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Self-healing capacity of asphalt mixtures with steel fiber, steel slag and graphite powder, evaluated with microwave induction and fatigue test

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ABSTRACT

Self-healing in asphalt mixtures can be induced by adding particles that are susceptible to heating by electromagnetic microwaves. This process allows the closure of microcracks caused by the fatigue phenomenon and can extend the service life of the asphalt pavement. In this article, the self-healing index of asphalt mixtures without and with the addition of steel slag (15% and 65.7%), steel fibers, (0.2% and 0.4%), and graphite powder (15% and 65.7%) was evaluated. The index was determined after subjecting the mixtures to fatigue damage, microwave heating, rest, and fatigue damage again. Results showed that all additions led to mixtures susceptible to microwave heating and with healing capacity. A higher self-healing index was observed when the mixture was produced with slag than with graphite powder. It was found that the use of a higher content of steel fibers was more effective for healing, and for successful healing, the mixtures must be heated to temperatures ranging between 50°C and 75°C. The results also showed that it is possible to achieve high healing values without having to subject the mixtures to microwave heating.

Keywords: Self-healing asphalt mixtures; Steel slag; Steel fibers; Graphite powder; Fatigue.

1. INTRODUCTION

The self-healing of an asphalt mixture is the ability of the material to seal its microcracks from vehicle traffic, in a natural way during a resting period and in the absence of external loads [1]. This phenomenon is possible due to microcrack filling by the asphalt, which becomes fluid at a higher temperature. The phenomenon of capillarity that occurs between the walls of the cracks also facilitates the process [2, 3]. There is a possibility, however, of inducing healing artificially, as shown by CONTRERAS and GARCÍA [4], WANG *et al*. [5], ZHU *et al*. [6], SUN *et al*. [7], and FRANESQUI *et al*. [8]. This process has been studied extensively over the past decade [9] and has become a possible alternative for the recovery of microcracked asphalt pavement.

One of the techniques used to induce the healing of asphalt mixture involves using an external energy source, such as electromagnetic microwaves, and adding particles that make the mixture susceptible to heating, such as steel fibers, graphite, and steel slag [5, 10, 11]. The additions in the asphalt mixture are heated by microwaves that raise the temperature of the asphalt, reduce its viscosity and allow the filling of the microcracks in a process similar to what already occurs naturally [8].

One of the procedures used to evaluate the healing capacity of asphalt mixtures in the laboratory is to subject a sample to consecutive cycles of fatigue damage and healing. These cycles consist of the following sequences: subjecting the sample to fatigue damage, heating the sample with microwaves, leaving the sample to rest for a certain period, and subjecting the sample again to fatigue damage [6]. Performing this procedure allows for obtaining the necessary data to determine the mixture's self-healing index (HI). Hence, for example, if a sample was subjected to a cycle of fatigue damage and healing, the HI of the mixture would be equal to the quotient between the fatigue resistance that the sample presents immediately after the end of the fatigue damage test of the last test that the sample presents immediately after the end of the first test. The fatigue resistance, in this case, corresponds to the number of load applications that are necessary to reduce the initial resilient modulus of the sample to a certain level [6, 12].

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The HI, however, does not have a fixed value since the asphalt mixtures do not heal in the same proportion [13]. due to the influence of several factors. Thus, very severe damage induced by fatigue, for example, can impair the self-healing capacity of the mixture. In this case, ZHU *et al.* [6] assert the application of fatigue damage with a reduction of the resilient modulus of the mixture in a magnitude greater than 60%, causing structural damages in the specimen, which significantly compromise the self-healing capacity. In their studies, the authors concluded that the self-healing index was reduced from 1.33 to 0.24 when the resilient modulus was reduced from 50% to 60%.

The resting period, which corresponds to the period in which the specimen remains without load application, between the first and the second fatigue damage, is another factor that strongly influences the HI. However, the ideal resting period to promote a higher HI has not yet been consolidated in the literature. In the reviewed papers, some researchers, such as GARCÍA *et al*. [3], apply a two-hour resting period, while ZHU *et al.* [6] and ZHAO *et al*. [14] apply a three-hour resting period, MENOZZI *et al*. [15] apply a six-hour resting period, and there are still studies that use resting periods of more than 24 hours [4, 12, 16, 17].

The heating temperature also interferes considerably with the self-healing capacity of the mixtures and there is no consensus in the literature of what would be the ideal value. There is a heating temperature range in which the HI increases proportionally to the increase of the temperature; however, there is a limit at which a certain temperature will reverse the HI performance [6]. According to LIU *et al.* [18], a heating temperature between 70 and 85°C is ideal to achieve a higher HI. According to GARCÍA *et al.* [3], the most appropriate way to promote the healing of asphalt mixtures is to heat the material above the Newtonian transition temperature and maintain it for a certain period. So, for example, for SMA (Stone Mastic Asphalt) mixtures, ZHU *et al.* [6] indicate that the ideal temperature, for a higher HI, is 55°C. For dense asphalt mixtures containing bitumen 70/100, MENOZZI *et al*. [15] concluded that the temperature of 55°C promotes a higher HI; this value is different from that indicated by LIU *et al*. [19], who state that for asphalt mixtures, formed by mastic asphalt, this value must be 85°C, and, differently, from the conclusions of GARCÍA *et al.* [3], which indicate that this value should be 100°C.

Likewise, the type and amount of addition used also has a major influence on the self-healing capacity of the asphalt mixture. In this context, GARCÍA *et al.* [20] reported excellent results of HI in asphalt mixtures containing steel fibers with an average length of 10 mm and content of 0.2% of the mass of the asphalt mixture. GALLEGO *et al.* [21] state that levels of 0.2% and 0.4% of steel fibers per mass of the asphalt mixture promote asphalt mixtures susceptible to heating by microwave radiation in a similar way; that is, with similar heating rates. When this type of addition is used in the production of mixtures, one of the problems reported is the formation of clusters during mixing. To remedy this situation, WANG *et al*. [22] recommend using fibers with a length of 10 mm, while GARCÍA *et al*. [3] suggest using short and thicker fibers. In addition to causing heterogeneity in the asphalt mixture, clusters may influence the void volume and, consequently, may modify the mechanical characteristics of the same.

Regarding the use of steel slag, SUN *et al.* [7] indicate that the addition of this material allows asphalt mixtures to be more susceptible to microwave heating and to present greater uniformity in temperature distribution than mixtures with the addition of steel fibers. As for the resistance of the mixtures, PASETTO and BALDO [23] reported excellent results of mechanical behavior in asphalt mixtures containing this addition.

In the case of the addition of graphite powder, WANG *et al*. [5] found that asphalt mixtures containing this material are susceptible to microwave heating, while KÖK *et al*. [24] obtained excellent results of mechanical behavior with mixtures containing 15% graphite powder compared to asphalt mixtures containing 10 and 20% graphite powder.

This article aimed to investigate the self-healing capacity of microcracks by fatigue in dense asphalt mixtures with Brazilian asphalt binder 50/70 pen, through the addition of steel fibers, steel slag and graphite powder w. To meet this objective, this study determined the self-healing index of asphalt mixtures containing steel slag, steel fibers and graphite powder. Additionally, there are many studies about Self-healing in asphalt mixtures outside of Brazil. But, most studies tend to use the four-point bending fatigue tests to evaluate self-healing. So, in this study, the fatigue test was carried out by applying tensile stresses by diametrical compression in cylindrical specimens, that's very common in Brazil. The results showed which levels and types of additions were more effective in the regeneration of the mixtures and the level of damage, temperature, and resting period.

2. MATERIALS AND METHODS

2.1. Materials

In this study, crushed gneiss is used as aggregate, conventional Brazilian asphalt binder 50/70 pen, and the following additions: steel slag, steel fibers, and graphite powder. The slag used comes from the production of pig iron and was subjected, in the laboratory, to an initial grinding process in the rotating drum of the equipment used in the Los Angeles test; right after grinding, it passed through a jaw crusher and lastly, it passed a ball mill. Steel fibers are classified by the manufacturer as Type 2, thick, and were purchased in small rolls, cut manually until reaching lengths between 5 and 15 mm. The graphite powder was purchased from local stores and consists of a product based on natural crystalline graphite, which is normally used for seed lubrication in the agricultural industry. All additions used are shown in Figure 1 (a) (b) (c).

Table 1 shows the characteristics of the asphalt binder 50/70, used in the research.

2.2. Methods

The stages taken to achieve the research objectives are described in more detail in the following items.

2.2.1. Design

Seven types of asphalt mixtures were produced: a control mixture, two mixtures with the addition of steel slag, two mixtures with the addition of steel fibers, and two mixtures with the addition of graphite powder. The control asphalt mixture, named as C mixture, was designed according to the recommendations of the Superpave method [29], and its granulometric composition abides by the reference points for a maximum size of 25 mm (maximum nominal size of 19 mm), as shown in Figure 2. After that, the design binder content of the control mixture was 4.3%. The other mixtures, with additions, were produced with the same granulometry and binder content as the control mixture. In this research, the samples were produced with cylindrical shapes and dimensions of 100 mm in diameter and 63.5 mm in height.

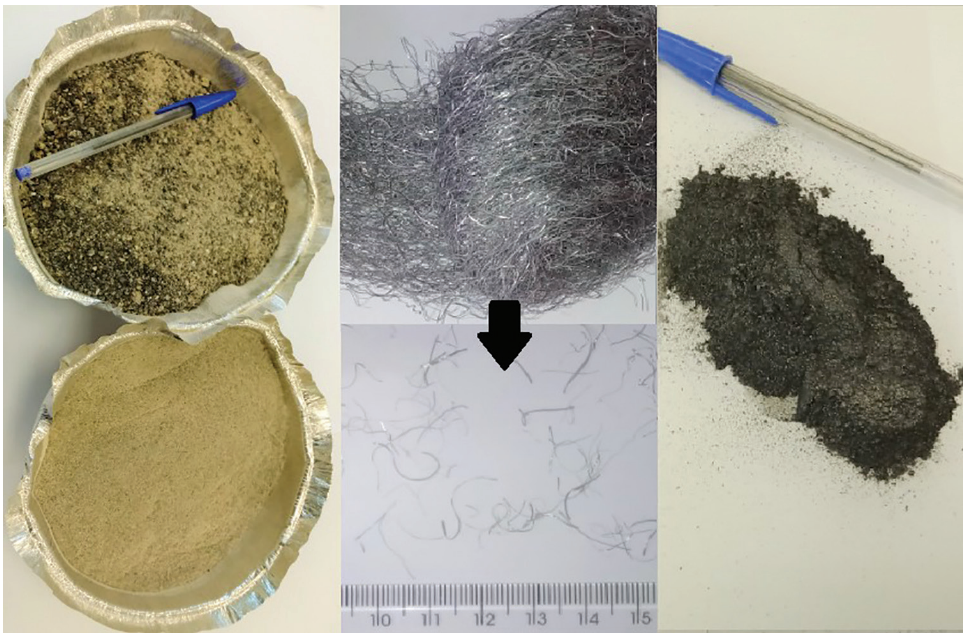

Figure 1: Additions used: (a) steel slag before and after grinding; (b) steel fibers in roll and after cutting; and (c) graphite powder.

Table 1: Basic properties of asphalt binder 50/70.

PROPERTIES	RESULT	SPECIFICATION LIMITS	TEST METHOD
Penetration (25°C, 100 g, 5s, 0,1 mm)	40.3	50–70	DNIT ME 155/2010 [25]
Softening Point, min., (°C)	51.5	46 (min.)	DNIT ME 131/2010 [26]
Density (25°C, g/cm³)	0.99	–	DNER-ME 193/96 [27]
Rotational viscosity at 135°C (cP)	317.5	274 (min.)	ABNT NBR 15184/2004 [28]
Rotational viscosity at 150°C (cP)	204.3	112 (min.)	ABNT NBR 15184/2004 [28]
Rotational viscosity at 177°C (cP)	93.5	57–285	ABNT NBR 15184/2004 [28]

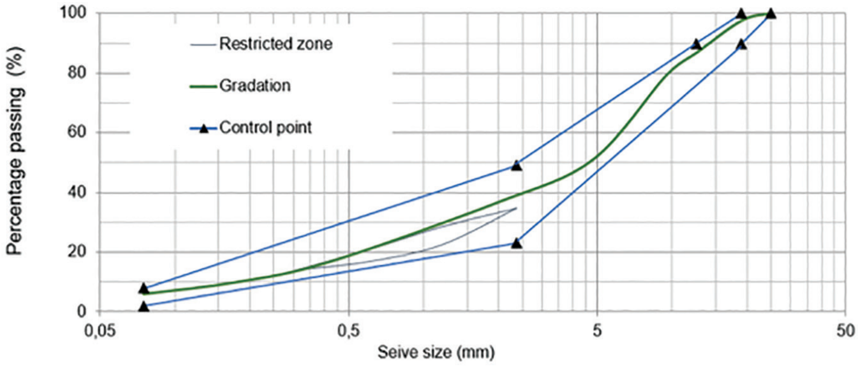

Figure 2: Granulometric curve of the studied asphalt mixtures.

The two types of mixtures containing slag were called SA mixture and SB mixture. The SA mixture was produced with 15% of slag out of the total weight of the binder, replacing the filler fraction of the granulometry (through the sieve with a 0.075 mm opening). The SB mixture was produced with 65.7% of slag out of the total weight of the binder, replacing the filler fraction itself. The mixtures containing graphite powder were called GA mixture and GB mixture. The GA mixture was produced with 15% of graphite powder out of the total weight of the binder, replacing the filler fraction. The GB mixture was produced containing 65.7% of graphite powder out of the total weight of the binder, replacing the filler fraction itself. The content adopted was 65.7%, because previous of the mixture with graphite powder showed that mixtures with percentages above this value required an excessive number of gyrations in the Superpave gyratory compactor to reach a void volume of 4%. Furthermore, the mixes had a dry appearance, as if they were missing binder. The content of 15% graphite powder was adopted based on the studies by [24]. To compare the healing results of the mixtures produced with both additions, the same contents of graphite powder were adopted in the additions with steel slag.

As for the two mixtures with steel fibers, they were named mixture FA and mixture FB. The FA mixture was produced with the addition of 0.2% of fibers out of the total weight of the mixture, and the FB mixture was produced with 0.4% of fibers out of the total weight of the mixture. The 0.2% content was adopted based on GALLEGO *et al.* [21] studies and the 0.4% content was adopted due to the higher proportion of fibers that did not allow the excessive formation of clusters, as well as the production of visually homogeneous mixtures. Mixtures with the addition of steel fibers were produced to verify if the use of this addition is more effective in healing in comparison to mixtures produced with steel slag or graphite powder. Table 2 shows the design of the seven evaluated mixtures, according to the total weight of the mixture.

2.2.2. Determination of the heating rate

The purpose of this stage was to determine the heating rate of the asphalt mixtures, which corresponds to the time required to heat a test specimen to a certain temperature. Therefore, it is possible to heat a test specimen in the microwave to a given temperature just by controlling the heating time. To achieve the objectives, the same procedures adopted by WANG *et al* [5] were followed, in which the specimens were heated for 120 seconds

Table 2: Design of the studied mixtures.

MIXTURE	C	SA	SB	GA	GB	FA	FB
Asphalt binder (%)	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Coarse and fine aggregate (%)	90.05	90.05	90.05	90.05	90.05	89.85	89.65
Filer fraction (%)	5.65	5.00	2.82	5.00	2.82	5.65	5.65
Steel slag (%)		0.64	2.82				
Graphite powder (%)				0.64	2.82		
Steel fiber (%)						0.2	0.4
Total (%)	100	100	100	100	100	100	100

in a microwave with a power of 700 W. Before and after heating, the surface temperature of the test specimen was recorded using a 640 × 480 pixel infrared camera, brand Flir and model C2. The images were transferred from the camera to a computer and processed using the FLIR Tools software [30] which allows the analysis of infrared images. The surface temperature was determined from the average of three points chosen at random on the surface of the specimen. This procedure was repeated in three specimens for each studied asphalt mixture, the result was given by the arithmetic average of the results obtained. At the end of this stage, it was possible to estimate the speed in degrees Celsius per second of heating the mixture.

2.2.3. Assessment of heating temperature on the self-healing index (HI)

The purpose of this stage was to determine which type and content of addition (steel slag, graphite powder and steel fibers) are more efficient in the healing process when the heating temperature of the mixtures was 50, 75, or 100°C, or when the mixture was not heated. Thus, eight test specimens were divided into four groups of two specimens. After that, each group was subjected, only once, to the following cycle: fatigue damage, heating of the sample in the microwave, resting period for three hours, and, lastly, fatigue damage, as illustrated in Figure 3. Corresponding to microwave heating, the four groups were heated until reaching a single temperature value, which was 50°C, 75°C, or 100°C. To provide a reference parameter, one of the groups was not subjected to heating and was kept at a room temperature of 25°C.

The generation of fatigue damage was carried out by applying tensile stresses by diametrical compression in cylindrical specimens. The specimens were previously heated at 25°C, in a UTM *(Universal Test Machine*) machine, from the IPC Global company. All the regulations from the European standard EN 12697-24 [31] were followed. The samples were subjected to cyclic loads, at the frequency of two load applications per second, i.e., 2 Hz. The test was finalized when the initial resilient modulus of the mixture reached a 50% reduction [6]. The level of tension applied to the test specimen during the test corresponded to 30% of the tensile strength.

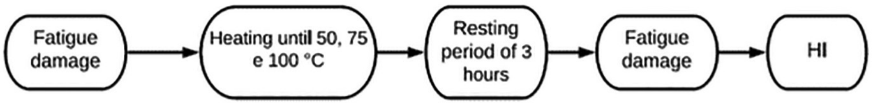

Figure 3: Diagram of the stages performed to assess temperature in the HI.

After completing the fatigue damage, the test specimen was heated in a microwave. The time was exactly the one necessary to reach the desired surface temperature (50°C, 75°C or 100°C). After heating, the test specimen was placed in a cylindrical metallic mold and left to rest for a period of three hours, to allow the closure of internal cracks and to allow the mixture to cool to a temperature of 25°C. The three-hour resting period was adopted based on the studies by ZHAO *et al.* [14] and ZHU *et al.* [6]. Considering that the test specimen tends to suffer from deformation after the heat process, the cylindrical mold was used to maintain the original specimen shape. Moreover, it also reproduced the confinement pressure of the asphalt mixture in real-life applications [6, 19].

After the resting period, the fourth stage, which corresponds to fatigue damage, was performed. The final criterion was the reduction of the test specimen resilient modulus by a value similar to that established in the first fatigue damage, which corresponds to a 50% reduction in the initial resilient modulus of the first test. After applying fatigue damage and healing cycles, the self-healing index (HI) was determined from the relationship between the number of fatigue damage load applications from the fourth stage and the number of fatigue damage load applications from the first stage, according to Equation 1 below [6]:

$$IR = \Delta C / C * 100 \quad (1)$$

Where: HI (%) is the self-healing index.

1. *C* is the number of fatigue damage load applications from the first stage that reduced the initial resilient modulus by 50%; and
2. *ΔC* is the number of fatigue damage load applications from the fourth stage that reduced the initial resilient modulus determined by the first fatigue damage activity by 50%.

2.2.4. Assessment of resting period on the self-healing index (HI)

To assess the effect of the resting period on the HI, the same procedure as in item 2.2.3 was performed. However, the resting period of the test specimens was changed to 24 hours [12, 16] instead of three, as was the heating temperature, being adopted as the one that allowed each mixture to reach the highest HI value, previously defined in item 2.2.3. Figure 4 illustrates the flowchart of the procedures performed to assess the effect of the resting period on the HI.

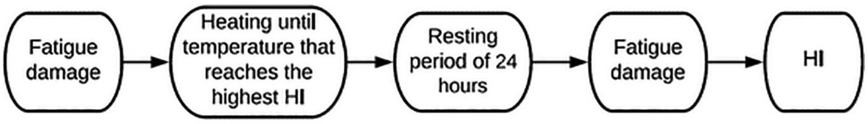

Figure 4: Diagram of the stages performed to assess the resting time in the HI.

3. RESULTS AND DISCUSSION

3.1. Determination of the heating rate

The results of the average heating rate are shown in Table 3. The table shows that all the additions, regardless of the content, presented a higher heating rate when compared to the control mixture C (0.34°C/s). The heating rate was higher in mixtures containing steel slag and graphite. Both additions were distributed evenly during the mixing process, which allows a more distributed heating. Additionally, during laboratory tests, it was observed that mixtures containing steel fibers reached a higher temperature in places where there was a higher concentration of fibers and a lower temperature in places in which there was a lack of steel fibers. Thus, samples with steel fibers took a little longer time to reach the desired temperature compared to mixtures containing slag or graphite powder.

The results demonstrate that the amount of 15% of slag out of the total weight of the binder is sufficient to obtain asphalt mixtures susceptible to microwave heating, since a greater amount does not lead to a significant increase in the heating rate. In the research of GALLEGO *et al.* [32], a steel slag fraction size of 0/2 mm was incorporated in quantities of 2%, 5%, 10% and 20% by weight of the mass of the bituminous mixture, for the production of mixtures susceptible to microwave heating, and the research concluded that a percentage at least 5% by weight of the mixture is sufficient to achieve the desired results. So, it may be observed that the most susceptible mixtures with steel slag to microwave energy are the ones containing between 5% and 15% of slag.

GALLEGO *et al.* [21] did not obtain a significant difference between the results of the temperature reached in asphalt mixtures containing the addition of 0.6%, 0.4% and 0.2% of steel fibers. Therefore, the conclusions obtained by the authors are the same as the present research, that the steel fiber in percentages of 0.2% over the mass of the asphalt mixture, is sufficient to achieve the desired results, as the susceptibility to the microwaves heating is not significantly less than that attained with higher percentages.

Table 3: Heating rate and time required to reach 50°C, 75°C and 100°C (superficial temperature of test specimens).

MIXTURE TYPE	RATE (°C/S)	HEATING TIME UP TO THE TEMPERATURE OF*		
		50°C	75°C	100°C
C	0.34	74	147	221
SA	0.40	63	125	188
SB	0.39	65	129	194
FA	0.38	66	131	197
FB	0.35	71	142	212
GA	0.39	65	129	194
GB	0.38	66	133	199

*The heating time is shown in seconds.

The same conclusions were obtained for the asphalt mixtures containing graphite powder, as contents greater than 15% did not significantly increase the asphalt mixture's susceptibility to microwaves. According to PAN *et al.* [33], quantities between 0% and 40% of graphite powder replacing the mineral filler fraction in asphalt binder increases the thermal conductivity, but this research demonstrated that there is a limited quantity of graphite powder in asphalt mixtures for significantly increasing the susceptibility to the microwaves heating.

3.2. Assessment of heating temperature on the self-healing index (HI)

Table 4 presents the HI results of the asphalt mixtures that were subjected to fatigue damage, heating, a three-hour resting period, and fatigue damage again. In Table 4, the highest HI results for each asphalt mixture that was effectively heated are highlighted in gray.

The results show that the SA, SB, FB, and GA mixtures, which did not undergo heating activity, achieved an HI above 40%, higher than the one obtained by the same mixtures when heated. One possibility for self-healing having occurred without heating after the resting period is related to the thixotropic phenomenon, which is different from the self-healing phenomenon. Thixotropy is characterized by a gradual reduction in viscosity under shear stress, followed by a gradual recovery when the stress is removed. It is the characteristic of asphalt materials to alter their microstructure, altering, in turn, their viscosity. Thus, during fatigue damage, there is a loss of stiffness due to such damage, but also due to microstructural changes that reduce asphalt viscosity. Afterward, during the resting period, the stiffness is recovered as a result of the return of the initial microstructures [34]. In this case, the thixotropic phenomenon of the mixtures assessed without heating, and which have in their composition the additions used, had a greater influence on self-healing than the heating effect.

In the mixtures with slag, disregarding the self-healing results of the mixtures without heating, it is concluded that the temperature of 75°C is the ideal one to promote a higher HI in the SA mixture; for the SB mixture, the temperature of 50°C was the one to promote a higher HI. In addition, it is observed that the SA mixture performed slightly better self-healing capacity than the SB mixture due to having a greater amount of asphalt available to flow between the microcracks; which is related to the lower presence of slag in its composition. Different from these results, it was also observed that the heating of the mixtures to 100°C did not promote a satisfactory HI for the SA and SB mixtures; in these, HI was less than 10%.

As for the mixtures with fibers, the heating of both mixtures, FA and FB, above 50°C did not result in a significant HI when compared with the results obtained when heating them at 50°C. Therefore, it can be concluded that the ideal temperature for these mixtures is 50°C. In Table 4, the FB mixture had a higher HI than the FA one when it was heated to 50°C; it is thus possible to conclude that additions of 0.4% of steel fibers favor greater self-healing than additions in the order of 0.2%. The best self-healing result in mixtures containing 0.4% of fibers is related to the fact that the mixture has a greater number of fibers distributed in its matrix, favoring heating in more internal regions of the asphalt mixture. This, in turn, promoted the fluidity of the asphalt to close the microcracks.

In mixtures with graphite powder, the heating temperature of 50°C was the most efficient for the self-healing of the GA mixture, since the increase in HI at a higher temperature was not so relevant. For the GB mixture, the heating temperature up to 75°C was the most effective for self-healing. In addition, the GB mixture showed a higher HI than the GA one, especially when heated up to 75°C. The better performance of the GB mixture at the self-healing level is due to its higher graphite content, which promoted internal heating in more regions than the GA mixture, making the asphalt flow and filling the microcracks caused by fatigue damage more easily. Thus, from the HI results of all the asphalt mixtures studied, it is concluded that the temperature range between 50°C and 75°C is the most efficient to promote self-healing.

Table 4: Average self-healing index of asphalt mixtures as a function of average surface temperature with a 3-hour resting period.

AVERAGE SURFACE TEMPERATURE	TYPE OF ASPHALT MIXTURE						
	C	SA	SB	FA	FB	GA	GB
Without heating	16.75%	49.40%	48.70%	1.5%	42.80%	71.30%	10.60%
Heating up to 50°C	0.02%	23.7%	24.00%	23.7%	39.47%	12.25%	13.90%
Heating up to 75°C	27.30%	31.8%	9.53%	28.7%	8.70%	12.40%	30.11%
Heating up to 100°C	15.90%	4.9%	4.90%	29.0%	22.59%	15.70%	1.50%

At this point, the GA mixture that did not undergo heating presented a very promising self-healing result, with an HI of 71.3%, which was the highest value among all the studied mixtures. For this situation, the hypothesis of the self-healing process from the heating of the asphalt mixture presented in this work would not apply, making it necessary to formulate other hypotheses and carry out additional tests that would allow a deeper assessment of the self-healing process of asphalt containing additions of graphite powder, without heating.

When comparing the three types of additions studied, steel slag, steel fibers and graphite powder, the highest HI results with a three-hour resting period were similar. The SA mixture presented an HI of 31.8%, the FB mixture one of 39.5%, and the GB mixture one of 30.1%; the difference between the values is just under 10%. Thus, it is possible to conclude that it is possible to achieve HI values in the order of 30% to 40%, approximately, with the appropriate use of these additions.

Regarding the fact that the HI did not reach values higher than 40%, it is possible that the damage applied during fatigue damage assessment, which had as a criterion for completion the reduction by 50% of the initial resilient modulus, was too aggressive. This fact was observed in the laboratory, where it was verified that several test specimens were deformed after the generation of fatigue damage. Thus, it can be presumed that the required level of the test caused damage to the mixtures that could not be self-healed during the heating and resting period.

In the research of LIU *et al.* [12], fatigue tests were stopped for healing when the resilient modulus of the sample decreased to 70% and 80% of its original value, respectively. In the case where the fatigue test was stopped for healing when the resilient modulus of the sample decreased to 70% of its original value, with 24 hours rest, only 23.05% of the damage was healed in the samples containing 10% steel wool. But, when the fatigue test was stopped when the resilient modulus had reduced to 80% of its original value, the damage in samples containing steel wool was completely healed.

3.3. Assessment of resting period on the self-healing index (HI)

Table 5 shows the results of the average self-healing index (HI) of the asphalt mixtures that were subjected to fatigue damage, heating, a 24-hour resting period, and fatigue damage again. In this case, the heating temperature used was the one that proved to be the most efficient to promote the self-healing of the asphalt mixture (Table 4). In addition, Table 5 shows the HI of the mixtures that had a three-hour resting period.

Some researchers adopted a 3-hour resting period [6, 14] and others adopted 24 hours [12, 16]. The results in the present research show that the HI of most of the mixtures that had a 24-hour resting period was higher than the one obtained for mixtures that had a 3-hour resting period. Therefore, it can be concluded that the longer the resting period, the higher the HI. In addition, the results of self-healing capacity about resting period contribute to the development of research on self-healing asphalt mixtures, since it is possible to conclude that the self-healing asphalt mixture after being subjected to an adequate temperature (obtained experimentally) should also be maintained at a long resting period. Therefore, after heating the asphalt mixture in the field, a certain period must be waited before releasing the road to traffic circulation.

It is also observed that the increase in HI did not follow a proportional trend for all the mixtures, since it is influenced by several factors: addition type, heating temperature, mixture heterogeneity, among others.

Finally, by analyzing the data obtained in this research and the practical experience acquired, it is possible to state that self-healing in asphalt mixtures is a complex process, as it requires an in-depth knowledge of

Table 5: Average self-healing index (HI) of asphalt mixtures with a resting period of 24 hours and 3 hours.

MIXTURE TYPE	TEMPERATURE (C°)	AVERAGE (MPA) – 24-HOUR RESTING PERIOD	AVERAGE (MPA) – 3-HOUR RESTING PERIOD
C	75	35.8%	27.3%
SA	75	36.7%	31.8%
SB	50	27.2%	24.0%
FA	75	47.3%	28.7%
FB	50	42.1%	39.5%
GA	50	54.4%	12.3%
GB	75	32.0%	30.1%

the viscoelastic behavior of asphalt and the difficult task of separating the effects of self-healing by heating from the effects of thixotropy. In this sense, few studies have been found on self-healing asphalt mixtures, many of which are recent, showing that the subject is innovative and needs to be further developed in several aspects.

4. CONCLUSIONS

The present study investigated the regenerative capacity of fatigue cracks in dense asphalt mixtures with asphalt binder 50/70, with and without the addition of steel fibers, steel slag and graphite powder. The influence of the heating temperatures of 50°C, 75°C and 100°C on the self-healing index (HI) was evaluated, as well as the effect of no heating and resting periods of 3 and 24 hours. Based on the results obtained, the main conclusions and considerations about this study are listed below:

- All asphalt mixtures studied that contained additions of steel fibers, steel slag and graphite powder were susceptible to microwave heating;
- The use of additions increases the heating rate of asphalt mixtures. In this case, steel slag and graphite powder additions can distribute themselves better in the mixtures and have the highest heating rate values;
- The HI of some mixtures containing additions that were not subjected to microwave heating was higher than the HI of the same mixtures when heated. The explanation for these results may be related to the thixotropy phenomenon of the asphalt binder;
- The ideal temperature for the self-healing of asphalt mixtures, heated by microwaves, is between 50 and 75°C; for these temperatures, it is possible to obtain HI values between 13% and 40%, approximately;
- In the case of steel slag mixtures, the use of 15% of the addition, out of the total binder weight, was more effective in the mixture self-healing than the use of 67.5%. This result was different in the case of graphite powder, as it was found that the use of a higher content of the addition was more effective for the mixture self-healing. For asphalt mixtures with steel fibers, the mixture containing 0.4% of added fibers showed a higher HI than the mixture with 0.2% of fibers;
- All studied mixtures had a higher HI when the resting period was 24 hours instead of three hours;
- For the assessment of HI, studies that induce microcracks by fatigue damage under diametral compression are suggested to limit the failure criteria for a reduction of the mixture's initial resilient modulus to percentages lower than 50%; this is to avoid excessive deformation of samples and the possibility that microcracks cannot self-heal after heating and resting.

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6. BIBLIOGRAPHY

[1] FRANESQUI, M.A., YEPES, J., GARCÍA-GONZÁLEZ, C., "Top-down cracking self-healing of asphalt pavements with steel filer from industrial waste applying microwaves", *Construction & Building Materials*, v. 149, pp. 612–620, 2017. doi: http://dx.doi.org/10.1016/j.conbuildmat.2017.05.161.

[2] GARCÍA, A., "Self-healing of open cracks in asphalt mastic", *Fuel*, v. 93, pp. 264–272, Mar. 2012. doi: http://dx.doi.org/10.1016/j.fuel.2011.09.009.

[3] GARCÍA, A., BUENO, M., NORAMBUENA-CONTRERAS, J., *et al*., "Induction healing of dense asphalt concrete", *Construction & Building Materials*, v. 49, pp. 1–7, 2013. doi: http://dx.doi.org/10.1016/j.conbuildmat.2013.07.105.

[4] CONTRERAS, J.N., GARCÍA, A., "Self-healing of asphalt mixture by microwave and induction heating", *Materials & Design*, v. 106, pp. 404–414, 2016. doi: http://dx.doi.org/10.1016/j.matdes.2016.05.095.

[5] WANG, H., APOSTOLIDIS, P., LIU, X., *et al*., "Laboratory test and numerical simulation of microwave heating properties of asphalt mixture", In: Loizos, A., Al-Qadi, I., Scarpas, T. (eds), Bearing Capacity of Roads, Railways and Airfields, London, CRC Press, 2017. doi: http://dx.doi.org/10.1201/9781315100333-30.

[6] ZHU, X., CAI, Y., ZHONG, S., *et al.*, "Self-healing efficiency of ferrite-filled asphalt mixture after microwave Irradiation", *Construction & Building Materials*, v. 141, pp. 12–22, 2017. doi: http://dx.doi.org/10.1016/j.conbuildmat.2017.02.145.

[7] SUN, Y., WU, S., LIU, Q., *et al.*, "Self-healing performance of asphalt mixtures through heating fibers or aggregate", *Construction & Building Materials*, v. 150, pp. 673–680, 2017. doi: http://dx.doi.org/10.1016/j.conbuildmat.2017.06.007.

[8] FRANESQUI, M.A., YEPES, J., GARCÍA-GONZÁLEZ, C., "Top-down cracking self-healing of asphalt pavements with steel filer from industrial waste applying microwaves", *Construction & Building Materials*, v. 149, pp. 612–620, 2017. doi: http://dx.doi.org/10.1016/j.conbuildmat.2017.05.161.

[9] AYAR, P., MORENO-NAVARRO, F., RUBIO-GÁMEZ, M.C., "The healing capability of asphalt pavements: a state of the art review", *Journal of Cleaner Production*, v. 113, pp. 28–40, 2016. doi: http://dx.doi.org/10.1016/j.jclepro.2015.12.034.

[10] CONTRERAS, J.N., SERPELL, R., VALDÉS VIDAL, G., *et al.*, "Effect of fibers addition on the physical and mechanical properties of asphalt mixtures with crack-healing purposes by microwave radiation", *Construction & Building Materials*, v. 127, pp. 369–382, 2016. doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.10.005.

[11] SUN, Y., LIU, Q.T., WU, S.P., *et al.*, "Microwave Heating of Steel Slag Asphalt Mixture", *Key Engineering Materials*, v. 599, pp. 193–197, 2014. doi: http://dx.doi.org/10.4028/www.scientific.net/KEM.599.193.

[12] LIU, Q., SCHLANGEN, E., VAN DE VEN, M., *et al.*, "Healing of porous asphalt concrete via induction heating", *Road Materials and Pavement Design*, v. 11, n. sup1, pp. 527–542, 2010. doi: http://dx.doi.org/10.1080/14680629.2010.9690345.

[13] HUANG, S., DI BENEDETTO, H., *Advances in asphalt materials road and pavement construction*, Reino Unido, Elsevier Ltd., 472 p., 2015.

[14] ZHAO, H., ZHONG, S., ZHU, X., *et al.*, "High-efficiency heating characteristics of ferrite-filled asphalt-based composites under microwave irradiation", *Journal of Materials in Civil Engineering*, v. 29, n. 6, pp. 04017007, 2017. doi: http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001845.

[15] MENOZZI, A., GARCIA, A., PARTL, M.N., *et al.*, "Induction healing of fatigue damage in asphalt test samples", *Construction & Building Materials*, v. 74, pp. 162–168, 2015. doi: http://dx.doi.org/10.1016/j.conbuildmat.2014.10.034.

[16] HUANG, M., HUANG, W., "Laboratory investigation on fatigue performance of modified asphalt concretes considering healing", *Construction & Building Materials*, v. 113, pp. 68–76, 2016. doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.02.083.

[17] CONTRERAS, J.N., CONCHA, J.L., "Self-healing of asphalt mixtures via microwave heating", In: *ISAP 2016 Symposium*, Jackson, United States, 2016, https://www.researchgate.net/publication/305847215_Self healing_of_asphalt_mixtures_via_microwave_heating, accessed in November, 2022.

[18] LIU, Q., SCHLANGEN, E., VAN DE VEN, M., *et al.*, "Evaluation of the induction healing effect of porous asphalt concrete through four point bending fatigue test", *Construction & Building Materials*, v. 29, pp. 403–409, Apr. 2012. doi: http://dx.doi.org/10.1016/j.conbuildmat.2011.10.058.

[19] LIU, Q., WU, S., SCHLANGEN, E., "Induction heating of asphalt mastic for crack control", *Construction & Building Materials*, v. 41, pp. 345–351, 2013. doi: http://dx.doi.org/10.1016/j.conbuildmat.2012.11.075.

[20] GARCÍA, A., CONTRERAS, J.N., PARTL, M.N., "A parametric study on the influence of steel wool fibers in dense asphalt concrete", *Materials and Structures*, v. 47, n. 9, pp. 1559–1571, 2013. doi: http://dx.doi.org/10.1617/s11527-013-0135-0.

[21] GALLEGO, J., DEL VAL, M.A., CONTRERAS, V., *et al.*, "Heating asphalt mixtures with microwaves to promote self-healing", *Construction & Building Materials*, v. 42, pp. 1–4, 2013. doi: http://dx.doi.org/10.1016/j.conbuildmat.2012.12.007.

[22] WANG, Z., DAI, Q., PORTER, D., *et al.*, "Investigation of microwave healing performance of electrically conductive carbon fiber modified asphalt mixture beams", *Construction & Building Materials*, v. 126, pp. 1012–1019, 2016. doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.09.039.

[23] PASETTO, M., BALDO, N., "Fatigue performance of asphalt concretes with RAP aggregates and steel slags", *RILEM*, v. 2012, pp. 719–727, 2012. doi: http://dx.doi.org/10.1007/978-94-007-4566-7_70.

[24] KÖK, B.V., YILMAZ, M., ERKUS, Y., "Effects of graphite on mechanical properties of stone mastic asphalt pavement", *Journal of Civil Engineering and Management*, v. 23, n. 8, pp. 1013–1020, 2017. doi: http://dx.doi.org/10.3846/13923730.2017.1374302.

[25] DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES, *DNIT 155/2010 ME: Material asfáltico – Determinação da penetração – Método de Ensaio*, Rio de Janeiro, DNIT, 2010.

[26] DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES, *DNIT 131/2010 ME – Materiais Betuminosos Líquidos e Semi-Sólidos – Determinação da Densidade e da Massa Específica – Método de Ensaio*, Rio de Janeiro, DNIT, 1996.

[27] DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES, *DNIT 193/1996 ME: Materiais Asfálticos – Determinação do Ponto de Amolecimento – Método do Anel e Bola – Método de Ensaio*, Rio de Janeiro, DNIT, 2010.

[28] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, *ABNT NBR 15184: Bituminous Materials – Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer*, Rio de Janeiro, ABNT, 2004.

[29] FEDERAL HIGHWAY ADMINISTRATION, National Highway Institute, *Superpave Fundamentals reference manual, FHWA-NHI-131053*, Washington, FHWA, 2000.

[30] FLIR SYSTEMS, *Software FLIR tools*, New York, FLIR Systems, Inc., 2016.

[31] COMISSÃO EUROPEIA DE NORMALIZAÇÃO, *EN 12697-24: 2018. Bituminous mixtures – Test methods. Part 24: Fatigue resistance*, Bruxelas, CEN, 2018.

[32] GALLEGO, J., DEL VAL, M.A., CONTRERAS, V., *et al*., "Use of additives to improve the capacity of bituminous mixtures to be heated using microwaves", *Materiales de Construcciónn*, v. 67, n. 325, pp. 110, Feb. 2017. doi: http://dx.doi.org/10.3989/mc.2017.00416.

[33] PAN, P., WU, S., XIAO, Y., *et al*., "Influence of graphite on the thermal characteristics and anti-aging properties of asphalt binder", *Construction & Building Materials*, v. 68, pp. 220–226, 2014. doi: http://dx.doi.org/10.1016/j.conbuildmat.2014.06.069.

[34] SUN, D., SUN, G., ZHU, X., *et al*., "A comprehensive review on self-healing of asphalt materials: Mechanism, model, characterization and enhancement", *Advances in Colloid and Interface Science*, v. 256, pp. 65–93, 2018. doi: http://dx.doi.org/10.1016/j.cis.2018.05.003. PubMed PMID: 29789126.