Trends in advanced sciences and technology

Trends in Advanced Sciences and Technology

Volume 1 | Issue 1 Article 8

2024

Producing Self-Healing Asphalt Pavement Mixture using Induction and Microwave Heating

Ahmed Abdelghani Mahmoud
Civil Engineering Department, Faculty of Engineering - Mataria, Helwan University, Cairo, Egypt, traffic_roads@yahoo.com

Catherine Gamil Shafik
Civil Engineering Department, Egyptian Russian University, Cairo, Egypt

Mohamed R. Elshahat
Civil Engineering Department, Egyptian Russian University, Cairo, Egypt

Abdelzaher E. A. Mostafa
Civil Engineering Department, Faculty of Engineering - Mataria, Helwan University, Cairo, Egypt

How to Cite This Article

Mahmoud, Ahmed Abdelghani; Shafik, Catherine Gamil; Elshahat, Mohamed R.; and Mostafa, Abdelzaher E. A. (2024) "Producing Self-Healing Asphalt Pavement Mixture using Induction and Microwave Heating," *Trends in advanced sciences and technology*: Vol. 1: Iss. 1, Article 8.
DOI: 10.62537/2974-444X.1010
Available at: https://tast.researchcommons.org/journal/vol1/iss1/8

ORIGINAL STUDY

Producing Self-healing Asphalt Pavement Mixture Using Induction and Microwave Heating

Ahmed Abdelghani Mahmoud [a,*], Catherine Gamil Shafik [b], Mohamed Rabah Elshahat [b], Abdelzaher Ezzeldeen Ahmed Mostafa [a]

[a] Department of Civil Engineering, Faculty of Engineering – Mataria, Helwan University, Cairo, Egypt
[b] Department of Civil Engineering, Egyptian Russian University, Cairo, Egypt

Abstract

Asphalt pavement is a common type of road construction worldwide. It provides excellent performance in terms of comfort, durability, and water resistance. Asphalt pavement roads are susceptible to different types of pavement distresses, which affects its service life. In addition, excessive use of nonrenewable materials and massive construction waste has a negative environmental impact. However, asphalt pavements' self-healing techniques decrease the need for frequent maintenance and repairs of cracks, making them more sustainable over time. Therefore, this paper aims to produce a sustainable asphalt pavement mixture, reduce maintenance costs, reduce the use of natural materials for road maintenance, and dispose of industrial waste. To achieve the above-mentioned goals, up to 20% electric arc furnace slag (EAFS) as a replacement of natural coarse aggregate, and three different percentages of steel wool fibers (SWF) were used to prepare asphalt mixtures. Mechanical properties such as Marshall stability, crack resistance, indirect tensile strength, and moisture resistance were studied. Also, thermal distribution was analyzed and the three-point bending test (TPB) was used to evaluate the self-healing efficiency. According to the results, EAFS has good wave absorption capability because it contains a lot of metal oxides. Using both EAFS and SWF in the asphalt mixture results in significant time and energy savings. Also, substituting 20% of natural coarse aggregate with EAFS and adding 0.2% SWF by weight of asphalt mixture is a promising approach. EAFS not only provides the best healing results, but it also improves the mixtures' mechanical properties. The use of EAFS in asphalt mixture is a notable solution that supports sustainable development.

Keywords: Electric arc furnace slag, Induction heating, Microwave radiation, Self-healing, Steel wool fibers, Sustainable asphalt pavement

1. Introduction and background

In recent years, there has been a growing interest in the construction of sustainable infrastructure (Mostafa et al., 2015, 2019). Asphalt mixtures have the highest use rate among pavement materials, making their sustainable application of utmost importance (Liu et al., 2023; Rafat Saad et al., 2023). Asphalt mixtures are subjected to various factors such as extreme environmental conditions and additional loads during use. To ensure that they reach their service life, maintenance treatment is usually necessary. Different asphalt mixes (virgin and RAP) are evaluated on skid resistance performance. Which is subjected to various environmental and contaminated conditions. Otherwise, if noticeable rutting or large-scale cracks appear, it will require significant repair or rehabilitation (Ding et al., 2020). Such an approach is not sustainable and can lead to waste of resource utilization and environmental harm. Therefore, it is crucial to develop long-lasting asphalt mixtures that are resource-efficient and environmentally friendly by designing suitable materials (Eraky et al., 2022; Fakhri et al., 2023).

The degradation of asphalt pavement is primarily attributed to the cracking caused by load and

---

Received 24 March 2024; revised 23 April 2024; accepted 1 May 2024.
Available online 13 June 2024

* Corresponding author at: Department of Civil Engineering, Faculty of Engineering, Mataria, Helwan University, Cairo, 13113, Egypt.
E-mail address: traffic_roads@yahoo.com (A.A. Mahmoud).

https://doi.org/10.62537/2974-444X.1010

temperatures (Etheridge et al., 2019; Youssef et al., 2023). At the initial stage of crack development, it is hard to detect small-scale cracks, and their impact on asphalt pavement is limited, which does not significantly affect its service life. However, over time, the cracks can expand and allow moisture to penetrate asphalt pavement, resulting in a reduction of its durability (Wang et al., 2022). This gradual process can decrease road pavement performance and, in turn, reduce the service life of asphalt pavement. Therefore, investigating alternative maintenance methods is essential for restoring asphalt pavement performance and prolonging its service life. This is crucial for economic and environmental reasons. One such method involves utilizing the self-healing properties of bituminous materials. Fortunately, asphalt materials have this ability, as it allows for the sealing of cracks and reduces their negative impacts (Yamaç et al., 2021).

The ability of a material to repair itself automatically over time is referred to as self-healing. This implies that during hot summers or extended periods of rest, asphalt concrete materials can repair themselves, resulting in an extension of the pavement's service life. The mechanism of asphalt materials' self-healing is like that of a zipper, which can be opened and then closed again (i.e., crack initiation and propagation and crack healing). The healing process involves microcracks repairing themselves under higher temperatures and/or rest periods, which serve as the driving forces behind the process. In both cases, the microcracks are repaired during the healing process (Behnia and Reis 2019).

Asphalt mixtures have a self-healing ability due to their viscoelastic characteristics (Schuster et al., 2023). The bitumen can infiltrate and dissolve in the cracks to reach the self-healing action of the asphalt mixture. Although asphalt mixture can naturally restore its mechanical properties to some extent, this process can last for more than a few hours or days. In addition, the actual traffic flow involves continuous loading, and the performance cannot be effectively restored (Nalbandian et al., 2022). To address this issue, many techniques have been evaluated by researchers to improve the self-repairing qualities of asphalt pavement and prevent further damage and crack propagation. These techniques involve the application of induced heating and microwave radiation (Moharam and Mostafa 2023).

In the induced heating technique, temperatures are a key factor that affects the self-healing of the asphalt mixture. Low temperatures significantly decrease the healing index of asphalt mixtures (Sun et al., 2019). However, at high temperatures, the fluidity of the bitumen increases, making it easier to close the microcracks that occur. This also helps in restoring the mechanical properties of the asphalt mixture (de Oliveira et al., 2022). Therefore, heating the asphalt mixture to accelerate the self-healing process is an effective method to extend the service life of the asphalt mixture. To this end, the application of external heating sources to heat asphalt mixtures has become increasingly popular. Various technologies, such as infrared radiation, induction heating coils, and microwave radiation, are available to accelerate the healing process of asphalt pavement. Out of these methods, induction heating coils and microwave heating are more commonly used. Although infrared radiation can be used as a solar radiation simulator, it is less efficient in inducing heating compared with coil and microwave radiation approaches (Karimi et al., 2021).

One of the first techniques for increasing the temperatures of asphalt pavement is the use of induction heating coils. This is accomplished by mixing electrically conductive materials within asphalt concrete and exposing the mixture to the coil's electromagnetic field. To create eddy currents and closed-loop circuits, electrically conducting materials must be present (Apostolidis et al., 2017; Sun et al., 2017).

In induced heating by microwave radiation technology, microwave-absorbing materials can convert microwaves into heat energy through the mechanisms of dielectric and magnetic loss (Kavussi et al., 2020). Some wastes, such as magnetite, steel wool fibers (SWF), and steel slag (SS), possess microwave-absorbing properties due to the presence of metal elements (Hasita et al., 2020). Steel slag, in particular, has gained attention in recent years due to its large output and potential for use in infrastructure construction (Gao et al., 2023). With its superior mechanical properties and alkaline characteristics, SS is used in road engineering. Therefore, it is completely possible to use the microwave-absorbing properties of SS to prepare steel slag asphalt mixture and enhance its sensitivity to microwaves.

In addition, the lightweight bitumen component of the rejuvenator agent can significantly rejuvenate aged bitumen and enhance the asphalt binder's self-healing properties (Ruiz-Riancho et al., 2021b). Recent studies have shown that oils such as vegetables, waste (vegetable, cooking, and mineral) (Yamaç et al., 2021), sunflower, and palm oils can promote self-healing of asphalt (Kargari et al., 2022). The capsules containing these oils need to be strong and impermeable, and the technique may reduce stiffness and promote rutting in asphalt (Ruiz-Riancho et al., 2021a).

The self-healing abilities of asphalt pavements are influenced by several factors due to their complex service environment. These factors can be divided into two main categories: internal and external factors. Internal factors include the constituents of the asphalt concrete, such as the properties of the bitumen, aggregate type, and gradation. External factors include physical damage such as crack width, crack density, damage level, and breaking temperatures. In addition, chemical changes caused by moisture, freeze—thaw cycles, and aging can also affect the self-healing abilities of asphalt pavements. Wu et al. (2019) reported that the mechanical properties and self-healing performance of asphalt mixtures are significantly weakened by UV (ultraviolet radiation), which has a negative impact on their macrostructural continuity. According to Shu et al. (2020), self-healing capacity is influenced by severe environmental factors such as acid rain and saline-alkali. Liang et al. (2021) conducted a review of the factors that influence the self-healing properties of asphalt mixtures. This study revealed that the ambient temperatures, humidity, and healing time are among the external factors that affect the self-healing properties of asphalt. Mirzamojeni et al. (2023) discovered that the self-healing capacity of asphalt is restricted by pavement depth and aging.

Also, previous studies have indicated that nanomaterials are used to improve the mechanical properties (Mostafa 2015, 2016) and moisture sensitivity (Mostafa et al., 2016, 2018) of asphalt pavement, as well as to enhance the quality and behavior of bitumen in diverse conditions (Naser et al., 2019). Furthermore, the utilization of polymer-modified asphalt cement (PMA) can effectively enhance the quality of asphalt cement (Nasser et al., 2017, 2018). This, in turn, leads to a direct improvement in its durability, and it can also increase the self-healing capacity of asphalt mixtures (Ganjei and Aflaki 2019). Cheng et al. (2022) discovered that the combination of nano-silica and styrene-butadiene-styrene (SBS) can significantly improve the self-healing ability of asphalt mixtures. According to Abbad El Andaloussi and Zaoui (2023) adding nano-silica to asphalt pavements improves its mechanical properties by more than 19% of its initial performance, extending the asphalt's lifetime.

The process of naturally healing macrocracks in the pavement is slow, but it can be accelerated through artificial induction, which can extend the pavement's service life. Sun et al. (2017) proposed that using microwave and induction heating, it is possible to heat both the fibers and aggregates to fix asphalt mixtures. According to Lou et al. (2020), metal waste can be effectively used for repairing asphalt mixtures through microwave heating. (Karimi et al. (2020) found that adding 0.2% SWF to asphalt mixtures can provide heating and crack healing with minimal adverse effects on its mechanical and rheological properties. Yang et al. (2022) and Liu et al. (2022a) have shown that utilizing industrial steel waste in road construction can decrease pollution and mitigate the negative effects of pavement cracks. Nalbandian et al. (2022) found that the self-healing technology induced by heat is a new and alternative method for maintaining asphalt pavements. Phan et al. (2018); Liu et al. (2022b) tried steel slag as a replacement for coarse aggregate with a percentage range of up to 30% from one or two sieve sizes and the results indicated that steel slag can increase the healing efficiency of the mixtures.

The main objective of this paper is to produce a sustainable asphalt pavement mixture using 20% electric arc furnace slag (EAFS) with different percentages of SWF. Studying the effects of microwave and induction heating on the ability of asphalt to self-healing, reduce maintenance costs, decrease the use of natural materials for road maintenance, and dispose of industrial waste.

2. Methodology

Based on the literature review and prior authors' experience, three different percentages of SWF—0.1%, 0.2%, and 0.3%—were tried with 20% EAFS by weight of the asphalt mixture. In this paper, the experimental program is described in six steps as follows:

(a) Step 1: Materials' Physical and Chemical Properties
(b) Step 2: Sample Preparation.
(c) Step 3: Mechanical Properties tests.
(d) Step 4: Self-Healing Performance.
(e) Step 5: Validation of Theoretical Healing Index.
(f) Step 6: Conclusion.

Table 1 illustrates the experimental program flowchart.

3. Patients' physical and chemical properties

Tables 2 and 3 show the physical properties of bitumen and natural aggregate, respectively. The gradations of the used aggregate are compatible with the Egyptian Code gradation 4C. Fig. 1 presented the gradation of conventional asphalt mixtures and 20% EAFS-modified mixtures including the allowable limits. SWF and EAFS were used as self-healing additive materials under induction and

Table 1. Experimental program flowchart.

	Materials physical and chemical properties						
Step 1	Aggregate (Natural aggregate + EAFS aggregate)	Los Angeles abrasion	(ASTM C131)		Penetration (0.01 mm)	ASTM D5-06	
		Bulk Density	(ASTM C127)	Bitumen (60/70)	Kinematic Viscosity (CST)	AASHTO T201	SWF
		Bulk SSD S. G					
		Apparent S. G			Softening point (°C)	ASTM D36	
		Absorption (%)					
Step 2	Sample Preparation (ASTM D6926-20)						
	Conventional asphalt mixtures	20EAFS + SWF modified asphalt Mixtures					
	CM	$Mix_{0.1}$		$Mix_{0.2}$		$Mix_{0.3}$	
	0% EAFS + 0% SWF	20% EAFS + 0.1% SWF		20% EAFS + 0.2% SWF		20% EAFS + 0.3% SWF	
	12 Sample	15 Sample		15 Sample		15 Sample	
Step 3	Mechanical Properties tests						
	Marshall stability	Indirect tensile strength	Tensile strength ratio	Marshall stability ratio		Fracture energy and fracture toughness	
	ASTM D6927-20	AASHTO T283	AASHTO T283	AASHTO T165		AASHTO TP105	
Step 4	Self-Healing Performance						
	Thermal distribution (Induction and microwave heating)			Healing index			
	Infrared thermometer (ANSI/ASHRAF 41.1–2020)			Three-point bending test (AASHTO TP105)			
Step 5	The validation of theoretical healing index						
Step 6	Conclusion						

Table 2. Bitumen 60/70 Physical properties.

Test	Specification	Results	Limits
Penetration (0.01 MM)	ASTM D5-06	67	60–70
Kinematic viscosity (CST)	AASHTO T 201	+369	+320
Softening point (°C)	ASTM D36	53	45–55

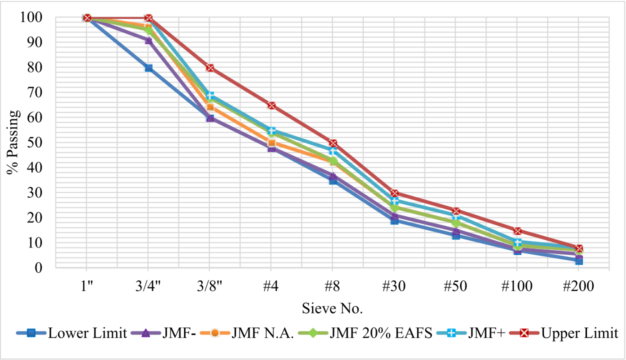


Fig. 1. Natural aggregate and 20% electric arc furnace slag gradation.

Table 4. Steel wool fibers properties.

Type	SWF
Average diameter	70–130 (μm)
Density	7.180 g/cm^3
Length	4–8 (mm)
Thermal conductivity	80 (W/m.K)

microwave heating. SWF properties are shown in Table 4. EAFS were provided by EZZ Steel company with a size range from 19 mm to 1.18 mm. EAFS was used as a replacement for natural coarse aggregate in asphalt mixtures with a percentage of 20% by weight of the mixture. Tables 5 and 6 present the chemical and physical properties of EAFS, respectively.

4. Results and discussion

4.1. Marshall stability test result

It has been previously demonstrated through research that by adding EAFS to an asphalt mixture, its stability is enhanced, while the addition of SWF reduces the stability of the mixture. The Marshall test results of the modified asphalt mixture with both additives showed that the impact of SWF on stability is more significant than that of EAFS. Therefore, in the mixture containing both 20%EAFS and varying contents of SWF, as the content of SWF increases, the stability decreases. However, $Mix_{0.1}$ has higher stability than the CM by 1.54%, $Mix_{0.2}$ has stability approximately equal to CM, while $Mix_{0.3}$ has lower stability than CM by 3.13%, as depicted in Fig. 2a. Fig. 2b and c present the flow and MQ results for 20%E + SWF modified mixtures, respectively. As illustrated in the figures, the flow of the 20%E + SWF modified mixture increases as the SWF contents increase, while the Marshall quotient (MQ) decreases as the SWF contents increase.

4.2. Volumetric properties

Figure 3a and c demonstrate the impact of increasing SWF content on the air void percentages (AV%) and the voids filled with bitumen (VFB%) of the asphalt mixture, respectively. The figures show that adding SWF to the conventional mixture (CM) increases the AV% of the mixture. Moreover, the AV % continues to increase as the percentage of SWF increases. However, adding SWF also increases VFB %. But, the VFB% decreases with an increase in the percentage of SWF. The maximum AV% of 4.875% was observed at 0.3% SWF, which falls within the acceptable limit range of the Egyptian code (3–5%). The SWF was expected to have a positive correlation with temperatures, which enhances the self-healing properties. It should be noted that VFB% represents the volume of free bitumen within the mixture, which is crucial for self-healing. When there is a higher VFB%, more free asphalt can flow and fill in cracks after being supposed to the heating source. Therefore, although higher SWF leads to higher heating efficiency, its negative impact on free asphalt should not be disregarded. This observation can explain why increasing the SWF content does not always improve HI.

The graph in Fig. 2b displays how the voids in mineral aggregate (VMA%) of asphalt mixtures

Table 3. Physical properties of natural aggregates.

Test	Specifications	(25–20) mm	(19–16) mm	Limits
Abrasion value (%) after 500 laps after washing		19.16	20.16	Not exceed 40%
Abrasion value (%) after 100 laps after washing	(ASTM C131)	4.2	5.06	Not exceed 10%
Bulk density		2.566	2.650	–
Bulk SSD S. G		2.612	2.684	–
Apparent S. G	(ASTM C127)	2.689	2.743	–
Absorption (%)		1.77	1.27	Not exceed 5%

Table 5. Electric arc furnace slag chemical properties.

MgO	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MnO	Na_2O	Cr_2O_3	V_2O_5	P_2O_5	TiO_2	K_2O
%	%	%	%	%	%	%	%	%	%	%	%	%
5.82	13.96	6.59	36.44	33.52	0.10	1.98	0.02	0.40	0.14	0.49	0.54	0.01

Table 6. Electric arc furnace slag physical properties.

Test	Specifications	EAFS 1	EAFS 2	Limits
Absorption (%)	(ASTM C127)	3.656	2.165	not exceed 5%
Bulk S.G		3.194	3.367	–
Bulk S.G (SSD)		3.311	3.440	–
Apparent S.G		3.616	3.632	–
Abrasion value (%) after 500 laps after washing	(ASTM C131)	20.2%	16.6%	Not exceed 40%
Abrasion value (%) after 100 laps after washing		4.4%	4.0%	Not exceed 10%

change as the SWF content increases. The data indicates that all SWF% had a lower VMA% than CM, and as the SWF percentage increased, the VMA% also increased. According to the Egyptian code, the minimum limit for VMA% is 13.2%, and all values in this paper meet this requirement. The consistent decrease in bulk density of mixtures is depicted in the graph presented in Fig. 2d, with an increase in SWF content. The chart clearly shows that $Mix_{0.1}$, $Mix_{0.2}$, and $Mix_{0.3}$ had a higher bulk density when compared with the CM. This increase is because the specific gravity of natural aggregates is lower than that of EAFS, leading to an overall increase in the bulk density of the modified mixtures.

4.3. Indirect tensile strength (ITS)

The indirect tensile strength test was carried out to determine the shear resistance of the CM and modified mixtures. As shown in Fig. 4, $Mix_{0.1}$ and $Mix_{0.2}$ exhibited greater shear resistance than CM by 4.5% and 1.1%, respectively, while $Mix_{0.3}$ displayed the lowest shear resistance as compared with CM by 2.0%.

4.4. Tensile strength ratio (TSR)

The resistance of asphalt mixtures to stripping can be assessed by measuring the decrease in the loss of

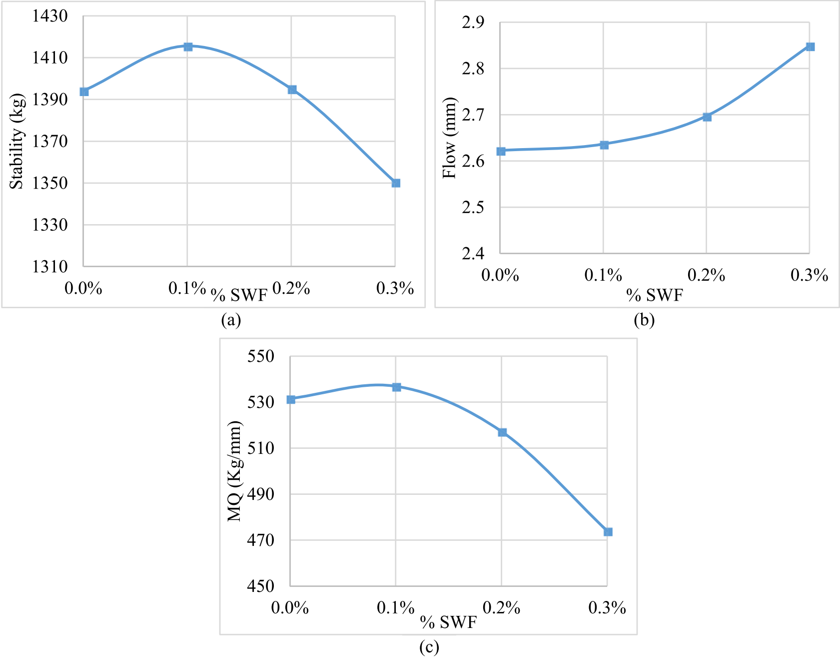
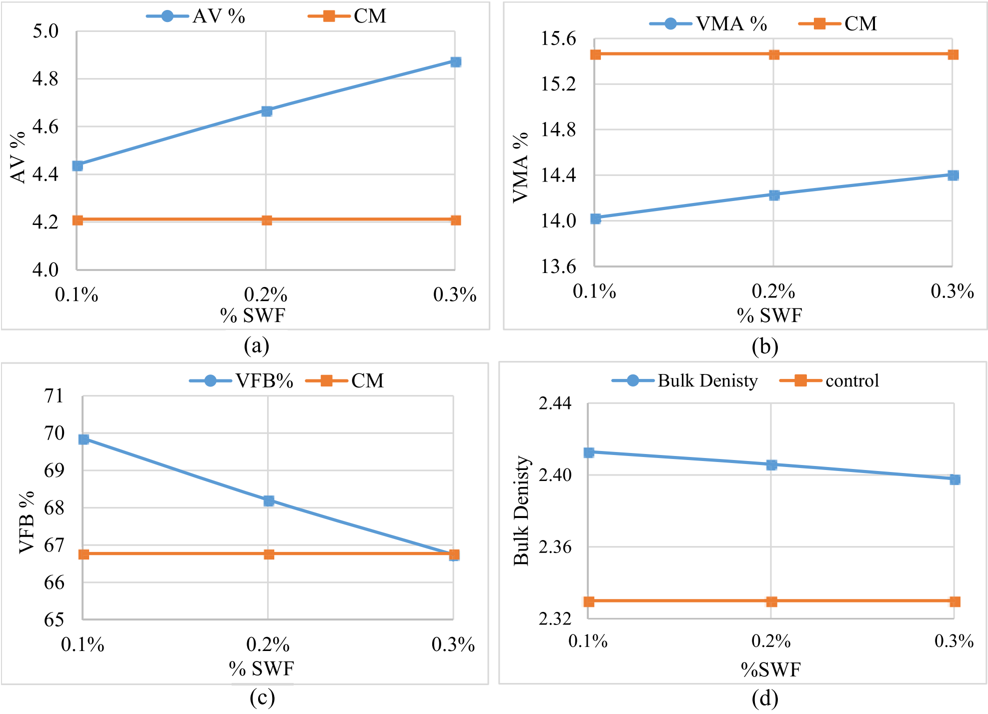


Fig. 2. Marshall test result for the 20 electric arc furnace slag + SWF modified mixture: (a) Marshall stability, (b) Marshall flow, and (c) Marshall quotient.



(a) (b)

(c) (d)

Fig. 3. 20 electric arc furnace slag + SWF modified mixture volumetric properties: (a) air voids, (b) voids in mineral aggregate, (c) voids filled with bitumen, and (d) bulk density.

indirect tensile strength (ITS). When water or moisture gets inside the asphalt mixture, it can create a buildup of pore pressure. If this pressure continues to build up, it will weaken the adhesive bond strength between the bitumen (bitumen—filler mastic) and aggregate, which can cause the development of microcracks in the asphalt mixture (Mostafa, 2005; Mostafa and El-desouky, 2015). For each mix, six samples were prepared, and the ITS and loss of ITS were measured. The ITS for the unconditioned case, ITS for the conditioned case, and TSR values for all mixtures are shown in Fig. 5. Fig. 5 shows that the TSR increases until 0.2% SWF and then decreases. Mix$_{0.2}$ has a maximum value of TSR of 91.69% which is higher than CM by 13%, while Mix$_{0.3}$ has a minimum value of TSR of 78.53% which is lower than CM by 3.2%. Mix$_{0.2}$ demonstrated the greatest stripping resistance, indicating improved adhesion bonding between the binders and aggregate.

4.5. Marshall stability ratio (MSR)

The impact of EAFS and steel wool fiber on the moisture stability of the asphalt mixture was evaluated using the immersion Marshall test. The

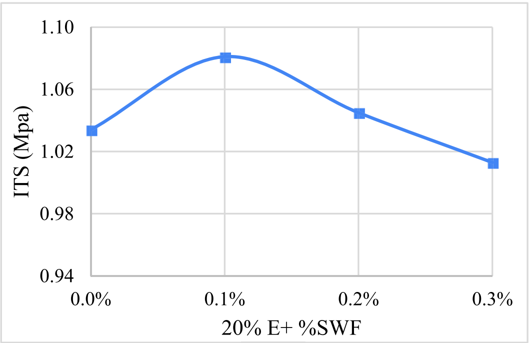


Fig. 4. 20 electric arc furnace slag + SWF modified asphalt mixtures' indirect tensile strength.

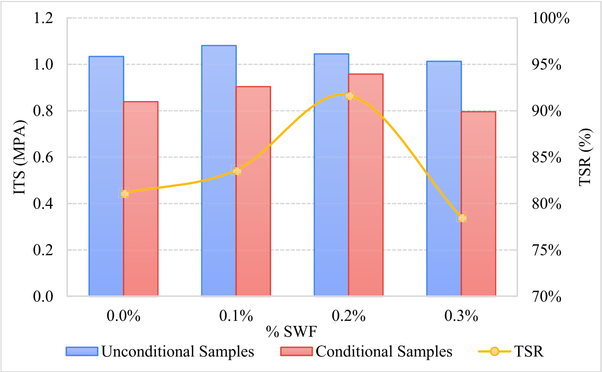


Fig. 5. 20 electric arc furnace slag + SWF modified asphalt mixtures' tensile strength ratio test results.

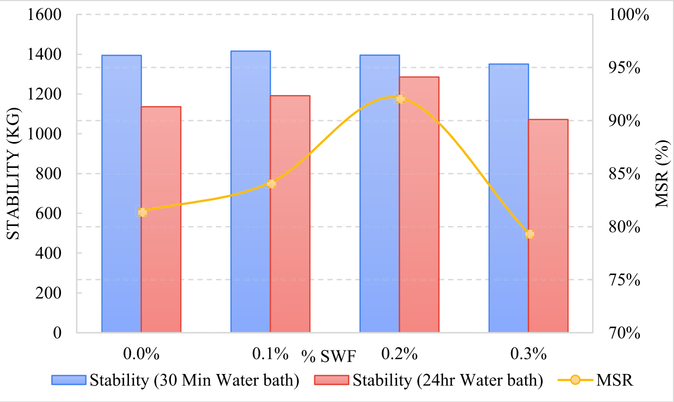


Fig. 6. 20 electric arc furnace slag + SWF modified asphalt mixtures' Marshall stability ratio.

residual Marshall stability for specimens after soaking in water at 60 °C for 24 h, known as the Marshall stability ratio (MSR), was measured. Fig. 6 displays the test results for various modified asphalt mixtures. The MSR% trend is comparable to that of TSR%. The MSR% increases until 0.2% SWF and then decreases. The MSR% of 92.15% was recorded by $\text{Mix}_{0.2}$, which is 13.1% higher than CM. Meanwhile, $\text{Mix}_{0.3}$ has a minimum TSR value of 78.53%, which is 2.5% lower than CM.

4.6. Fractural energy and fractural toughness

The fracture toughness results of the three-point bending test (TPB) at a temperature range of −10 to −15 °C for modified asphalt with 20%E + SWF are shown in Fig. 7a. According to the figure, the mixtures containing 0.1% and 0.2% SWF exhibit a fracture toughness that is 10% and 21.4% higher than the control mixtures, respectively. However, mixtures containing 0.3% of SWF show a fracture toughness that is almost the same as control mixtures. Therefore, an increase in the SWF content beyond 0.2% with 20% EAFS might lead to a decrease in the fracture toughness of mixtures. The impact of combining EAFS and SWF on the fracture energy is demonstrated in Fig. 7b. According to the results, the highest fracture energy is observed in mixtures containing 20% EAFS and 0.2% SWF when compared with the control mixture and other SWF percentages. However, the fracture energy values of mixtures with 0.1% and 0.3% SWF are almost identical to the control mixtures.

As discussed in the volumetric properties section, the addition of 20%E + SWF to the asphalt mixture caused an increase in AV% and a reduction in VFB %. It was observed that despite the fact that SWF caused a decrease in VFB%, it was still higher than the control mixtures, as illustrated in Fig. 6c.

A reduction in the VFB percentage may result in decreased cohesiveness and adhesion within the mixture. This, in turn, may cause the mixture to become more vulnerable to low-temperature cracking. Nevertheless, it has been observed that the addition of 0.1% and 0.2% of SWF can enhance the mixture's resistance to low-temperature cracking.

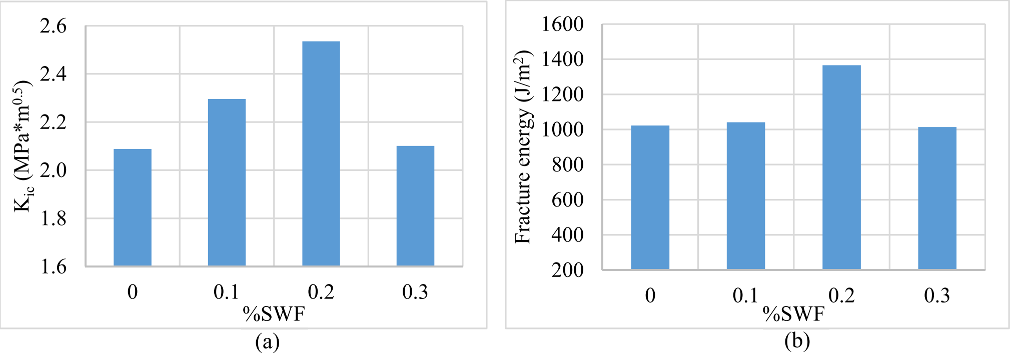


Fig. 7. (a) 20%E + SWF fracture toughness and (b) 20%E + SWF fracture energy.

The reason behind this improvement is the strengthening and toughening effects of SWF. In other words, while the decrease in VFB percentage can have an adverse effect on the mixture's adhesion and cohesion, the combined effects of SWF's reinforcement and toughening properties can bolster the mixture's resistance to low-temperature cracking.

4.7. Thermal distribution analysis

To achieve the best possible healing results, initial studies suggest that control of the surface temperatures at approximately 90 °C is necessary (Refaey et al., 2020). Therefore, an infrared thermometer was used to conduct a thermal test for each mixture and determine the required heating time. The time required to heat the control sample to 90 °C was 12 min using induction heating and 120 s using microwave heating. Fig. 8a and b show the modified asphalt mixture heating times for induction and microwave heating, respectively. The results showed that the modified mixtures reached the required temperatures faster than the control mixtures. In addition, the heating time decreased as the percentage of SWF increased.

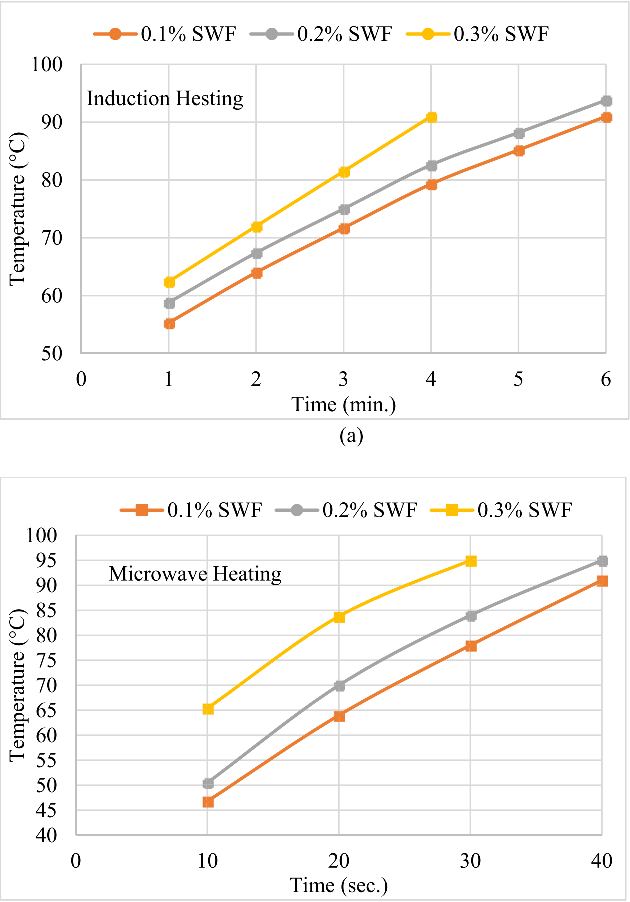


Fig. 8. 20% E + SWF thermal distribution analysis: (a) Induction heating and (b) microwave heating.

These results are explained by the presence of SWF which has a positive correlation with temperatures, and the fact that electric arc furnace slag has a high content of metallic elements. In addition, the oxygen percentage is also high, suggesting that these metallic elements exist in the form of oxides on the surface of the EAFS. Electric arc furnace slag comprises various metal oxides, including but not limited to MgO, SiO_2, Al_2O_3, Fe_2O_3, CaO, and others (as shown in Table 5). These metal elements increase the complex permittivity and loss angle, enhancing the electromagnetic wave absorption capacity of the mixture. In comparison to rock aggregate, steel slag has a higher thermal conductivity, which means that it cannot only be used as a wave-absorbing material to improve the microwave heating ability of steel slag asphalt mixture but also transfer heat rapidly to the surrounding aggregate. Significant reductions in time and energy consumption were observed for the 20% E + SWF-modified asphalt mixture, as compared with the CM. The percentage of reduction for induction heating and microwave heating is shown in Fig. 9.

4.8. Self-healing performance

The self-healing results of the modified mixtures for induction heating and microwave heating are presented in Fig. 10a and b. It can be observed from the graphs that the healing performance of the SWF mixture was superior and improved significantly by adding 20% EAFS as coarse aggregate, compared with the CM, for both induction heating and microwave heating. The healing index (HI) of the control samples subjected to induction heating after one loading cycle was only 52.27%. The HI further decreased to 31.42% after four loading cycles. Similarly, the HI of the control samples subjected to microwave heating after one loading cycle was 52.39%, which decreased to 31.84% after four loading cycles. These results indicate the poor self-healing capabilities of the control mixtures. Both induction and microwave heating restored the self-healing ability of the $Mix_{0.1}$ and $Mix_{0.2}$ samples to above 70% until the fourth cycle, while the self-healing ability of the $Mix_{0.3}$ was restored to above 65%.

Based on the results of the TPB test, it was found that $Mix_{0.2}$ has the best healing performance for both induction heating and microwave heating. For $Mix_{0.2}$ and after the fourth cycle, the healing

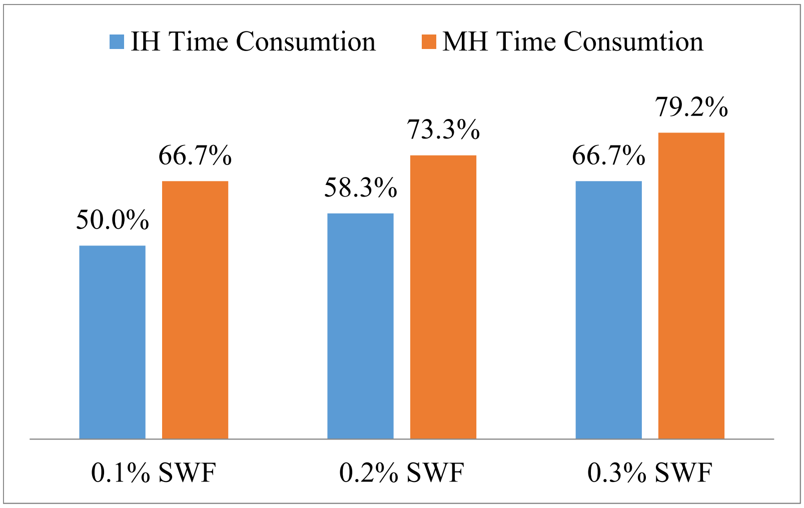


Fig. 9. 20% E + SWF time and energy consumption.

performance for induction heating was a~81.75%, which is 2.62 times higher than the control mixtures. However, the healing performance for microwave heating was ~80.57%, which is 2.53 times higher than the control mixtures. It is believed that the improved healing performance is due to the high thermal conductivity of EAFS compared with rock aggregate, the ability of EAFS to transfer heat rapidly to the surrounding aggregate, and steel slag particles are more sensitive to microwave radiation.

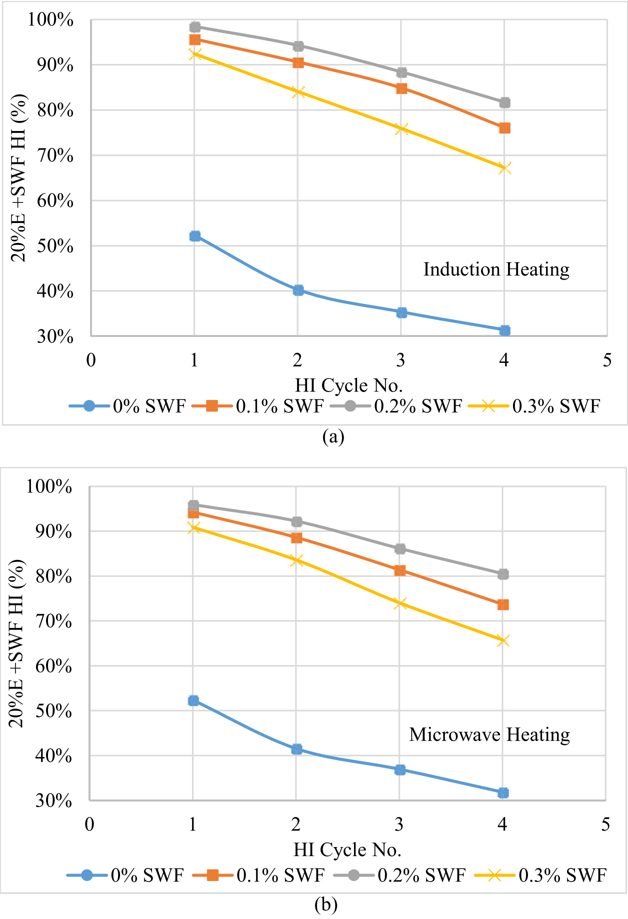


Fig. 10. 20%E + SWF healing index: (a) induction Healing and (b) microwave healing.

5. Validation of the theoretical healing index

The table below displays the equations from Fig. 10a and b that can be used to predict the healing index for $Mix_{0.2}$, as the number of healing cycles increases. To verify the accuracy of these equations, an additional healing cycle was conducted. The healing index value obtained from the laboratory test was compared with the healing index value obtained from the equation. The validity percentage of the relationship between Cycle No. and HI was then calculated as the ratio between the healing index value obtained from the equation and the one obtained from the laboratory test as shown in Table 7. Based on the results, the relationship validity was high in both cases (induction and microwave heating), indicating that the equations used for these calculations are valid and can be applied Table 8.

Table 7. HI expected equations.

Mixture	Equation	R^2
$Mix_{0.2}$ IH	$y = -0.006x^2 - 0.025x + 1.016$	1.000
$Mix_{0.2}$ MH	$y = -0.005x^2 - 0.028x + 0.994$	0.997

Table 8. Equations' validity.

% Of additives	Experimental	Theoretical	Validity	Error
$Mix_{0.2}$ IH	73.60%	74.10%	100.68%	−0.68%
$Mix_{0.2}$ MH	73.06%	72.90%	99.78%	0.22%

5.1. Conclusion

The findings of this research can be summarized as follows:

(a) It is valid to use up to 20% coarse EAFS as an alternative to natural aggregate to enhance both the mechanical properties and the healing process of asphalt mixtures through the methods of induction heating and microwave heating.
(b) Adding 20% EAFS with 0.1% and 0.2% SWF contents increased the mixture TSR and MSR, indicating improvement in adhesion bonding between the binders and aggregate, while 0.3% SWF had the opposite effect.
(c) Steel wool fiber percentage of up to 0.2% can enhance the mixtures' resistance to cracking, as SWF toughens and strengthens the mixture.
(d) The TPB specimens showed the highest fracture energy and fracture toughness at low temperatures when the SWF content was at 0.2%. This value was 33.53% higher for fracture energy and 21.44% higher for fracture toughness than the CM.
(e) Significant time and energy consumption savings can be achieved by incorporating both EAFS and SWF into the asphalt mixtures.
(f) The healing index for mixtures containing both EAFS and SWF was greater than 65% after four cracking–healing cycles. Among all SWF contents, the mixtures containing 20% EAFS and 0.2% SWF produced the best healing performance.
(g) For all mixtures, the improvement in the healing index is nearly the same in value but it depends on the duration of heating. For $\text{Mix}_{0.2}$ 80% improvement in the healing index takes 35 s in the case of microwave, while it takes 5 min in the case of induction heating.
(h) Healing index equations for both microwave and induction heating are valid to apply with errors 0.22%, and 0.68%, respectively.

5.2. Future work

1. Utilization of EAFS aggregate can benefit the environment and reduce the amount of natural resources in highway construction. However, rutting should be studied to fully evaluate the performance of such mixtures. Also, the resilient modulus (Mr) should be studied to analyze the stiffness of mixtures with loading–healing cycles.
2. The self-healing properties of induction and microwave heating need to be further verified by actual roads.

Funding

We confirm that all the work is done by the authors and no external funds were provided by any organizations.

Author contributions

Prof. Abdelzaher E. A. Mostafa: Supervision, Conceptualization, Methodology, Validation, Reviewing and Editing **Dr. Ahmed Abdelghani Mahmoud:** Supervision, Methodology, Validation, Reviewing and Editing **Dr. Mohamed Rabah Elshahat:** Supervision, Methodology, Validation, Reviewing and Editing **Catherine Gamil Shafik:** Conceptualization, Methodology, Formal analysis, Writing - Review & Editing.

Ethics information

Ethics approval and consent to participate not applicable.

Conflicts of interest

We have no conflicts of interest to disclose.

All authors declare that they have no conflicts of interest.

Acknowledgments

First of all, I am most grateful to ALLAH who has guided me on this journey, and only with His aid that I have completed this work.

Each of the members of my Dissertation Committee has provided me with extensive personal and professional guidance and taught me a great deal about both scientific research and life in general.

I would extend special thanks to Prof. Abdelzaher E. A. Mostafa, Professor of Highway and Airport Engineering. As my teacher and mentor, he has taught me more than I could ever give him credit for. He has shown me, by his example, what a good scientist (and person) should be, and deep thanks to him, for his guidance, and indispensable help during the preparation of this paper.

A special acknowledgement to Dr. Mohamed Rabah, Assistant Professor of Highway and Airport Engineering for his support and for sharing his expertise with me in the development and improvement of this work.

I would like to express my gratitude to Dr. Ahmed Abdelghany, Assistant Professor of Road and Airport Engineering for his motivation and guidance that continuously improved my knowledge and understanding.

Sincere appreciation is due to the Laboratory of Highway and Airport Engineering, Mataria, Helwan University and Egyptian Russian University.

Nobody has been more important to me in the pursuit of this work than the members of my family. I would like to thank my parents and my sister, whose love and guidance are with me in whatever I pursue. They are my ultimate role models.

References

Abbad El Andaloussi, N., & Zaoui, A. (2023). Enhancing mechanical and self-healing properties of asphalt binder through the incorporation of nano-silica. *International Journal of Pavement Research and Technology, 16*, 1–14.

Apostolidis, P., Liu, X., Kasbergen, C., Scarpas, A. T., & Van De Ven, M. (2017). Toward the design of an induction heating system for asphalt pavements with the finite element method. *Transportation Research Record, 2633*, 136–146.

Behnia, B., & Reis, H. (2019). Self-healing of thermal cracks in asphalt pavements. *Construction and Building Materials, 218*, 316–322.

Cheng, P., Zhang, Z., Yang, Z., & Li, Y. (2022). Evaluation of self-healing performance and mechanism analysis of nano-montmorillonite-modified asphalt. *International Journal of Pavement Research and Technology, 15*, 876–888.

de Oliveira, L. S., Lucas Júnior, J. L. O., Babadopulos, L. F. A. L., & Soares, J. B. (2022). Stiffness and fatigue evaluation in cyclic tests with rest periods for asphalt mixtures with or without fly ash. *Construction and Building Materials, 322*(December 2021): 126426.

Ding, X., Ma, T., Gu, L., & Zhang, Y. (2020). Investigation of surface micro-crack growth behavior of asphalt mortar based on the designed innovative mesoscopic test. *Materials & Design, 185*:108238.

Refaey, M. El, Zakaria, M., Zahw, M., & Eltahan, M. (2020). Self-healing of asphalt mixtures via microwave heating. *Al Azhar Uni Civil Eng Res Magazine (CERM), 42*, 36–46.

Eraky, A., Ayoub, H. S., Osman, O., Ouf, M. E., & Mostafa, A. Z. E. A. (2022). Improving the performance grade and traffic loading of egyptian asphalt binders by recycled polyethylene modification. *IOP Conference Series: Earth and Environmental Science*, 1056.

Etheridge, R. A., Wang, Y. D., Kim, S. S., & Kim, Y. R. (2019). Evaluation of fatigue cracking resistance of asphalt mixtures using apparent damage capacity. *Journal of Materials in Civil Engineering, 31*, 11.

Fakhri, M., Javadi, S., Norouzi, M. A., Bahmai, B. B., & Karimi, M. M. (2023). The induced heating–healing of inductive warm-mix asphalt mixture containing copper-slag filler. *Journal of Materials in Civil Engineering, 35*:04023039.

Ganjei, M. A., & Aflaki, E. (2019). Application of nano-silica and styrene-butadiene-styrene to improve asphalt mixture self healing. *International Journal of Pavement Engineering, 20*, 89–99.

Gao, W., Zhou, W., Lyu, X., Liu, X., Su, H., Li, C., & Wang, H. (2023). Comprehensive utilization of steel slag: A review. *Powder Technology, 422*(March):118449.

Hasita, S., Suddeepong, A., Horpibulsuk, S., Samingthong, W., Arulrajah, A., & Chinkulkijniwat, A. (2020). Properties of asphalt concrete using aggregates composed of limestone and steel slag blends. *Journal of Materials in Civil Engineering, 32*, 1–7.

Kargari, A., Arabani, M., & Mirabdolazimi, S. M. (2022). Effect of palm oil capsules on the self-healing properties of aged and unaged asphalt mixtures gained by resting period and microwave heating. *Construction and Building Materials, 316*(February 2021):125901.

Karimi, M. M., Darabi, M. K., Jahanbakhsh, H., Jahangiri, B., & Rushing, J. F. (2020). Effect of steel wool fibers on mechanical and induction heating response of conductive asphalt concrete. *International Journal of Pavement Engineering, 21*, 1755–1768.

Karimi, M. M., Amani, S., Jahanbakhsh, H., Jahangiri, B., & Alavi, A. H. (2021). Induced heating-healing of conductive asphalt concrete as a sustainable repairing technique: A review. *Cleaner Engineering and Technology, 4*(June).

Kavussi, A., Karimi, M. M., & Ahmadi Dehaghi, E. (2020). Effect of moisture and freeze-thaw damage on microwave healing of asphalt mixes. *Construction and Building Materials, 254*:119268.

Liang, B., Lan, F., Shi, K., Qian, G., Liu, Z., & Zheng, J. (2021). Review on the self-healing of asphalt materials: Mechanism, affecting factors, assessments and improvements. *Construction and Building Materials, 266*:120453.

Liu, J., Zhang, T., Guo, H., Wang, Z., & Wang, X. (2022a). Evaluation of self-healing properties of asphalt mixture containing steel slag under microwave heating: Mechanical, thermal transfer and voids microstructural characteristics. *Jof Cleaner Production, 342*(January):130932.

Liu, J., Zhang, T., Guo, H., Wang, Z., & Wang, X. (2022b). Evaluation of self-healing properties of asphalt mixture containing steel slag under microwave heating: Mechanical, thermal transfer and voids microstructural characteristics. *Journal of Cleaner Production, 342*(September 2021):130932.

Liu, J., Wang, Z., Jing, H., Zhang, T., Wang, X., Zhou, X., & Xu, X. (2023). Self-healing properties of steel slag asphalt mixture based on experimental characterization and 3D reconstruction. *Materials & Design, 234*(September).

Lou, B., Sha, A., Li, Y., Wang, W., Liu, Z., Jiang, W., & Cui, X. (2020). Effect of metallic-waste aggregates on microwave self-healing performances of asphalt mixtures. *Construction and Building Materials, 246*:118510.

Mirzamojeni, M., Aghayan, I., & Behzadian, R. (2023). Evaluation of field aging effect on self-healing capability of asphalt mixtures. *Construction and Building Materials, 369*(February): 130571.

Moharam, O., & Mostafa, A. (2023). Improving life cycle of asphalt pavement mixture using Self-Healing Technique. *Journal of International Society for Science and Engineering, 5*(3), 63–72.

Mostafa, A. E. A. (2005). *The Stripping Susceptibility of Airfield Asphalt Mixes: The Development of Guidelines for a Laboratory Test Method (Issue February)*.

Mostafa, A. E. A. (2015). Studying the effect of using nano-materials on the performance of cold recycled asphalt pavement mixes. *International Journal of Advanced Engineering and Nano Technology (IJAENT), 1*, 1–6.

Mostafa, A. E. A. (2016). Examining the performance of hot mix asphalt using nano-materials. *IOSR Journal of Engineering (IOSRJEN), 6*, 2–25.

Mostafa, A. E. A., & El-desouky, A. (2015). Validating newly developed criteria of stripping prediction using egyptian mixes. *International Journal of Advanced Engineering and Nano Technology (IJAENT), 11*, 7–12.

Mostafa, A. E. A., Ouf, M. S., & Jamal, A. (2015). Developing an environmentally sustainable hot mix asphalt using recycled concrete aggregates. *Journal of Engineering Research and Applications, 5*, 1–6.

Mostafa, A. E. A., Tawhed, W. M. F., & Elshahat, M. R. (2016). Performance assessment of asphalt pavement mix modified by nano-silica and nano-clay. *International Journal of Advanced Engineering and Nano Technology (IJAENT), 3*, 3.

Mostafa, A. E. A., Tawhed, W. M. F., Elshahat, M. R., & Sherif, A. G. (2018). Developing New Design Criteria of

Asphalt Pavement Mix Using Nano-Materials and Polymer-Materials. *International Journal of Advanced Engineering and Nano Technology (IJAENT), 4*, 335–347.

Mostafa, A. E. A., Ouf, M. S., & Elkerdany, M. M. (2019). Development of Sustainable Asphalt Pavement Mixture Using Polymers and Waste Engine Oil. *International Journal of Scientific Engineering and Research, 10*, 10.

Nalbandian, K. M., Carpio, M., & González, Á. (2022). Assessment of the sustainability of asphalt pavement maintenance using the microwave heating self-healing technique. *Journal of Cleaner Production, 365*(June).

Naser, A. M., Abd El - Wahab, H., Moustafa El Nady Maef, E. A., Mostafa, A., Lin, L., & Sakr, A. G. (2019). Preparation and characterisation of modified reclaimed asphalt using nano-emulsion acrylate terpolymer. *Pigment & Resin Technology, 48*(0), 363–374.

Nasser, A. M., El-wahab, H. A., El-fattah, M. A., Mostafa, A. E. A., & Sakr, G. (2017). Study on modification of reclaimed asphalt pavements by using some acrylate polymers. *Al Azhar Bulletin of Science, 28*(Issue 1-A), 31–41.

Nasser, A. M., Abd El-Wahab, H., Abd El-Fattah, M., Mostafa, A. E. A., & Sakr, A. G. (2018). Preparation and characterization of modified reclaimed asphalt by using styrene – Butyl acrylate nanoemulsioncopolymer. *Egyptian Journal of Chemistry, 61*, 269–380.

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*, 503–511.

Rafat Saad, E., Salah Eldeen, Z., & Ezzeldeen, Ahmed Mostafa A. (2023). Development of sustainable asphalt pavement mixture using recycled concrete aggregate, crumb rubber and waste engine oil. *Engineering Research Journal, 180*, 39–58.

Ruiz-Riancho, N., Garcia, A., Grossegger, D., Saadoon, T., & Hudson-Griffiths, R. (2021a). Properties of Ca-alginate capsules to maximise asphalt self-healing properties. *Construction and Building Materials, 284*:122728.

Ruiz-Riancho, N., Saadoon, T., Garcia, A., Grossegger, D., & Hudson-Griffiths, R. (2021b). Optimisation of self-healing properties for asphalts containing encapsulated oil to mitigate reflective cracking and maximize skid and rutting resistance. *Construction and Building Materials, 300*:123879.

Schuster, L., Staub de Melo, J. V., & Villena Del Carpio, J. A. (2023). Effects of the associated incorporation of steel wool and carbon nanotube on the healing capacity and mechanical performance of an asphalt mixture. *International Journal of Fatigue, 168*(September 2022).

Shu, B., Wu, S., Dong, L., Norambuena-Contreras, J., Li, Y., Li, C., et al. (2020). Self-healing capability of asphalt mixture containing polymeric composite fibers under acid and saline-alkali water solutions. *Journal of Cleaner Production, 268*: 122387.

Sun, Y., Wu, S., Liu, Q., Zeng, W., Chen, Z., Ye, Q., & Pan, P. (2017). Self-healing performance of asphalt mixtures through heating fibers or aggregate. *Construction and Building Materials, 150*, 673–680.

Sun, G., Sun, D., Guarin, A., Ma, J., Chen, F., & Ghafooriroozbahany, E. (2019). Low temperature self-healing character of asphalt mixtures under different fatigue damage degrees. *Construction and Building Materials, 223*, 870–882.

Wang, X., Liu, J., Wang, Z., Jing, H., & Yang, B. (2022). Investigations on adhesion characteristics between high-content rubberized asphalt and aggregates. *Polymers, 14*, 24.

Wu, S., Ye, Y., Li, Y., Li, C., Song, W., Li, H., Li, C., Shu, B., & Nie, S. (2019). The effect of UV irradiation on the chemical structure, mechanical and self-healing properties of asphalt mixture. *Materials, 12*, 15.

Yamaç, Ö. E., Yilmaz, M., Yalçõn, E., Kök, B. V., Norambuena-Contreras, J., & Garcia, A. (2021). Self-healing of asphalt mastic using capsules containing waste oils. *Construction and Building Materials, 270*.

Yang, C., Wu, S., Xie, J., Amirkhanian, S., Liu, Q., Zhang, J., et al. (2022). Enhanced induction heating and self-healing performance of recycled asphalt mixtures by incorporating steel slag. *Journal of Cleaner Production, 366*(July).

Youssef, G.,E. A., Mostafa, A., Ouf, M., & M Wahby, A. (2023). Analysis of pavement distresses using the image processing technique for Egyptian roads. *The Egyptian International Journal of Engineering Sciences and Technology*.