df*	MS	*F*	*p* value
Corrected model	822,952.384[a]	18	45,719.577	99.305	< 0.001
Intercept	1,442,072.236	1	1,442,072.236	3132.255	< 0.001
EAFS	8612.538	2	4306.269	9.353	< 0.001
Temperature	390,991.916	2	195,495.958	424.627	< 0.001
Re-compaction	222,987.599	2	111,493.799	242.170	< 0.001
EAFS-temperature	8301.184	4	2075.296	4.508	0.003
EAFS-Re-compaction	8609.396	4	2152.349	4.675	0.002
Temperature-Re-compaction	167,601.479	4	41,900.370	91.010	< 0.001
Error	28,084.048	61	460.394		
Total	2,318,863.509	80			
Corrected total	851,036.431	79			

[a] $R^2 = 0.967$ (Adjusted $R^2 = 0.957$)

the compaction of the mixtures heated by microwaves is more effective than the original compaction in cold conditions, as has also been observed by other authors [42]. In other words, the thermomechanical treatment produces densification of the mixture, which lead to higher ITS with respect to the original resistance.

In addition, it should be considered that CRAMs had relatively lower initial ITS, between 0.53 and 1.1 MPa for all the tested specimens than those of hot mixtures [36], between 2.45 and 3.02 MPa. After the thermomechanical treatment, the CRAMs reached values of ITS similar to those of hot mixtures. In other words, it seems that the thermomechanical treatment can lead the specimens to ITS values of approximately 2.50 MPa. As the initial ITS of hot asphalt mixtures was already around those values, the resulting HR was lower.

Another difference between cold recycled and hot mixtures is the different effects of temperature on the HR. In hot asphalt mixtures, the dependence of the temperature (ranging between 60 and 120 °C) was minimal [36, 37]. However, in the present work, the temperature, ranging between 20 and 80 °C, strongly affected the HR. The knowledge of temperature dependence is fundamental for healing applications. If the healing can be achieved with lower temperature (less exposition to microwaves), it would result in significant energy savings for maintenance operations. For this reason, further research is needed to evaluate the temperature dependency on a wider temperature range.

4.4 Optimum EAFS content for healing

The EAFS content was found to affect the healing performance of CRAMs (p-value < 0.001). Post hoc Tukey HSD tests (Table 4) revealed no differences between 0 and 5%, but the addition of 10% of EAFS had the effect of worsening the healing capability. Mixtures with 10% of EAFS had high MW-susceptibility, meaning that the heating process is very rapid and more efficient from the energetic point of view. However, the result of the healing test seems to suggest that an excessive heating rate may hinder the healing process.

Furthermore, the interaction effects of EAFS/temperature and EAFS/re-compaction were significant, and Fig. 9 allows to better understand this interaction effect. As shown in Fig. 9a, at a temperature of 20 °C, the EAFS content did not affect the healing capability,

Table 4 Effect of EAFS on HR-post hoc Tukey HSD test

EAFS		Mean difference	SE	p-value	99% Confidence interval	
					Lower bound	Upper bound
0	5	−5.73	5.896	0.597	−23.57	12.11
	10	19.18	5.896	0.005	1.34	37.02
5	0	5.73	5.896	0.597	−12.11	23.57
	10	24.91	5.840	< 0.001	7.23	42.58
10	0	−19.18*	5.896	0.005	−37.02	−1.34
	5	−24.91	5.840	< 0.001	−42.58	−7.23

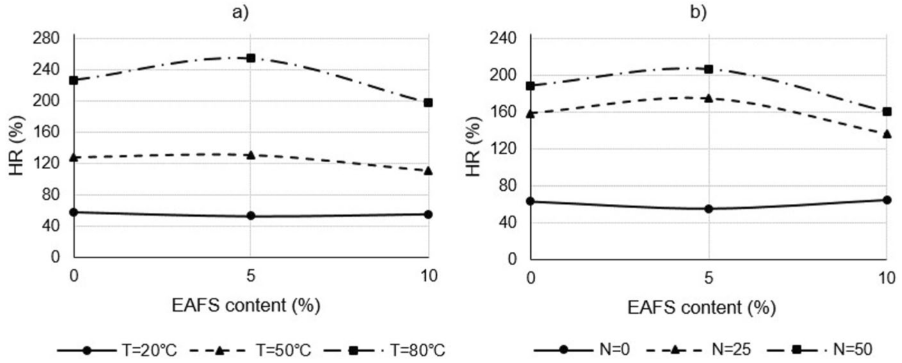

Fig. 9 Interaction effect of **a** EAFS/temperature and **b** EAFS/re-compaction

as in this case, the specimen was not submitted to microwaves. At temperatures of 50 °C and 80 °C, a bell shape trend of the EAFS vs. HR is observed. The addition of EAFS was beneficial up to 5%, while the rapid heating process to which 10% EAFS mixtures were subjected reduced the healing capability.

Figure 9b shows the interaction effect of EAFS and re-compaction. Without re-compaction, the effect of EAFS content on the healing performance was minimum. On the contrary, when re-compaction was applied (25 or 50 gyrations), HR increased when 5% of EAFS is added, while the addition of 10% of EAFS reduced the HR.

The previous analysis showed that, although the addition of EAFS as a MW-absorber allows a substantial reduction of energy consumption during the heating process, an excessive increase in the EAFS content (10%) could reduce the healing capability. Therefore, 5% of EAFS is recommended for healing CRAMs. However, it should be pointed out that this result is not in line with those obtained in the case of hot mixtures [30, 37], in which the EAFS content did not affect the healing performances.

4.5 Energy consumption for healing

This section presents an evaluation of the energy consumption for healing the CRAMs. It is believed that this kind of analysis is fundamental for evaluating the technical viability of the microwave-assisted self-healing technique. In the present work, only the energy consumed for heating the mixtures was taken into account, while the energy spent for re-compacting was neglected at this stage.

Figure 10 shows the energy consumption for healing the mixtures. The graph only refers to the results obtained with re-compaction energy of 50 gyrations.

The healing of the reference mixture (0% EAFS) required more energy, as the microwave heating process is very slow. On the other hand, adding 5% EAFS allows to obtain comparable healing results but with less energy consumption. For example, to heal the reference mixture up to an HR of 335%, 0.039 kWh was consumed to heat the mixture at 80 °C. Mixtures with 5% required 0.025 kWh, corresponding to a reduction of 36% of the energy consumption, for healing the mixture up to 366%. Although mixtures with 10% of EAFS required less energy for the heating process, 0.023 kWh, the healing capability was lower than the reference mixture, and HR of 287 was obtained.

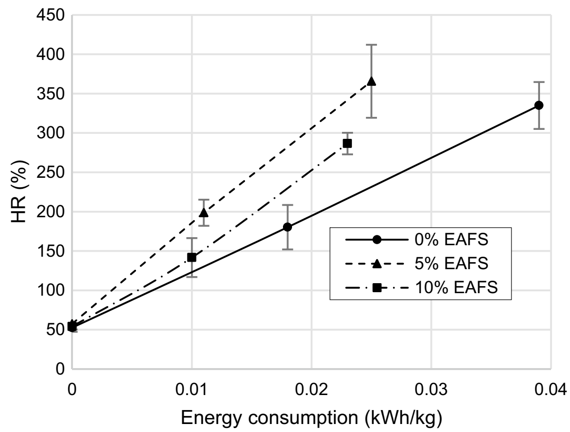

Fig. 10 Energy consumption for healing

5 Conclusions

The research aimed at assessing the healing effect of a thermomechanical treatment (i.e., microwave heating + re-compaction) on Cold Recycled Asphalt Mixtures (CRAMs) with Electric Arc Furnace Slag (EAFS). The specimens were broken and then subjected to thermomechanical treatment. The healing response was then assessed in terms of recovery of their initial indirect tensile strength. The following conclusions can be drawn:

- The addition of EAFS enhanced the microwave-absorbing properties of CRAMs. The addition of 5 and 10% of EAFS allows for saving 36% and 41% of the necessary energy for the heating process
- Microwave heating and re-compaction in the ranges studied do not themselves cause healing. However, the synergic effect of microwave heating and re-compaction energy produced excellent healing performance, and the initial mechanical properties of the CRAMs were exceeded.
- The best results were obtained for the combined effect of heating the specimens up to 80 °C and the re-compaction of 50 gyrations with the gyratory compactor (half of the initial compaction energy of the samples).

- The addition of EAFS was beneficial up to 5%, while the rapid heating process achieved with 10% EAFS reduced the healing capability of the asphalt mixtures.

Some limitations of the study must be acknowledged. In this work, a slight reduction in the Indirect Tensile Strength (ITS) of the asphalt mixture was observed with the addition of EAFS, potentially attributable to difference in effective bitumen content. Given that the dosage of the bituminous emulsion in EAFS mixtures was based on existing literature findings, it is imperative for future investigations to evaluate the actual effective bitumen content in EAFS mixtures and its impact on mechanical properties.

Another important concern is related to the actual temperature of the asphalt mixture during microwave treatment. In this work, the temperature of the asphalt mixture was determined based on the temperature of the cut faces of the samples after been radiated while keeping them together, which does not strictly represent the internal thermal field of the mixture. Further research should be conducted to analyze the actual thermal field inside the mixture during Microwave (MW) heating treatment.

The results of the paper indicate that the application of both heating and re-compaction effectively healed the CRAMs, resulting in a final ITS that far exceeded the initial ITS. This significant improvement is likely attributed to changes in the air voids within the sample (i.e., densification). However, it was not feasible to measure the air voids of the mixture after conducting the final ITS test, as the cracks formed during the test inevitably affected the air voids. Further investigation is therefore necessary to better assess this phenomenon.

In conclusion, besides the benefits in terms of sustainability which characterized the cold recycling (CR) technologies, the application of the thermomechanical treatment with microwaves can prolong the service life of the pavement, further reducing the environmental impact of the sector.

Currently, CRAMs could have various limitations in terms of mechanical performance, which hinder their widespread adoption in the asphalt industry. However, given the promising results obtained in this study, it appears that the use of assisted self-healing technologies could be beneficial for this type of mixture, suggesting a need for further investigations in this field. For instance, one of the potential limitations of CRAMs is their fatigue resistance, so conducting further research to evaluate the effectiveness of self-healing treatments in prolonging the fatigue life of these mixtures is needed. Future research should be also conducted to evaluate the use of different microwave-absorbing additives on the healing performance of CRAMs. Additionally, it is crucial to investigate the influence of different types of microwave ovens on energy consumption, as well as to examine the actual thermal energy transferred to the specimen.

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