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Comparative evaluation of (external oven and microwave induction) heating influence on healing mode and flow number (FN) of asphalt concrete (AC)

Saad Issa Sarsam*

ABSTRACT

Asphalt cement is a viscoelastic material and has self-healing abilities due to its viscous part. The interaction between fatigue and self-healing influences the fatigue life of asphalt concrete (AC). An attempt has been made in this work to evaluate and compare the influence of external oven and microwave induction heating on the mode of healing, permanent deformation (PD), and flow number (FN) of AC, while two sets of AC Marshall specimens were prepared with optimum binder requirement; the first set is denoted as the control while the second set is prepared with 5 % of iron slag. Specimens were subjected to fatigue under dynamic indirect tensile stress (DITS) until the stiffness declined to 50 % of its original value. Specimens were subjected to healing using two heating modes, (external oven and microwave induction) heating, then tested for fatigue using DITS. The variation in PD and FN among the healing modes between the control and the iron slag-treated specimens are analyzed and modeled. It was observed that implementation of iron slag has increased the FN by (four and nine) folds, and declined the PD by (37.5, and 50) % after practicing the healing with (microwave induction and external oven) heating respectively. External oven heating exhibited a lower PD healing index for control and iron slag-treated AC mixtures. However, implementation of 5 % iron slag exhibited lower healing index in general as compared with the control AC mixture. The obtained power regression mathematical models with high coefficients of determination can be implemented for fast and preliminary prediction of the expected PD within the limitations of the investigated material ranges and testing conditions when practicing the healing process.

Keywords: Healing; Asphalt Concrete; Deformation; Induction Heating; slag; external heating; Flow number, Microwave.

1. INTRODUCTION

Asphalt cement binder is a high viscous material with fluidity properties under hot environment, it has the ability of self-healing to repair micro-cracks of AC pavement by itself, and thus prolonging the service life of the pavement. Incorporating

conductive metals into AC mixtures can support sustainable infrastructure, enable inductive heating, and enhance the self-healing capability. Healing of cracked AC mixture by heating is considered an effective pavement maintenance strategy in recent times. Self-healing AC as a new approach as the road material can repair its own cracks with minimal intervention. It was stated that the most promising technologies for self-healing are induction healing, and microcapsule-based healing. The mechanisms of healing, and the design of microcapsules were reviewed. It was concluded that induction heating systems can recover 71 to 92 percent of fatigue life. In comparison, microcapsule systems can recover 71 to 90 percent of the original tensile strength and close 76 to 93 percent of crack width.

Boutgoulla et al, (2026) examined the induced self-healing potential of AC mixtures with varying black steel mill slag contents. It was observed that the high healing rate could be achieved, showing recovery of the initial indirect tensile strength while microwave heating exhibited mechanical integrity of the mixture. It was concluded that 20 % slag significantly enhanced microwave absorption and heating efficiency and it was recommended as cost-effective and sustainable approach to prolong AC pavement service life, promote environmentally friendly road rehabilitation and reduce maintenance costs. Shu et al, (2026) developed a modified healing model by simplifying the indirect tensile fatigue-healing test. A fatigue life prediction method considering healing parameters was established within the asphalt fracture mechanics framework. The results showed that the normalized healing rate serves as a measure of self-healing degradation during fatigue. It was concluded that the logarithm of the predicted fatigue life varied linearly with temperature. Incorporating healing parameters could improve the fatigue life prediction accuracy when compared with conventional models that used fixed healing parameters. Li et al, (2025) selected steel slag to enhance microwave heating performance in AC. It was stated that heating AC mixture with the aid of microwave is a sophisticated technique suitable for flexible pavement facility maintenance while it is effectively enhancing the self-healing of cracks in AC. Findings demonstrated that optimization of steel slag distribution and content can improve the self-healing performance and exhibits a healing efficiency of 79.62 %.

Chen et al, (2025) used steel slag which is considered as low-carbon and eco-friendly building material for partial replacement of the aggregate in AC to enhance its microwave absorption ability. Fatigue-healing test was conducted, and the rest duration, healing temperature and damage degree were assessed. Healing index [ratio of fatigue load cycles after healing, to fatigue load cycles before healing] was verified. It was observed that the healing rate declined gradually as the residual bending stiffness modulus increases, it initially increased and then declined with healing temperature and increased with rest duration. Optimum healing conditions were achieved at 80°C and 8 h of rest duration. It was concluded that the healing performance of the treated AC mixture with steel slag can be effectively characterized through laboratory tests including macro-scale fatigue-healing-fatigue test.

Wang et al, (2025) conducted Fatigue-healing-fatigue tests to examine the changes in self-healing properties and flow behavior of AC practicing secondary ageing. It was reported that through the aging process, the flow behavior of the binder gradually deteriorates, which impacts the self-healing performance. It was observed that self-healing performance and the flow behavior are affected by aging process. It was concluded that the flow behavior index of aged asphalt declined by 9.8 % when compared to the corresponding virgin asphalt, while the self-healing performance declined by 83.9 %.

Yan et al, (2025) explored thermal self-healing in AC mixtures when steel slag was implemented as a functional aggregate to enhance durability and sustainability. Microwave heating and electromagnetic induction methods were analyzed. It was reported that steel slag can improve skid resistance through mechanical interlock in mixtures and facilitate efficient heat generation through microwave heating. It was concluded that healing efficacy is influenced by microwave power, binder properties, and operational and environmental factors. Amani et al, (2025) explores the potential of using waste toner and waste engine oil to modify the asphalt binder to enhance crack healing through electromagnetic radiation. It was stated that the proposed approach is an environmentally friendly solution and can increase electrical conductivity of AC mixture and reduces costs. Cyclic breaking-healing cycles using indirect tensile strength were implemented under intermediate and low-temperature conditions to assess the microwave healing efficiency and crack-healing capacity. It was concluded that such additives can improve flow characteristics, limiting heat generation during microwave exposure, enhances mechanical and rheological properties, and significantly increases crack-healing potential.

Noojilla and Kusam, (2025) investigated heat-induced healing ability of cracked AC mixture specimens prepared using both modified and control binders with gap and dense gradations. Healing of specimens was conducted by heating to different temperatures (from 60 to 120) °C using the microwave induction method. It was observed that Gap-graded AC mixtures exhibited better healing characteristics than dense-graded mixtures due to their larger binder s. Mathematical models were developed to estimate the healing capacity of different mixtures. It was concluded that the microwave heating method exhibited better healing when compared with the induction method due to longer retention of heat and the greater uniformity of heating. Mahrokh Jalali & Mirabdolazimi (2025) evaluated the self-healing capability of conductive warm AC mixed with the aid of induction heating. AC samples with activated carbon and iron powder were prepared and tested at −16°C and 25°C. Induction heating was performed with variable heating time of

(60, to 120) seconds. Results indicated that a higher healing index could be achieved after increasing heating time. It was concluded that the use of iron powder as an inductive agent showed that inductive heating can serve as a suitable healing method for AC pavements which contribute to the development of eco-friendly and sustainable road infrastructure.

Fu et al, (2025) adjusted the type and content of steel wool fibers and waste steel shavings in the AC mixture. They developed magnetically conductive AC mixture to regulate the magnetic field distribution. Bending strength, stability, and crack resistance were evaluated. Damage-healing-damage cyclic tests were conducted to assess the healing efficiency and heating rate. Results showed that implementing 6 % of steel wool fibers achieves the highest performance. Mangiafico et al, (2025) highlighted various models to simulate the self-healing properties of AC materials based on numerical simulations and experimental observations for describing the healing behavior of AC under various loading and thermal conditions. A literature review of developed models that are proposed for estimation and analysis of self-healing in asphalt concrete mixtures was presented. It was concluded that modeling of self-healing AC mixtures is important mainly due to the complex, multi-scale nature of the healing processes.

Jahanbakhsh et al, (2024) investigated the induction heating and induced healing provided by application of conductive additives, including steel slag, and Iron slag, in asphalt concretes. The mechanical properties were evaluated through the Indirect tensile strength at intermediate temperature. The healing indices for the breaking-healing cycles were investigated. The results demonstrate that the addition of such additives significantly improves the mechanical properties under microwave radiation. It was concluded that incorporating fine steel slag into AC mixture is more cost-effective and sustainable when compared with conventional AC mixtures. He et al, (2024) analyzed and compared the healing mechanism of self-healing technology using microwave induction heating, electromagnetic induction heating, and Microcapsule method. The experimental results exhibited that the self-healing mechanism is mainly based on capillary flow theory, molecular diffusion theory and surface energy theory, which explains the self-healing phenomenon of asphalt from different scales. It was concluded that the variation between different self-healing technologies may be a feasible way for self-healing technology to move from experimental section to practical application.

Li et al, (2024) attempted to replace mineral filler with iron tailing filler in an AC mixture to improve its microwave self-healing properties. The electromagnetic loss and microwave heating capacity properties of iron tailings were explored. The self-healing behavior of the mixtures were tested by dynamic fracture-healing cycles with three-point bending beam test. The crack resistance at low temperature and the stability at high temperature were evaluated. It was observed that mixture with iron tailing filler exhibits favorable microwave heating ability. The healing capacity of AC mixture treated with 80 % iron tailing filler had increased by 2.75 folds when compared with that of the control mixture. Eren et al, (2024) performed a series of test cycles on a waste steel fiber for reinforcing AC thin surface layers and AC binder layer, the induction heating for healing was implemented. The crack healing ability before and after healing was investigated. The healing indexes were obtained through peak load and critical stress intensity factor with the indirect tension to cylindrical specimen test. It was concluded that AC mixtures containing waste steel fibers can heal cracks through induction heating. The healing ability may be improved depending on the waste steel fiber content in the binder and wearing AC pavement layer.

Liu et al, (2024) analyzed the local overheating and temperature distribution characteristics of side and upper surfaces of AC with different steel fiber contents after continuous heating by conducting a pixel-level quantitative analysis. Results indicated that high steel fiber content accelerated the heating rate of AC while decreasing the temperature uniformity. Localized overheating caused structural disintegration due to thermal expansion damage in AC mixtures. It was found that faster heating rates and higher heating uniformity could be achieved for samples with 6% steel fiber content. Mahmoud et al, (2024) produced a sustainable AC pavement mixture which can dispose of industrial waste and reduce maintenance costs. Coarse aggregates were partially replaced by different percentages of Electric Arc Furnace Slag and Steel Wool Fibers. Thermal distribution was analyzed and the self healing efficiency was evaluated using three Point bending test. It was observed that using such additives in the AC mixture results in significant energy savings. It was concluded that substituting 20% of coarse aggregate with Electric Arc Furnace Slag and adding 0.2% steel wool fiber by weight of AC mixture is a promising approach for improving the mechanical properties of the AC mixture.

Penalva-Salinas et al, (2024) investigated the practical application of self-healing AC mixtures incorporating induction heating and steel wool fibers to enhance the induction heating methodology for AC mixture. The induction heating parameters were refined to improve self-healing capabilities. The findings reveal that additive percentage and higher current intensity correlate with reduced energy consumption and improved heating speed. AC mixtures with steel slag coarse aggregates exhibited slightly higher specific heat, which is preferable for sustainability. It was concluded that the optimized mixtures can rapidly reach high temperatures and facilitate effective crack repair which offers an environmentally friendly, durable, and cost-effective solution for road maintenance. Zhang et al, (2023) reviewed and summarizes crack-healing theories and evaluation methods in AC mixtures. It was revealed that their extension of the life of the AC pavement is relatively limited. Microwave heating demonstrated significant efficacy in enhancing the microcrack

healing capability of AC pavement. It was concluded that encapsulated agent technologies can rejuvenate the aged AC pavement. More field test sections need to be implemented to promote industrial application.

Grossegger et al, (2022) assessed the effect of porous aggregates in AC and the filler content in asphalt mortar. The contribution of flow of the AC mixture to self-healing was determined by material drainage into an artificial gap during the healing process on asphalt mortar beams. It was reported that the filler content did not affect the maximum healing efficiency of the mixture or the breaking force, though it influenced the flow speed. Garcia et al, (2020) assessed induction heating to accelerate the self-healing of AC mixture. The process was to add metal fibers to the AC mixture, and, when the road is cracked, it can be heated by applying an alternating electromagnetic field, which can melt the binder and contribute to repairing the cracks. Cyclic loading tests were implemented and the extension in the number of cycles quantified while the optimum moment to apply the induction heating was identified. It was concluded that quantifying the air voids in the asphalts before and after cyclic loading, and after induction heating exhibited that such optimum moment occurs at approximately 35% of the lifetime of the AC.

Sarsam, (2020) assessed the PD of the wearing course under dynamic healing and cracking cycles. AC specimens were tested in the pneumatic repeated load system under dynamic punching shear and tensile stresses at 25°C. Specimens were subjected to 1000 load repetitions then allowed to heal by external heating of 60°C for 120 minutes. The loading and the healing cycles were repeated three times. The crack healing of AC was evaluated as a function of the reduction in PD under repeated shear and tensile stresses. It was observed that the PD declines as the healing cycles increase. The crack closure after several cracking-healing periods was quantified by the healing Index. It was concluded that the crack healing index in terms of decline in PD of asphalt concrete increases significantly after the second and third healing cycles when tested under repeated shear or tensile stresses.

Li et al, (2019) investigated the gradient healing behavior and the heating temperature field of AC contained steel fibers through induction heating and monitored with an infrared camera. The healing rate of the specimens in different healing conditions were investigated by testing the fracture resistance recovery after healing. It was concluded that induction heating temperature field could be related to time and heating distance. Healing and gradient heating resulted an effective healing depth of asphalt concrete, which can be determined according to the softening point of the binder and the temperature distribution.

The present work aims to compare and evaluate the influence of (external oven and microwave induction heating) on healing mode, deformation, and FN of AC. Two sets of AC Marshall specimens are prepared with optimum binder requirement; the first set is denoted as the control, while the second set is prepared with 5 % of iron slag. Specimens are subjected to fatigue under DITS until the stiffness declines to 50 % of its original value. Specimens are subjected to healing using two heating modes, (external oven and microwave) heating, then tested for fatigue using DITS. The variation in PD and FN among the healing modes between the control and the iron slag treated specimens are analyzed and modeled.

2. METHODOLOGY

Asphalt cement

Asphalt cement was obtained from Al-Nasiriyah Oil Refinery; it has a penetration grade of (40-50). The important physical properties of asphalt cement are listed in Figure 1. The test was in accordance with ASTM, (2015).

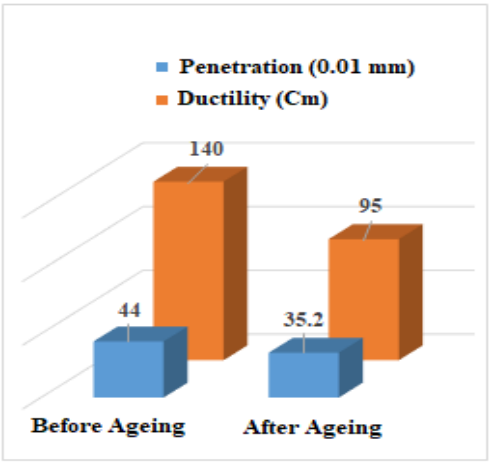


Figure 1. Physical properties of asphalt cement

Coarse and fine aggregates

The Aggregates were obtained from Badra quarry in Wasit province. Figure 2 demonstrates the physical properties of coarse and fine aggregates. The test was in accordance with ASTM, (2015).

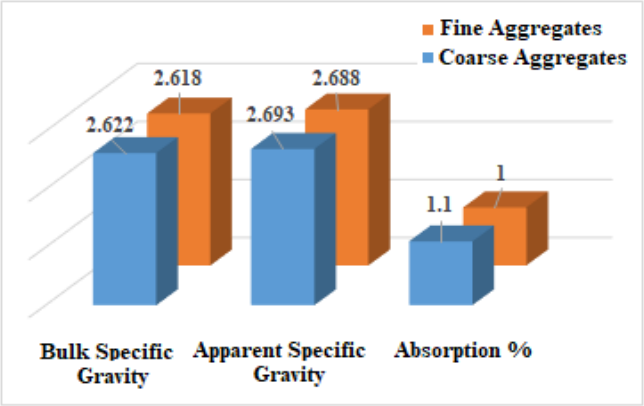


Figure 2. Properties of Aggregates

Mineral filler

Limestone dust was implemented as a mineral filler; it was obtained from the asphalt plant of the Ministry of Housing and Construction. The specific gravity of the mineral filler is 2.850, and the specific surface area is 355 m^2/Kg, while 95 % of the filler is finer than 75-micron size.

Iron slag

The iron slag is brought from the blacksmith's factories in Samawah province. One size of iron slag has been implemented; the iron slag has a maximum size of 2,36 mm and a minimum size of 0,3 mm. The unit weight of iron slag is 7.14 gm/cm^3.

Overall gradation of aggregates

The prepared overall gradation of aggregates was in accordance with SCRB, (2003) requirement for AC wearing course- type 111-B. Figure 3 shows the aggregates gradation.

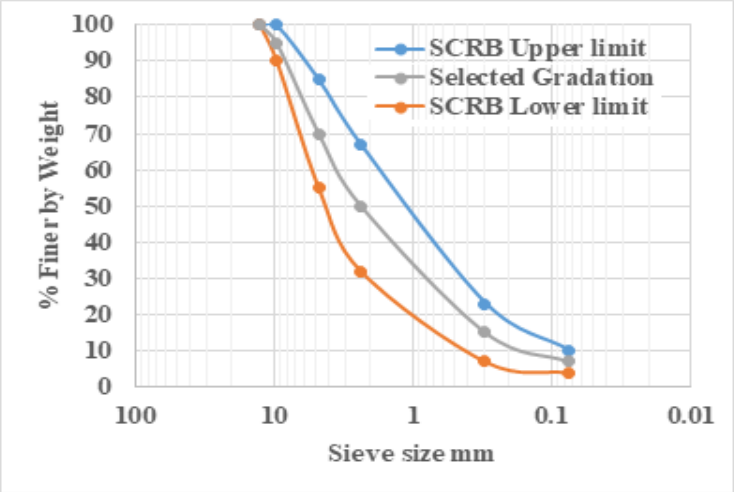


Figure 3. Overall gradation of aggregates for AC mixture as per SCRB, 2003

Preparation of AC mixtures and specimens

Mineral filler was combined with fine and coarse aggregates according to specified gradation of AC wearing course layer as per SCRB, (2003) specifications. The mixture of combined aggregates was heated to 150 ºC, the asphalt cement was also heated to the same

temperature, then it was added to the desired amount and mixed thoroughly until all aggregate particles were coated with thin film of asphalt. Such mixture is denoted as control AC mixture. Marshall specimens of AC mixture were prepared according to ASTM D1559, (2015) using Marshall hammer with 75 blows on each face of the specimen. The optimum binder content was 4.9 %. Another AC mixture was prepared with addition of 5 % of iron slag as partial replacement of fine aggregates. The specimens were tested for DITS, then subjected to the healing process, and tested again for DITS. Table 1 shows the Marshall properties of the prepared (control and slag-treated) AC mixture. A total of 18 Marshall AC specimens were prepared for the dynamic testing process of DITS. Specimens were tested in triplicate, and their average value was considered for further analysis. Such limited sample size may be used to preliminary prediction of FN and PD within the material ranges investigated and the testing conditions. More details on preparation of specimens could be found in Al Tuwayyij and Sarsam, (2020). It can be noted from Table 1 that the Marshall properties of the iron slag-treated mixture were improved as compared with those of the control AC mixture. The mixture exhibits stiffer structure with higher Marshall stability and lower flow, voids, VMA, values.

Table 1. Marshall properties of the prepared AC mixture

Property	Control mixture	Iron slag-treated mixture
Optimum binder (%)	5.1	4.9
Marshall stability (kN)	10.7	11.4
Marshall flow (mm)	3	2.8
Air voids (%)	5	4.1
VMA (%)	16.5	15.6
Unit weight (gm/cm^3)	2.350	2.410
VFA (%)	70	76
Iron slag	0 %	5 %



Figure 4. PRLS and DITS test setup

Testing of AC specimens under DITS

The dynamic indirect tensile stress test DITS as specified by ASTM, (2015) was conducted using the pneumatic repeated load system (PRLS). The testing was performed on AC Marshall size specimens, 102 mm in diameter with 63.5 mm thickness. The DITS loading was applied to the diametral specimen, and the vertical strain is monitored throughout the load repetitions as demonstrated in Figure 4. Diametral loading is applied with a constant stress of 0.138 MPa through 60 cycles per minute while the loading sequence for each cycle is 0.1 sec for load duration and 0.9 sec for rest period. The testing temperatures of 25 ºC was implemented throughout the test. The DITS loading continued for 1200 load repetitions, then the test was terminated. Such load repetitions are expected to be the limit where the possible crack initiation changes from micro to macro mode as reported by Miljković et al, (2025); Tang et al, (2024). This loading repetitions supports the failure criteria which indicates that the stiffness of the specimen declines to 50 % of its original value as

reported by Sarsam and Al Tuwayyij, (2020c); Garcia et al, (2020); Penalva-Salinas et al, (2024). Specimens were tested in triplicate, and the average value was considered for analysis. The accepted standard deviation between the maximum and minimum values was 5 %. Such limited sample size may be used to preliminary prediction of FN and PD within the investigated material ranges and the testing conditions.

Healing Process

Healing process was conducted with the aid of two techniques; the first one is by the oven external heating. The Specimens were withdrawn from the PRLS testing chamber after performing the DITS test and stored in an oven for two hours at 60 °C to allow microcrack healing. The possible healing can occur in the structure of AC specimen due to the reduction in the viscosity of asphalt binder and flow of the binder to close the Microcracks as well as the heating of the iron slag. The second technique is healing by microwave induction heating. Specimens were withdrawn from the PRLS testing chamber and stored in the microwave oven of (900 Watt) for 150 second then the cooling process was carried out by placing the specimens at room temperature of 25ºC for 120 minutes. More details on microwave heating may be referred to Sarsam and Al Tuwayyij, (2020a). Specimens were rested and cooled to room temperature for 24 hours, then transferred to the PRLS chamber and conditioned for 120 minutes at 25 ºC. Specimens were subjected to another 1200 load cycles of DITS. Similar testing for healing was suggested and conducted by Qiu et al, (2012); Sarsam, (2019); Tang et al, (2016); and Sarsam and Hamdan, (2019).

3. RESULTS AND DISCUSSIONS

Influence of heating mode on healing, PD and FN of control AC mixture.

Figure 5 demonstrates the influence of heating mode on pd, healing, and FN of the control AC mixture. It can be noted that the PD declined after practicing oven or microwave heating. However, the FN increased after the heating process by ninefolds regardless of the heating mode. This behavior may be attributed to the oxidation and stiffening of asphalt binder due to heating, atiles evaporate, binder soften and flow to seal the possible microcracks. The PD when the test was terminated after 1200 repetitions declined by (16.6, and 25) % for microwave and oven heating respectively. Such behavior could be attributed to the fact that oven heating through 60 minutes was able to distribute the temperature evenly throughout the AC specimen while the microwave heating period exhibited lesser impact of heating. The FN of AC mixture for both heating techniques increased by ninefolds indicating stiffening effect of the heating processes.

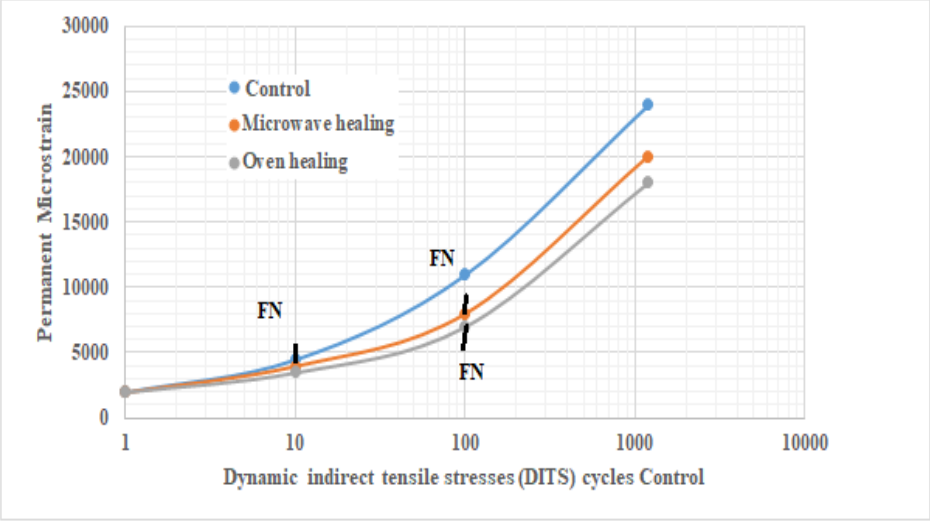


Figure 5. Influence of heating mode on heating, PD and FN of control AC mixture

Table 2 exhibits the power regression Mathematical models obtained representing the influence of heating mode on the PD of AC mixture, it can be observed that the intercept which represent the PD declines after practicing the healing as compared with that of the control specimens. The slope which represents the rate of change in PD due to healing also declined showing smoother trend of

deformation after healing when compared with the case of control specimen. Such obtained Mathematical models with high coefficients of determination (R^2) can be implemented for fast and preliminary prediction of the expected PD within the limitations of the investigated material ranges and testing conditions when practicing the healing process. Due to the limited number of tested specimens, high R^2 exhibits empirical nature and limited domain.

Table 2. Mathematical models for control AC mixture

AC mixture	Intercept	Slope	Mathematical model	Coefficient of determination
Control	2023.4	0.3539	$Y=2023.4\ X^{(0.3539)}$	0.9975
Microwave induction healing	1933.1	0.3228	$Y=1933.1\ X^{(0.3228)}$	0.9969
External oven healing	1844.4	0.3096	$Y=1844.4\ X^{(0.3096)}$	0.9925
Y= Permanent deformation (microstrain); X=Rate of deformation				

Influence of heating mode on healing, PD, and FN of iron slag-treated AC mixture.

Based on the literature, Boutgoulla et al, (2026); Li et al, (2025); and Yan et al, (2025), incorporating conductive metals such as iron slag into AC mixtures can support sustainable infrastructure, enable inductive heating, and enhance the self-healing capability. As demonstrated in Figure 6, a high healing rate in terms of reduction in PD and increase in FN could be achieved. Both heating techniques exhibited healing efficiency. Iron slag significantly enhanced microwave absorption and heating efficiency. Such additives can improve flow characteristics, limiting heat generation during microwave exposure, enhances mechanical and rheological properties, and significantly increases crack-healing potential. The use of iron slag as an inductive agent showed that inductive heating can serve as a suitable healing method for AC mixture. Similar behavior was reported by Mahrokh Jalali & Mirabdolazimi et al., (2025). It was felt that iron slag had developed a magnetically conductive AC mixture to regulate the magnetic field distribution. The PD of the iron slag treated AC mixture declined by (37.5, and 50) % after the healing with (microwave induction and external oven) heating respectively. This could be attributed to the fact that microwave heating improved the mechanical integrity of the mixture. On the other hand, the FN increased by (four and nine) folds of the iron slag-treated mixture after practicing the healing with (induction microwave and external oven) heating respectively. The results demonstrate that the addition of iron slag additives significantly improves the mechanical properties under both microwave radiation and external oven heating. Such behavior agrees with Jahanbakhsh et al, (2024) findings.

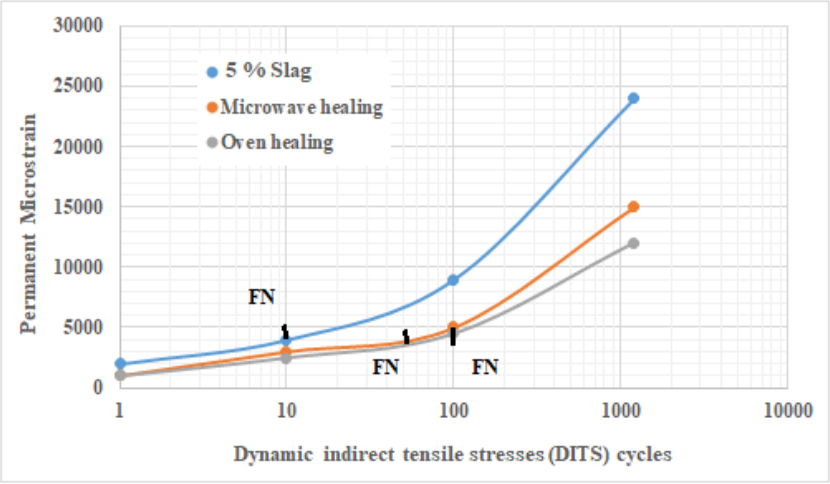


Figure 6. Influence of heating mode on heating, PD and FN of iron slag-treated AC mixture

Table 3 exhibits the power regression mathematical models obtained representing the influence of implementing iron slag and heating mode on the PD of AC mixture, it can be observed that the intercept which represent the PD declines after practicing the healing as compared with that of the control specimens. The slope which represents the rate of change in PD due to healing also declined showing smoother trend of deformation after healing when compared with the case of specimen before heating. It can be

noticed that implementation of iron slag into the structure of AC exhibited a reduction in the PD by (25, and 33.3) % when the AC mixture practiced (microwave induction and external oven) heating. On the other hand, the FN of AC mixtures declined by 50 % at microwave heating while oven heating demonstrated no significant variation in FN after implementing iron slag. Similar behavior was reported by Sarsam and Al Tuwayyij, (2020b).

Table 3. Mathematical models for iron slag-treated AC mixture

AC mixture	Intercept	Slope	Mathematical model	Coefficient of determination
Control	1887.7	0.366	$Y=1887.7\ X^{(0.351)}$	0.9976
Microwave induction healing	1073.8	0.351	$Y=1073.8\ X^{(0.366)}$	0.9905
External oven healing	1032.1	0.3414	$Y=1032.1\ X^{(0.3414)}$	0.9949
Y= Permanent deformation (microstrain); X=Rate of deformation				

Healing indices

Healing index is the ratio of PD after healing, to those before healing as addressed by Chen et al, (2025); Abadeen et al, (2022); and Ashouri et al, (2021). Table 4 demonstrates the healing indices of AC mixture in terms of PD. It can be observed that the external oven heating exhibited the lowest PD healing index for control and iron slag treated AC mixtures. However, implementation of 5 % iron slag exhibited lower healing index as compared with the control AC mixture.

Table 4. Healing indices

Variable	Microwave heating	Oven heating	Microwave heating	Oven heating
	Control AC		Iron slag treated AC	
PD healing index	0.83	0.75	0.62	0.50

4. CONCLUSION

The following remarks could be addressed based on the limitations of materials and the executed testing program.

1- The FN of control AC increased by ninefolds while the PD declined after practicing the healing process.

2- The PD of control AC declined by (16.6, and 25) % after healing with (microwave induction and external oven) heating respectively.

3- The PD of the iron slag-treated AC mixture declined by (37.5, and 50) % after practicing the healing with (microwave induction and external oven) heating respectively.

4- The FN increased by (four and nine) folds of the iron slag treated mixture after practicing the healing with (induction microwave and external oven) heating respectively.

5- Implementation of iron slag into the structure of AC exhibited a reduction in the PD by (25, and 33.3) % when the AC mixture practiced (microwave induction and external oven) heating. On the other hand, the FN of AC mixtures declined by 50 % at microwave heating while oven heating demonstrated no significant variation in FN after implementing iron slag.

6- External oven heating exhibited a lower PD healing index for control and iron slag-treated AC mixtures. However, implementation of 5 % iron slag exhibited lower healing index in general as compared with the control AC mixture.

7- The obtained power regression Mathematical models with high coefficients of determination can be implemented for fast and preliminary prediction of the expected PD within the limitations of the investigated material ranges and testing conditions when practicing the healing process.

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Author Contributions

Contribution to this work was made by the author.

Informed consent
Not applicable.

Conflicts of interests
The authors declare that they have no conflicts of interest, competing financial interests or personal relationships that could have influenced the work reported in this paper.

Ethical approval & declaration
Not applicable. This article does not contain any studies with human participants or animals performed by any of the authors.

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Data and materials availability
All data related to this study are included in the article.

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