Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2022) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

Use of steel industry by-products as promoters of pavement repair solutions

Carlos D.A. Loureiro[a,*], Hugo M.R.D. Silva[a], Joel R.M. Oliveira[a]

[a]*ISISE, Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal*

Abstract

This study evaluated the effect of microwave heating on the self-healing of asphalt mixtures. Three asphalt concrete mixtures were produced: i) conventional one; ii) with metallic fibres; iii) with steel slag aggregates and metallic fibres. After evaluating the microwave heating induced in the different asphalt mixtures through a thermographic camera, their healing capacity was determined through multiple cycles of induction, self-healing, and fracture. The heat induction results of cylindrical specimens demonstrated that steel slag and metallic fibres promoted higher healing temperatures than conventional mixtures for equal induction time. The asphalt mixture with steel slag and fibres presented the best healing capacity, with significant strength recovery after total damage in fracture tests, while the mixture with only metallic fibres presented the worst healing results.
© 2022 The Authors. Published by ELSEVIER BV This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference
Keywords: Self-healing; Industrial by-products; Steel fibres; Asphalt mixtures; Thermal induction; Microwaves

1. Introduction

Road infrastructures have limited durability, and improved rehabilitation technologies are needed to increase their life cycle. The population growth has led to a significant increase in traffic and heavy vehicle loads using road pavements. Thus, the service required from these infrastructures raises, as well as the need for their rehabilitation, conservation, and monitoring. Nevertheless, it is essential to mitigate the effects and costs of these interventions. Therefore, some processes to promote or increase the self-healing capacity of asphalt mixtures have been studied recently due to the need to develop more durable infrastructures with high-quality materials.

Even though asphalt pavements have many advantages (e.g. cost, noise reduction, comfortable driving), asphalt concrete undergoes functional and structural degradation after a few years of service, mainly due to traffic and weather

* Corresponding author. Tel.: +351-253-510-200.
E-mail address: id9629@alunos.uminho.pt

2352-1465 © 2022 The Authors. Published by ELSEVIER B.V. This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference

conditions. For example, as the asphalt binder ages, it becomes more brittle, initially leading to the appearance of microcracks that evolve into macro cracks, which leads to failures in pavement performance, both from a structural and functional point of view (Li et al., 2019). In recent years, self-healing processes have been expanded from chemistry to engineering. This phenomenon has multiple and unique characteristics that make it a promising approach to increasing the durability of asphalt pavements by regenerating microcracks and restoring initial performance without destroying the original pavement (Tabaković and Schlangen, 2015). Moreover, compared to conventional rehabilitation techniques, self-healing methods reduce pavement maintenance costs, CO_2 emissions into the atmosphere and road safety problems (Butt et al., 2012).

Bitumen is a viscoelastic fluid that exhibits the behaviour of a self-healing material. Therefore, bitumen can close microcracks and recover its initial strength, but this mechanism is not yet fully understood. Developing the self-healing capacity of asphalt concrete is an excellent technological innovation, taking advantage of its ability to regenerate automatically or artificially when it suffers mechanical damage (García, 2012; NL Agency, 2011). However, the automatic effect is inefficient and cannot be controlled, as self-healing at room temperature can occur over hours or days, and the influence of traffic is also harmful during the recovery time (García et al., 2013). Recently, new technologies have been developed to improve self-healing efficiency through external stimuli (González et al., 2018; Norambuena-Contreras et al., 2016). For example, metallic fibres are added to asphalt mixtures to increase their ferromagnetic properties and conductivity, and thus the mixture becomes susceptible to heating by electromagnetic induction or microwave radiation (Franesqui et al., 2017; Norambuena-Contreras and Gonzalez-Torre, 2017; Phan et al., 2018). As the temperature of asphalt mixtures rises by induction, the asphalt binder melts and fills the existing microcracks by capillarity, regressing cracking and contributing to its self-healing process (NL Agency, 2011).

The present study aimed to develop asphalt mixtures with improved repair properties by incorporating steel slag aggregates (SSA) and metallic fibres. Therefore, this study assessed whether incorporating industrial by-products could increase the self-healing capacity of asphalt concrete when thermally induced by microwave radiation equipment by allowing an increase in the energy transfer rate to the asphalt mixture. With this new technological solution, the objective is to boost the lifespan of asphalt mixtures, thus reducing the number of interventions to be carried out over time while contributing to more sustainable development with a lower environmental impact.

2. Materials and methods

2.1. Materials

The materials used in this study were those presented in Figure 1, steel slag aggregates (a by-product from the steel industry), natural granitic aggregates (NGA), limestone filler (LF), metallic fibres and a 35/50 pen grade bitumen.

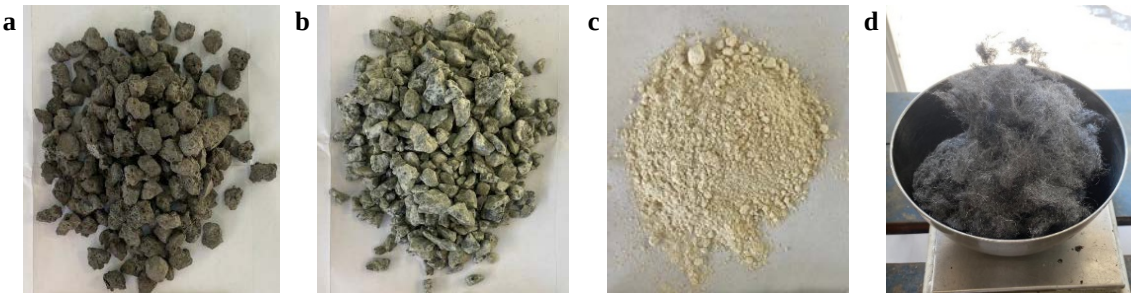


Fig. 1. Materials used in this study: (a) steel slag aggregates; (b) natural granite aggregates; (c) limestone filler; (d) metallic fibres.

2.2. Aggregates and bitumen characterisation

This study used natural granite and steel slag aggregates from the batches previous studied by Moura et al. (2022). In that study, several tests were performed to characterise the aggregates' properties, including particle density and water absorption, wear resistance through the micro-Deval coefficient, the resistance of coarse aggregates to polishing

and the binder-aggregates affinity. Moura et al. (2022) concluded that SSA has excellent potential to be incorporated into asphalt mixtures due to the excellent resistance to wear and polishing and good affinity with bitumen.

The particle size distribution of the different aggregates fractions, both for the SSA (0/10 and 10/14) and the natural aggregates (0/4, 4/6 and 6/14), was determined using the EN 933-1 standard. These results were essential to designing asphalt mixtures complying with the grading envelope of the Portuguese specifications (Estradas de Portugal, 2014).

The bitumen used in this study was characterised by the penetration test at 25 °C (EN 1426) and the softening point test using the ring and ball method (EN 1427).

2.3. Mix design, production and characterisation of asphalt mixtures

In order to evaluate the composition influence on the mechanical performance and self-healing capacity of asphalt mixtures, the following AC 14 surf 35/50 mixtures were produced:

- conventional asphalt mixture with natural aggregates labelled as mixture A (MA);
- asphalt mixture with natural aggregates and metallic fibres labelled as mixture B (MB);
- asphalt mixture incorporating steel slag aggregates and metallic fibres labelled as mixture C (MC).

The asphalt mixtures were designed based on the various aggregate fractions' density and particle size distribution, adjusting the final grading curves within the AC 14 surf grading envelope (Estradas de Portugal, 2014). Mixture C incorporated 50% steel slag aggregates, while mixtures A and B were produced only with natural aggregates.

In this study, all mixtures were produced with 5% bitumen content, typically used in this type of asphalt mixtures, to reduce the number of independent variables under analysis. Based on previous scientific studies, mixtures B and C added the same percentage (7% of bitumen or around 0.35% of the total mass of the mixture) and geometry of metallic fibres, with fibre length between 8 and 10 mm and diameter between 0.04 and 0.06 mm (Gallego et al., 2013; Liu et al., 2018; Tabaković et al., 2019).

A mixing temperature of 165 °C, specified in EN 12697-35 standard, was guaranteed by heating the aggregates at 170 °C and the bitumen at 165 °C. The materials of each mixture were mixed in a specific mixer roughly for 2 minutes until the aggregates were entirely covered by bitumen. In mixtures B and C, the metallic fibres were gradually placed into the mixer bowl during the total mixing time so that the fibres may be better distributed within the mixture. After production, the asphalt mixtures were compacted. Nine cylindrical specimens with a diameter of 101 mm and a height of nearly 60 mm were compacted at around 135 °C for each asphalt mixture using a Marshall impact hammer, applying 75 blows per face according to EN 12697-30.

After compaction, the bulk density (BD) was determined according to method B of EN 12697-6, the maximum density (MD) was determined according to method A of EN 12697-5, and both values were used to quantify the air voids content in each asphalt mixture. The air voids content control is essential during the initial phase of asphalt mixtures production and must be within limits specified in Portugal (Estradas de Portugal, 2014).

2.4. Microwave heating of asphalt mixtures

Two cylindrical specimens of each mixture were produced for a preliminary study to evaluate the thermal induction behaviour of the asphalt mixtures as a function of the microwave power and heating time. The analysis of several scientific studies showed different procedures for heating asphalt mixtures with microwave radiation. The ideal induction time to promote self-healing varies depending on the induction equipment, specimen's geometry, asphalt mixture type and induction time (Gallego et al., 2013; Liu et al., 2018; Tabaković et al., 2019).

Therefore, in this study, a preliminary analysis was performed to assess the temperature evolution of the specimens according to the different power levels installed (540 W, 720 W and 900 W), for a total period of 160 seconds, with partial temperature measurements, with a thermographic camera, every 20 seconds. Figure 2 shows the steps for measuring the surface temperature of each test specimen. It is important to note that before being tested, the specimens were placed in a thermal chamber at 20 °C to homogenise the initial test conditions, and a microwave turntable was used for a uniform heating distribution in the mixture.

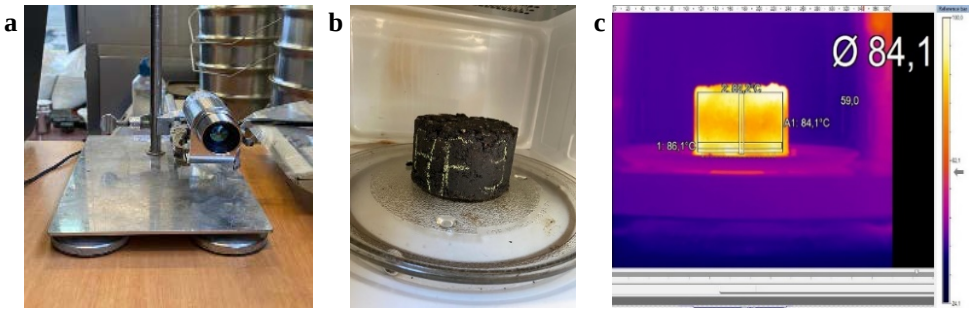


Fig. 2. (a) Thermographic camera in fixed support; (b) Specimen in the microwave; (c) Surface temperature of the specimen after the test.

2.5. Mechanical characterisation and self-healing assessment of asphalt mixtures

The mechanical characterisation is essential to analyse the performance of asphalt mixtures but had additional importance in this work. The fracture strength of the three mixtures will be used to compare their performance and calculate their healing ratio derived from a thermal induction process applied to some specimens. The mechanical characterisation of the mixtures was carried out by a three-point bending fracture test performed on semi-circular specimens, according to EN 12697-44. In this test, the performance of the three asphalt mixtures was compared, evaluating the maximum fracture load and the corresponding displacement for each specimen. The test was performed in a Matest Unitronic universal loading structure, in a bending test configuration with two support points spaced by 8 cm and a load application point at the specimen's midpoint. The load application speed was 0.5 mm/min. The test was performed at room temperature since the equipment had no temperature control. However, all specimens were placed in an environmental chamber at -20 °C (test temperature), performing the tests immediately after removing the samples from the chamber. This low temperature ensures a brittle fracture of the specimens, creating well-defined cracks more easily controlled during the healing phase. It should be noted that a notch with 1 cm depth was made in the semi-circular specimens to control the start and progression of the crack resulting from the fracture test.

The main objective of the fracture test was to determine the strength recovery (healing) capacity of the mixtures induced by heating after the complete rupture of the specimens. The average strength recovery was computed through the healing ratio (HR) of each specimen, according to Equation 1. This parameter is calculated using the ratio between the peak load reached by the specimen before the healing cycles ($F_{initial}$) and the peak load achieved by the same specimen after each induction heating cycle used in the healing process (F_{final}).

$$HR = \frac{F_{final}}{F_{initial}} \quad (1)$$

The procedure adopted to calculate the healing capacity of asphalt mixtures through cycles of mechanical characterisation tests and microwave radiation heating can be summarised in the following steps:

1. The semi-circular specimens were placed in a thermal chamber at a temperature of -20 °C for 24 hours;
2. The semi-circular bending (SCB) fracture test is carried out at a speed of 0.5 mm/min;
3. The broken specimens are placed in a ventilated thermal chamber at 20 °C for 3 hours to evaporate some moisture in the crack;
4. Heating induction is applied for 80 seconds using microwave radiation at a power of 900 W;
5. After induction, the specimens rest at room temperature for 2 hours before repeating procedures 1 to 5 for three consecutive cycles.

Finally, after concluding the three healing cycles, the necessary data were obtained to analyse how the healing capacity of the specimens was influenced by the composition of each asphalt mixture, namely by calculating the healing ratio of the asphalt mixtures after each healing cycle.

3. Results and discussion

3.1. Aggregates and bitumen characterisation

The particle size distributions of the various NGA and SSA fractions were obtained prior to designing the studied asphalt mixtures. The grading curves obtained showed that the SSA material has fewer fines than the NGA, which increased the use of limestone filler in mixture C. The density values determined by Moura et al. (2022) for these materials (2.65 Mg/m^3 for NGA and LF; 3.25 Mg/m^3 for SSA) were also used to design the asphalt mixtures.

In this work, a 35/50 pen grade bitumen was used because it is the most widely used in the country. The bitumen presented a penetration value of 44.9 tenths of a millimetre and a softening point temperature of 51.1 °C, and both values are within limits established by EN 12591 for this bitumen classification.

3.2. Mix design, production and characterisation of asphalt mixtures

Table 1 presents the compositions of the three asphalt mixtures (A, B and C) produced in this study by showing the percentage volume of each aggregate fraction used. The corresponding mass values used to produce the mixtures were determined based on the aggregates' densities. The composition was defined to obtain a final grading curve of each asphalt mixture fitting the grading envelope of an AC 14 surf and was based on the particle size distribution of the aggregates. It is essential to highlight that the percentage of fibres added was low, and consequently, their weight was not considered when adjusting the grading curve. The asphalt binder content of mixtures A and B was 5.0%, using an equivalent value in mixture C adjusted (i.e., reduced) to consider the high density of SSA.

Table 1. Composition of the different asphalt mixtures evaluated in this study.

Fraction	NGA 0/4	NGA 4/6	NGA 6/14	SSA 0/10	SSA 10/14	Limestone filler	Metallic fibres
Mixture A	40%	14%	42%	0%	0%	4%	0%
Mixture B	40%	14%	42%	0%	0%	4%	7% of bitumen
Mixture C	27%	0%	17%	36%	14%	6%	7% of bitumen

The volumetric characteristics of the asphalt mixtures were obtained by assessing their maximum density (MD) and the bulk density (BD) of compacted specimens and calculating the air voids content (Vv) of each specimen. The characterisation results are presented in Table 2, which shows the average values for each asphalt mix. The high density and low air voids content of mixture C should be highlighted from these results. Therefore, mixture C presented good workability and solved the high air voids content problem previously mentioned in Moura et al. (2022) study for a similar mixture with 50% SSA.

Table 2. Volumetric characterisation of asphalt mixtures.

Mixture	MD (Mg/m^3)	BD (Mg/m^3)	Vv (%)
A	2.484	2.415	2.8
B	2.481	2.410	2.9
C	2.830	2.753	2.7

3.3. Microwave heating of asphalt mixtures

In the present work, the influence of the asphalt mixture composition was initially studied by assessing their thermal induction behaviour when heated by microwave radiation. The specimen temperature evolution was evaluated for 160 seconds with different microwave power levels (540 W, 720 W and 900 W) to find differences in the heating rate between the three mixtures produced. The tests were performed according to the procedures and techniques described in Section 2.4. Figure 3 shows the best fit to the average surface temperature of two specimens of each asphalt mixture (MA, MB and MC) as a function of the heating time for the three different microwave power levels used.

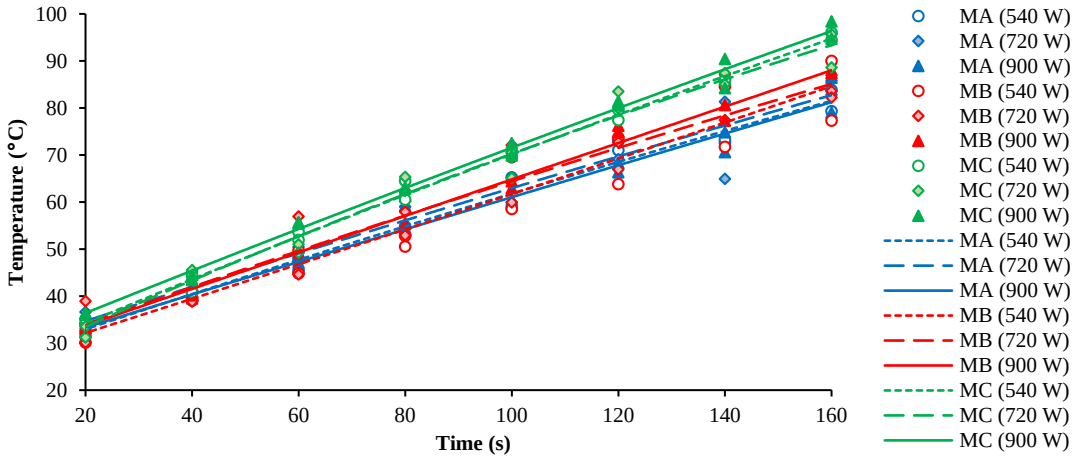


Fig. 3. Evolution of surface temperature of the different mixtures with the heating time for three microwave power levels.

The analysis of these results demonstrates that the specimens of mixture B present higher temperatures than those of mixture A for identical induction times. However, the specimens of mixture C showed higher temperatures for all induction times and power levels, especially for longer induction times (140 and 160 seconds). These tests demonstrated that SSA and metallic fibres could increase the heating rate in the microwave induction process. Nevertheless, it should be mentioned that the bitumen ageing is accelerated when very high induction temperatures are reached (near 100 °C), becoming stiffer and brittle and decreasing the fatigue and fracture resistance. Thus, long induction times (higher than 120 seconds) should be avoided to reduce bitumen ageing. Regarding the different power levels used, the differences were not as substantial as expected, probably due to the equipment used. However, the temperature evolved more rapidly and uniformly for the 900 W power, particularly in mixtures B and C, and that power was preferred for the remaining microwave heating tests performed in this study.

3.4. Mechanical characterisation and self-healing assessment of asphalt mixtures

In this study, a three-point semi-circular bending test (Figure 4a) was performed to evaluate the fracture resistance of the different asphalt mixtures and their ability to recover (Figure 4c) the mechanical performance after total failure (Figure 4b). It should be noted that the macro cracks observed in fracture tests may inhibit the self-healing action when compared to micro-cracks occurring in fatigue tests, but that difficulty was assumed when developing this work. This experimental test used 36 semi-circular specimens (twelve of each mixture) that underwent three healing cycles (four fracture test repetitions, before and after each of three cycles of induction heating via microwave radiation). A heating time of 80 seconds at 900 W power was defined, and an elastic band was used to wrap the specimens to facilitate the healing of the fractured faces of the semi-circular samples during the induction heating.

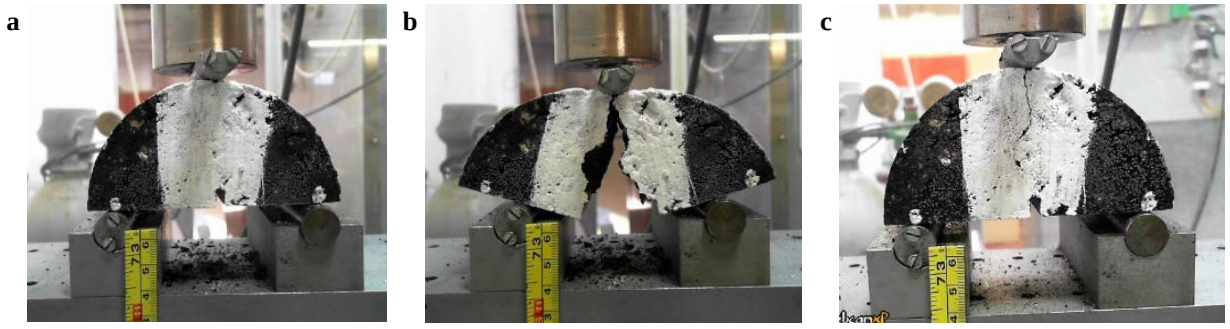


Fig. 4. Asphalt mixture specimen: (a) before the SCB test; (b) damaged after the fracture test; (c) after self-healing.

After collecting and organising the data from the SCB fracture tests (load and displacement), the most relevant results for each specimen, the maximum load and the peak displacement, were analysed. Although the four graphs of load *vs* displacement of the SCB tests were plotted for all the tested specimens, Figure 5 presents examples of only one characteristic specimen of each asphalt mixture studied. Concerning the healing ratio (HR), this value was calculated by the proportion of the peak load of the specimens after each healing cycle and the corresponding peak load of the undamaged mixture in the first SCB test. The HR values obtained are presented in Figure 6.

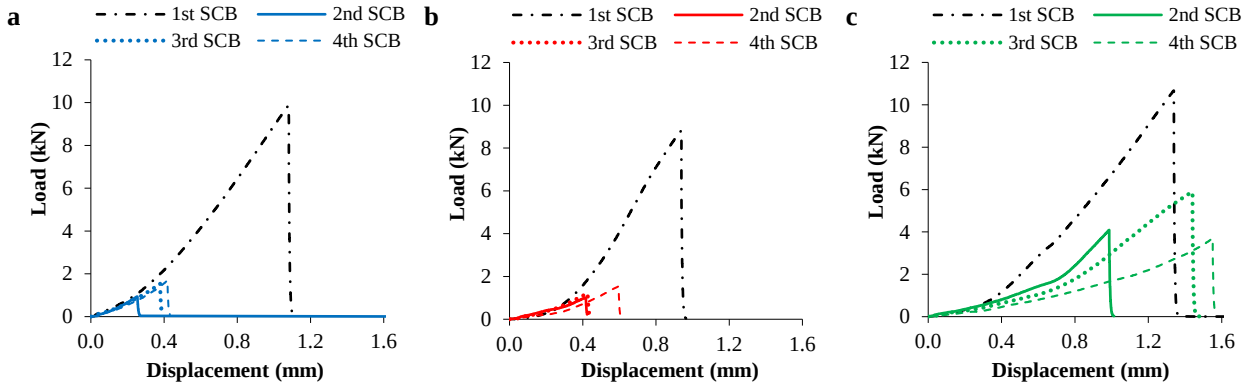


Fig. 5. Evolution of load with displacement in the four fracture tests: (a) Mixture A; (b) Mixture B; (c) Mixture C.

From the analysis of the results, it should be mentioned that the semi-circular specimens presented brittle behaviour in the SCB fracture test, as expected, due to the low test temperature (-20 °C). Based on the data obtained, it is noticeable that the damage induced by the fracture test was recovered much more significantly in mixture C. This mixture recovered about 40% of its initial fracture resistance in the second, third and fourth tests and incremented the displacement at rupture, demonstrating that multiple healing actions may be applied in road pavements. The other asphalt mixtures (A and B) show low levels of healing (around 10%) after the first fracture test performed on the intact mixtures, as can be confirmed from the healing ratio results presented in Figure 6.

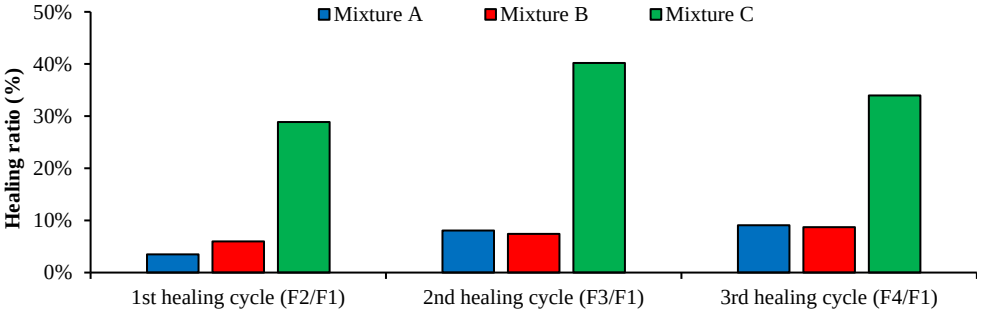


Fig. 6. Healing ratio of the semi-circular test specimens after the three healing cycles.

Finally, it was found that the asphalt mixture with steel slag aggregates and metallic fibres (mixture C) was the one that reached the highest induction temperatures in the microwave. Future work should define the induction time according to the expected healing temperature because this factor may be influencing the results obtained.

4. Conclusions

This study complemented the knowledge about the healing process in asphalt mixtures using a microwave radiation heating method. The main objective was to study the application of industrial by-products (SSA) and metallic fibres

in asphalt concrete mixtures to enhance their induction by external heating means and improve their healing capacity for future pavement repair solutions. The results obtained demonstrate that the objectives initially defined were successfully achieved since it was concluded that incorporating SSA and metallic fibres in asphalt mixtures improves the induction rate and healing capacity. Nevertheless, future work should be carried out to produce mixtures with different metallic fibres (type, geometry and percentages) and other compositions that may improve healing efficiency further. The following points summarise the main conclusions of this study:

- The adopted percentage of metallic fibres (7% of bitumen volume) was adequate, and no visible oxidation or crusts occurred on the specimens. However, the type of fibre and its geometry should be changed to improve their dispersion and healing capacity;
- Steel slag aggregates and metallic fibres enhanced the heating of asphalt mixtures by microwave radiation;
- The healing capacity of the mixtures measured through cycles of mechanical fracture tests and microwave radiation heating was satisfactory, as the specimens always recovered some resistance after total damage;
- The three-point bending test on semi-circular specimens detected the specimen strength recovery after healing induced by microwave heating. However, only mixture C (with SSA and metallic fibres) showed sufficiently high healing ratios, around 40%, while the other two mixtures showed healing ratios of only 10%.

Acknowledgements

This study was funded by *Fundação para a Ciência e a Tecnologia* through the PhD grant number 2021.06428.BD. The authors would like to acknowledge the University of Minho staff involved in this work, who contributed to achieving the objectives of this study.

References

Butt, A.A., Birgisson, B., Kringos, N., 2012. Optimising the Highway Lifetime by Improving the Self Healing Capacity of Asphalt. Procedia - Social and Behavioral Sciences 48, pp. 2190-2200.

Estradas de Portugal, 2014. Caderno de Encargos Tipo Obra. 14.03 - Pavimentação, Características dos Materiais. Estradas de Portugal. Almada, Portugal.

Franesqui, M.A., Yepes, J., Garcia-Gonzalez, C., 2017. Top-down cracking self-healing of asphalt pavements with steel filler from industrial waste applying microwaves. Construction and Building Materials 149, pp. 612-620.

Gallego, J., del Val, M.A., Contreras, V., Paez, A., 2013. Heating asphalt mixtures with microwaves to promote self-healing. Construction and Building Materials 42, pp. 1-4.

García, Á., 2012. Self-healing of open cracks in asphalt mastic. Fuel 93, pp. 264-272.

García, A., Bueno, M., Norambuena-Contreras, J., Partl, M.N., 2013. Induction healing of dense asphalt concrete. Construction and Building Materials 49, pp. 1-7.

González, A., Norambuena-Contreras, J., Storey, L., Schlangen, E., 2018. Effect of RAP and fibers addition on asphalt mixtures with self-healing properties gained by microwave radiation heating. Construction and Building Materials 159, pp. 164-174.

Li, J., Liu, J., Zhang, W., Liu, G., Dai, L., 2019. Investigation of thermal asphalt mastic and mixture to repair potholes. Construction and Building Materials 201, pp. 286-294.

Liu, Q., Chen, C., Li, B., Sun, Y., Li, H., 2018. Heating Characteristics and Induced Healing Efficiencies of Asphalt Mixture via Induction and Microwave Heating. Materials 11.6, pp. 913.

Moura, C., Nascimento, L., Loureiro, C., Rodrigues, M., Oliveira, J., Silva, H., 2022. Viability of Using High Amounts of Steel Slag Aggregates to Improve the Circularity and Performance of Asphalt Mixtures. Applied Sciences 12.1, pp. 490.

NL Agency, 2011. Self healing materials. Concept and applications. NL Agency. Ministry of Economic Affairs, Agriculture and Innovation. The Hague, The Netherlands.

Norambuena-Contreras, J., Gonzalez-Torre, I., 2017. Influence of the Microwave Heating Time on the Self-Healing Properties of Asphalt Mixtures. Applied Sciences 7.10, pp. 1076.

Norambuena-Contreras, J., Serpell, R., Vidal, G.V., Gonzalez, A., Schlangen, E., 2016. Effect of fibres addition on the physical and mechanical properties of asphalt mixtures with crack-healing purposes by microwave radiation. Construction and Building Materials 127, pp. 369-382.

Phan, T.M., Park, D.W., Le, T.H.M., 2018. Crack healing performance of hot mix asphalt containing steel slag by microwaves heating. Construction and Building Materials 180, pp. 503-511.

Tabaković, A., O'Prey, D., McKenna, D., Woodward, D., 2019. Microwave self-healing technology as airfield porous asphalt friction course repair and maintenance system. Case Stud. Constr. Mater. 10.

Tabaković, A., Schlangen, E., 2015. Self-Healing Technology for Asphalt Pavements. Self-healing Materials, pp. 285-306.