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Microwave-Assisted Self-Healing of AC-WC Modified with Iron Powder: Mechanical Performance and Healing Rate

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Abstract. Conventional asphalt mixtures have limited microwave absorption, reducing the effectiveness of microwave-assisted self-healing. This study evaluates the effect of iron powder (0–10% by mass of fine aggregate) as additional fine aggregate in AC-WC mixtures on mechanical performance and microwave-activated healing behavior. Cylindrical specimens (63 mm × 100 mm; three per mixture) were tested using Marshall Stability and Indirect Tensile Strength (ITS) at 25 °C. Healing efficiency was determined by the ratio of post-heating ITS to initial ITS. Results showed that 10% iron powder increased Marshall stability by 36% compared to the control and achieved the highest healing rate of 76% after the first microwave cycle. However, repeated heating reduced healing performance due to overheating and accelerated binder aging. Iron powder improves early-stage self-healing but requires controlled dosage and heating conditions for long-term durability.

Keywords: AC-WC, iron powder, microwave irradiation, Marshall stability, ITS ratio, healing rate, conductive filler

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1. Introduction

Road infrastructure is vital for economic development, facilitating the movement of people and goods. However, in developing countries like Indonesia, around 35% of the 542,000 km of roads are damaged [1]. The deterioration of asphalt pavements is caused by environmental factors such as water, temperature fluctuations, and UV exposure, exacerbated by traffic-induced fatigue [2]. The repetition of this load causes a decrease in the ability of the structure to accept loads that cause fatigue cracking [3]. Fatigue-induced damage in asphalt mixtures can, under certain conditions, be mitigated through the material's inherent self-healing properties. Asphalt pavements have self-healing capabilities, where cracks can close during rest periods, restoring stiffness and strength [4]. This self-healing capability has garnered attention for its potential to significantly extend pavement service life while reducing the frequency of repair activities. The application of self-healing asphalt offers numerous benefits, including improved traffic flow, enhanced road safety, reduced aggregate consumption, lower CO2 emissions, and overall maintenance cost savings [5]. The incorporation of industrial and waste-derived materials into construction materials has also been widely investigated as a strategy to improve resource efficiency and reduce environmental impacts [6–8]. Similarly, waste iron powder can be considered a conductive waste-derived material with additional functional benefits in asphalt mixtures. Previous studies have demonstrated that waste-derived fine aggregates can be successfully incorporated into AC-WC mixtures while maintaining or improving Marshall stability and volumetric performance [9].

The self-healing ability of asphalt pavements has been demonstrated in laboratory and field tests since the 1960s [10]. The increase in pavement healing occurred during heating at high temperatures and fast times [11]. Research shows that increasing pavement temperature accelerates the asphalt healing process by softening bitumen (30-70 °C), which helps seal cracks [12]. The study of [13] demonstrated that microwave heating can achieve rapid volumetric heating through radiant heat transfer. The microwave heating model itself has many advantages and is considered the most efficient because the time it takes is relatively short [14]. In addition, the use of microwave heating does not cause overheating and can be applied in the process of making and recycling conventional pavements [15].

However, conventional asphalt has low heat absorption, limiting the effectiveness of microwave heating [16]. Insufficient heating leads to suboptimal bitumen liquefaction, preventing cracks from being fully closed [17,18]. To overcome this limitation, recent advancements have focused on incorporating heat-conductive materials into asphalt mixtures. These materials enhance the pavement's thermal response, facilitating better crack closure through accelerated bitumen melting [19,20]. The method involves adding heat-conductive materials to accelerate the melting of asphalt which is useful in closing cracks. The performance of self-healing asphalt pavement is highly dependent on temperature [21] and is directly related to the resting time. Increasing rest and heating time has an impact on increasing the healing capacity of the asphalt mixture [22]. Several studies have explored the addition of conductive materials to asphalt mixtures, including recycled metal waste. The study of [21] investigated the use of steel fibers (~5 mm) in asphalt pavements, demonstrating improved heat absorption. However, the use of steel fiber as an aggregate material has the potential to cause overheating due to the uneven temperature distribution and can damage the asphalt quality. In another study conducted by [2] using a magnetic induction method with small iron particles (<1 mm). This small particle size has been shown to prevent the formation of a high-temperature gradient in the sample. However, the recovery time by magnetic induction is relatively long when compared to using microwave heating.

Further research by [23] demonstrated that the addition of iron powder and steel fibers to asphalt mortar significantly enhanced its heat absorption and mechanical properties. Iron powder, in particular, improves both the thermal and mechanical performance of asphalt pavements [24,25]. However, despite growing interest in conductive fillers for microwave-activated self-healing asphalt, most studies focus on steel fibers or magnetic induction particles, while quantitative evaluation of iron powder as a partial fine aggregate replacement in AC-WC mixtures remains scarce. Moreover, the trade-off between enhanced heating efficiency and potential thermal degradation has not been sufficiently addressed. Therefore, this study aims to investigate the influence of iron powder content on Marshall properties, moisture resistance, and microwave-induced self-healing performance of AC-WC mixtures. It is hypothesized that increasing iron powder improves microwave absorption and healing rate up to an optimum level, beyond which excessive thermal conductivity may induce overheating and performance loss.

2. Materials and Methods

2.1. Materials

The materials used in this study included coarse aggregates, fine aggregates, filler, waste iron powder, and 60/70 penetration-grade asphalt binder. The coarse aggregates consisted of two size fractions, namely 10/10 mm and 5/10 mm, while the fine aggregate was a locally sourced material with a particle size range of 0/5 mm. The filler material used in the mixture was defined as aggregate passing through a No. 200 sieve. The waste iron powder was obtained from a metal lathe workshop and was utilized as an additive in the asphalt mixture and had a maximum particle size retained on the No. 30 sieve. All materials were tested in the laboratory prior to specimen preparation to ensure compliance with asphalt mixture requirements. The physical properties of the asphalt binder are shown in Table 1.

Table 1. The physical properties of the asphalt

Parameters	Value
Density (kg/m^3)	1057
Mass Loss (%)	0.014
Penetration (0.1 mm)	78.40
Flash point (°C)	210
Fire point (°C)	225
Softening point (°C)	53.50
Ductility (cm)	156

2.2. Mixture Formulation and Research Method

The mixture composition in this study was formulated based on a combined aggregate gradation derived from multiple aggregate fractions in accordance with the highway code [26]. The combined aggregate proportions were designed using the Rothfuchs graphical method combined with a trial-and-error approach to obtain the optimum aggregate distribution for the AC-WC mixture. After all materials satisfied the required specifications, the planned asphalt content (Pb) was determined based on the highway code [26] to identify the Optimum Asphalt Content (OAC), which was subsequently used as the fixed asphalt content for preparing the modified AC-WC specimens. The OAC was established from several asphalt content variations through Marshall testing parameters, including Voids in Mixture (VIM), Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), Marshall stability, flow, and Marshall Quotient (MQ), while all testing procedures and acceptance criteria followed the Specifications of the highway code [26]. The obtained OAC was then applied as the constant asphalt content for the modified mixtures, in which fine aggregate was supplemented with waste iron powder at proportions of 0%, 2.5%, 5%, 7.5%, and 10% by weight of the fine aggregate retained on and above the No. 30 sieve, with the 0% mixture serving as the control specimen. The Marshall characteristics of these modified mixtures were subsequently evaluated using the same specification criteria applied during the OAC determination. Each asphalt content variation consisted of five specimens to ensure the consistency and reliability of the test results.

Specimen preparation started with sieving, grouping, and weighing the aggregates to achieve a total mass of 1200 g, followed by heating at 105-110 °C. Meanwhile, 60/70 penetration-grade asphalt was heated separately to 120 ± 1 °C. The heated aggregates and asphalt binder were then mixed according to the target asphalt content to produce a 1200 g asphalt mixture. The mixture was reheated to 155 ± 1 °C to maintain uniformity and ensure proper blending. After homogeneous condition was achieved, the hot mixture was placed into a standard Marshall mold until the temperature dropped to 93.3-148.9 °C. Compaction was then carried out using a Marshall hammer with 75 blows applied on each side of the specimen, resulting in a total of 150 blows for each sample. For ITS test specimens, provide impact variations of 25, 50, and 75 times to obtain mixed voids of up to 7±0.5%.

Before conducting the Marshall stability test, the specimens were allowed to remain in the mold at room temperature for 2–3 hours, followed by immersion in a water bath maintained at 60 °C for approximately 30 minutes. Subsequently, the specimens were subjected to loading according to the specified immersion duration in accordance with the standard Marshall testing procedure. In the ITS test, the Voids in Mixture (VIM) value was required to meet the standard of 7% ± 0.5. Therefore, if the VIM value at the optimum iron powder content did not satisfy this requirement, variations in the number of compaction blows were applied to achieve the specified VIM value. The Indirect Tensile Strength (ITS) test was conducted to evaluate the resistance of asphalt pavement to damage after the addition of iron powder through the healing rate parameter. The healing rate test was performed following the method proposed by [27]. To activate the self-healing capability of the modified asphalt mixture, the specimens were heated using a microwave oven operating at a frequency of 2.45 GHz with a power output of 800 W for 120 seconds at medium temperature, and then allowed to rest at room temperature for 6 hours, as described by [28]. Subsequently, the healing rate percentage (%) was calculated using **Equation (1)**.

$$Healing\ rate = \frac{tensile\ strength\ for\ each\ testing}{maximum\ tensile\ strength\ for\ the\ first\ testing}\ x\ 100\% \quad (1)$$

3. Results and Discussion

3.1. Determination of Optimum Asphalt Content

The key parameter established in this research was the Optimum Asphalt Content (OAC), which was determined using the Marshall mix design method. The OAC serves as a critical indicator in ensuring that the asphalt mixture achieves the required balance between strength, durability, flexibility, and volumetric performance. In this study, the determination of OAC was based on the average asphalt content corresponding to the specification limits of the main Marshall parameters, namely Voids in the Mix (VIM), Voids Filled with Asphalt (VFA), Voids in Mineral Aggregate (VMA), flow, Marshall stability, and Marshall Quotient (MQ) [26]. This approach ensures that the selected binder content satisfies both structural and functional performance requirements of AC-WC mixtures.

The calculation procedure for evaluating each Marshall parameter and selecting the OAC followed the methodology proposed by [9,29], which is widely applied in asphalt mixture design studies. The analysis was conducted by plotting the relationship between asphalt content and each Marshall parameter, followed by identifying the range of asphalt contents that met the standard specification criteria. Based on the results study, the asphalt content that satisfied the specification requirements for all Marshall parameters was 7.1%. This value was selected as the final Optimum Asphalt Content (OAC) because it provided the best balance among stability, workability, air void characteristics, and resistance to permanent deformation. Therefore, the OAC of 7.1% was considered the most appropriate asphalt binder content for the AC-WC mixture in this study and was subsequently used in the preparation of specimens containing waste iron powder as a fine aggregate substitute.

3.2. The effect of adding iron powder on marshall properties

The addition of waste iron powder significantly influenced the Marshall characteristics of AC-WC mixtures by modifying the volumetric structure, compaction behavior, and mechanical resistance of the asphalt mixture. Density initially decreased at 2.5% iron powder, indicating that the fine metallic particles had not yet effectively filled the interparticle voids; however, with increasing iron powder content, density gradually increased and reached the highest value of 2.395 g/cm^3 at 10% (see **Figure 1**), demonstrating improved compaction and aggregate interlocking due to the higher specific gravity, angularity, and rough surface texture of the iron powder. This result is consistent with [30], who reported that steel slag powder improved mixture density and Marshall stability through filler effects and enhanced internal friction, as well as [31] who found that waste iron powder strengthened the asphalt–aggregate interface and improved fatigue resistance. Similar behavior has been reported for AC-WC mixtures incorporating gold-mining residual sand waste, where changes in density were associated with aggregate gradation, particle shape, packing efficiency, and interparticle friction [9]. The increase in density was closely associated with the behavior of VIM, which increased from 4.45% in the control mixture to 5.20% at 7.5% iron powder before slightly decreasing to approximately 5.00% at 10% (see **Figure 2**). This trend indicates that at moderate dosages, iron powder disturbed the optimized aggregate gradation and increased air voids, while at higher contents it began to function more effectively as a filler by occupying micro-voids. Similar behavior was observed [32,33] who reported that metallic waste fillers increased VIM at excessive dosages but improved mixture structure and stability at optimum proportions. A comparable filler-dependent behavior has been reported in HRS-WC asphalt mixtures incorporating teak wood powder waste, where filler dispersion and agglomeration significantly affected void structure, compaction quality, and mechanical performance [34].

The increase in VIM was accompanied by a rise in VMA from 18.95% to 19.98% (see **Figure 3**)and a reduction in VFA from 77.96% to 73.80% at 7.5% iron powder (see **Figure 4**), indicating that larger intergranular void spaces increased asphalt binder demand while reducing the proportion of voids effectively filled by asphalt. This reflects the influence of the fine particle size, irregular geometry, and rough texture of iron powder, which reduced aggregate packing efficiency and required thicker asphalt film to maintain durability. Previous research has also demonstrated that variations in particle characteristics can affect packing behavior and density of particulate construction materials [35]. Study of [36] similarly explained that alternative fillers with non-uniform particle geometry increased VMA and reduced VFA due to changes in aggregate packing and asphalt film thickness, while [37] found that industrial waste fillers with high specific surface area increased asphalt absorption and altered volumetric balance. H. Xu et al., 2020 [30] also confirmed that steel slag powder increased VMA because of its porous structure and rough surface, although it still improved rutting resistance when used at optimum contents. These results confirm that VIM, VMA, and VFA are strongly interrelated and directly govern moisture resistance, durability, and long-term pavement performance.

The mechanical response of the mixtures also improved significantly with the addition of iron powder. Marshall Flow decreased sharply from 3.67 mm to 2.10 mm at 2.5% (see **Figure 5**), indicating increased stiffness and resistance to plastic deformation due to stronger aggregate interlocking and improved binder–aggregate adhesion; however, flow gradually increased again at higher dosages because excessive filler disturbed binder distribution and reduced workability. This trend agrees with [31], who reported that industrial metallic fillers reduced flow values and increased stiffness, while excessive filler content increased asphalt demand and reduced compaction efficiency. [38] also emphasized that filler morphology strongly controls deformation resistance, where angular and rough particles improve internal friction but excessive fines reduce mixture homogeneity. Correspondingly, Marshall Stability increased consistently from 810 kg in the control mixture to 1101.70 kg at 10% iron powder (see **Figure 6**), confirming that iron powder improved load-bearing capacity, rutting resistance, and shear strength through enhanced density, stronger internal cohesion, and better load distribution. Similar improvements were reported by [33,39,40] who concluded that waste-based fillers significantly improved Marshall Stability by increasing mixture stiffness and structural integrity when used within optimum dosage ranges.

These changes were further reflected in the Marshall Quotient (MQ), which increased substantially from 230.71 kg/mm in the control mixture to its optimum range at 2.5–7.5% iron powder (see **Figure 7**), indicating a better balance between stiffness and flexibility before slightly decreasing at 10% due to reduced compaction efficiency and excess filler content. Similar findings were reported by [24,41] who showed that metal-based fillers improved MQ by increasing stability while maintaining acceptable flow values. Overall, the results demonstrate that waste iron powder acts not only as a filler but also as a reinforcing conductive material that enhances volumetric performance, Marshall stability, and resistance to permanent deformation. The optimum content was found within the range of 7.5–10% for maximum mechanical strength, while 5–7.5% provided a better balance between stability, flexibility, durability, and long-term pavement performance, supporting its application as a sustainable alternative material for high-performance asphalt pavements.

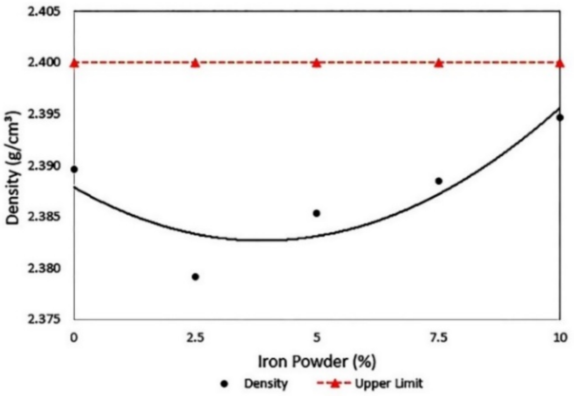

Figure 1. Density vs iron powder

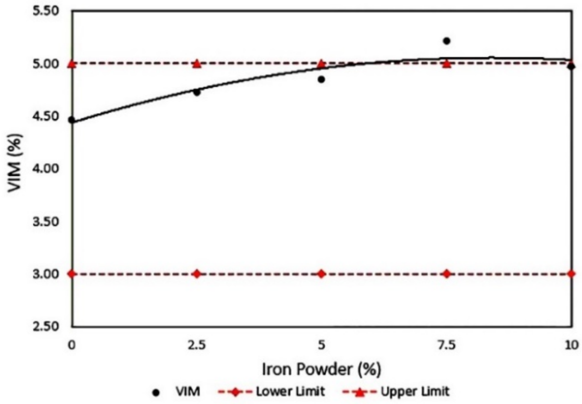

Figure 2. VIM vs iron powder

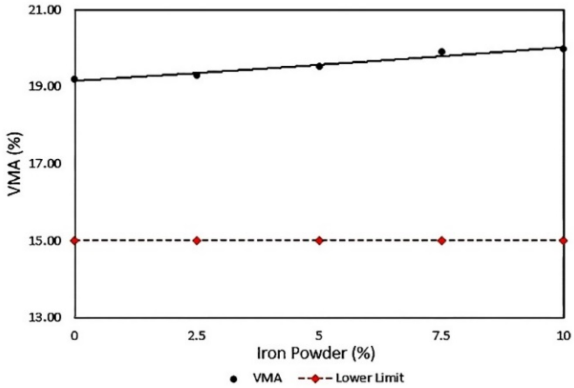

Figure 3. VMA vs iron powder

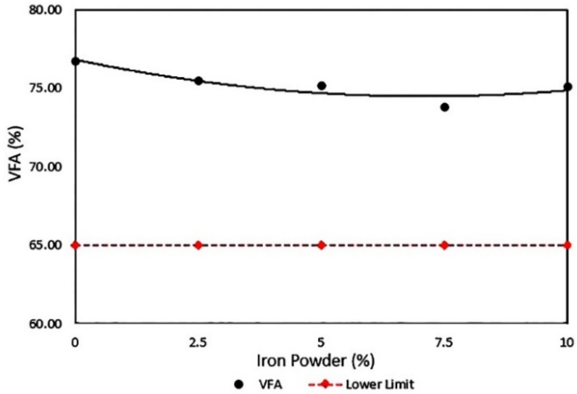

Figure 4. VFA vs iron powder

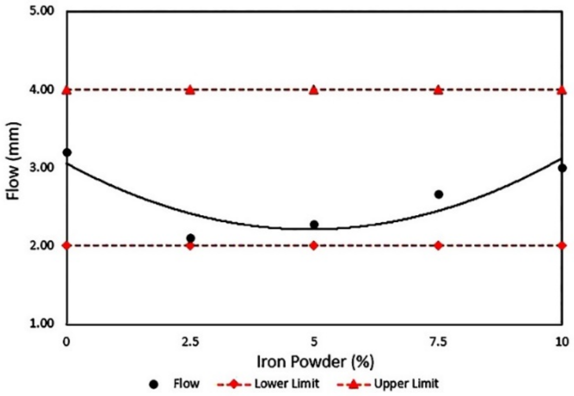

Figure 5. Marshall Flow vs iron powder

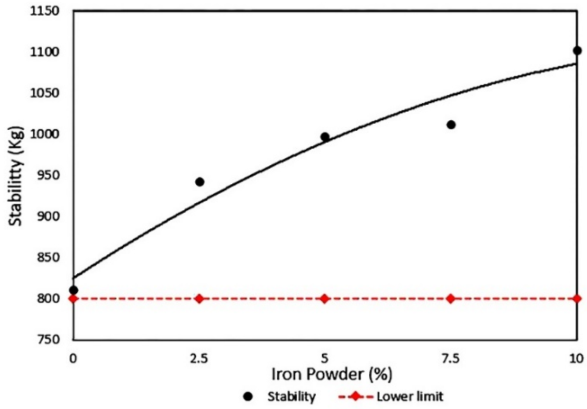

Figure 6 Marshall stability vs iron powder

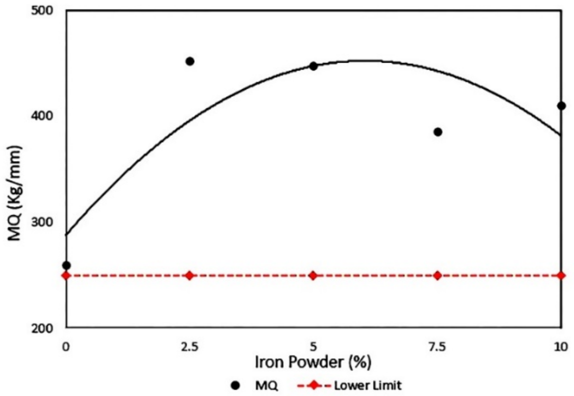

Figure 7 Marshall quotient vs iron powder

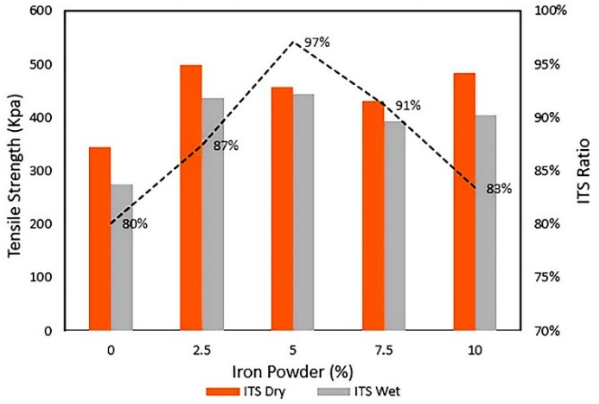

Figure 8 ITS vs iron powder

3.3. Indirect Tensile Strength (ITS)

The Indirect Tensile Strength (ITS) test was conducted to evaluate the tensile strength and moisture resistance of AC-WC mixtures containing waste iron powder as a fine aggregate additive. All specimens were prepared with a target Voids in Mix (VIM) value of 7 ± 0.5% by adjusting the number of compaction blows to ensure consistent testing conditions. The ITS test was performed at 25 °C under dry (ITS Dry) and wet (ITS Wet) conditions. The tensile strength ratio (TSR, %) was then calculated from the comparison between wet and dry ITS values to assess the mixture's resistance to moisture damage and stripping [42,43].

As shown in Figure 8, the ITS Dry values increased significantly with the addition of waste iron powder. The control mixture (0%) showed the lowest tensile strength of approximately 345 kPa, while the highest ITS Dry value was observed at 2.5% iron powder, reaching about 500 kPa. At 5%, 7.5%, and 10%, the tensile strengths were approximately 460 kPa, 430 kPa, and 485 kPa, respectively. A similar trend was found for ITS Wet, where all modified mixtures showed higher values than the control specimen. The highest ITS ratio was obtained at 5% iron powder with 97%, followed by 91% at 7.5%, while the control mixture showed the lowest ratio of only 80%. This indicates that iron powder improves both tensile strength and moisture resistance by enhancing aggregate interlocking, binder–aggregate adhesion, and internal cohesion due to its angular shape, rough texture, and high stiffness [44,45].

However, the ITS ratio decreased at iron powder contents above 5%, suggesting that excessive filler may reduce adhesion efficiency due to particle agglomeration and non-uniform binder distribution. This condition can weaken the interfacial bonding and reduce moisture resistance under wet conditions [46]. Similar findings were reported by [32,33] who stated that metal-based fillers improve ITS performance only when used at optimum proportions [32,46]. Therefore, 5% waste iron powder was considered the optimum content, providing the best balance between tensile strength, durability, and resistance to water-induced damage in AC-WC mixtures.

3.4. Healing Performance Analysis

The addition of waste iron powder had a highly significant effect on improving the healing rate of AC-WC mixtures because this material functions not only as a mechanical filler but also as a conductive medium that accelerates the self-healing process through microwave heating. In the repeated ITS test, the control mixture without iron powder showed the lowest healing rate of 56%, while the mixture containing 10% iron powder achieved the highest healing rate of 76% in the first heating cycle, as presented in Figure 9. This improvement indicates that iron powder effectively accelerated the reflow of asphalt binder and restored the interfacial bonding between aggregates after microcrack formation. This behavior is attributed to the high thermal conductivity, magnetic properties, and microwave absorption capacity of iron particles, which allow heat to be distributed more rapidly and uniformly throughout the mixture structure. As a result, binder flow toward the crack zone increased, enhancing the internal healing capability of the asphalt mixture. [47] reported that metal-based fillers such as steel slag powder significantly improved microwave heating efficiency and accelerated the self-healing process by increasing internal heat transfer and temperature retention within the mixture, as also reflected by the temperature variation during testing shown in Figure 10. Similar findings were reported by [48], who demonstrated that conductive metallic materials significantly improved asphalt healing rate compared to conventional mixtures by accelerating microcrack closure after heating.

The improvement in healing rate was also closely related to the initial ITS results, where mixtures containing 2.5–5% iron powder exhibited the highest initial tensile strength due to better aggregate interlocking and stronger binder–aggregate adhesion. However, the highest healing rate was observed at 10% iron powder, confirming that self-healing performance is more strongly influenced by heat transfer efficiency than by the initial mechanical strength of the mixture alone. [49] also explained that metallic fillers at optimum dosages can improve both ITS and healing performance, although through different mechanisms: ITS is mainly influenced by filler effect and structural stability, whereas healing rate is more dependent on thermal conductivity and microwave absorption capacity. In this study, the mixture containing 10% iron powder showed the highest temperature increase of 49%, which directly correlated with the highest healing rate, proving that internal temperature rise is the dominant factor controlling crack healing. [50] also emphasized that homogeneous heat distribution strongly determines self-healing effectiveness, where materials with higher thermal conductivity produce faster and more stable crack closure.

However, excessive waste iron powder does not always provide the best long-term performance. In Test 3, the healing rate of the 10% iron powder mixture dropped significantly to 50%, indicating that excessive heat accumulation may cause overheating, premature binder aging, reduced asphalt cohesion, and weakened interparticle bonding. [38] reported that excessive metallic filler content increases the risk of thermal aging and reduces mechanical performance after repeated heating cycles. Similar findings were also presented by [51], who showed that high conductive material content may improve initial healing rate but accelerates binder oxidation and reduces long-term durability. This explains why the mixture containing 7.5% iron powder showed more stable healing performance over multiple heating cycles, despite having a slightly lower initial healing rate than the 10% mixture. Therefore, this study confirms that waste iron powder has a strong positive effect on improving the healing rate of asphalt mixtures; however, the optimum dosage should not be determined solely based on the highest initial healing rate, but also on the stability of strength recovery after repeated heating. Accordingly, the range of 7.5–10% iron powder can be considered the optimum content for maximizing self-healing performance while maintaining thermal durability and long-term pavement service life.

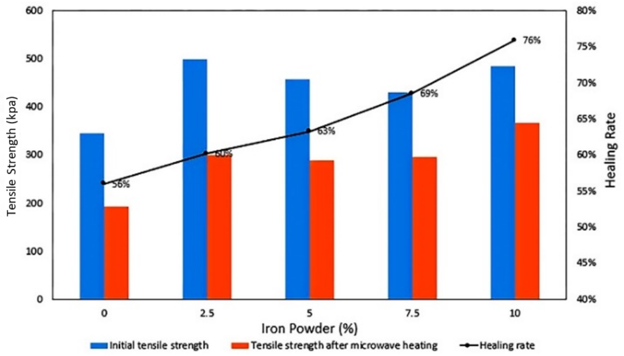

Figure 9 Effect of iron powder content variation on tensile strength and healing rate of asphalt pavement after microwave heating.

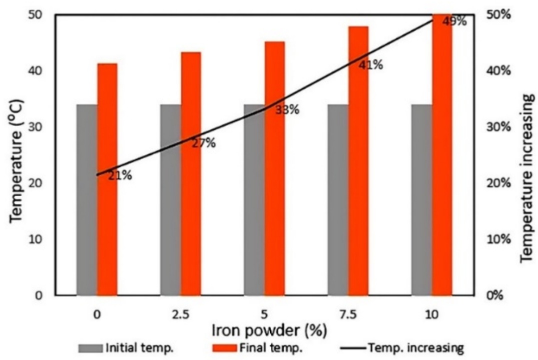

Figure 10 Temperature change after heating

4. Conclusion

The addition of waste iron powder (0–10% by mass of fine aggregate) significantly improved the mechanical performance of AC-WC mixtures by enhancing density, aggregate interlocking, internal friction, and binder–aggregate adhesion. The highest Marshall Stability (1101.70 kg) and density (2.395 g/cm³) were obtained at 10% iron powder, indicating better resistance to rutting and permanent deformation. The volumetric parameters (VIM, VMA, and VFA) showed that iron powder functioned not only as a filler but also as a modifier of aggregate packing and internal void structure. Moderate iron powder content improved compaction efficiency, while excessive filler increased air voids and asphalt demand, affecting long-term durability and workability. The ITS results confirmed that all modified mixtures had better tensile strength and moisture resistance than the control mixture. The highest ITS Dry value was achieved at 2.5% iron powder, while the optimum ITS ratio (97%) was obtained at 5%, indicating the best balance between tensile strength, durability, and resistance to moisture damage. Microwave-assisted self-healing performance was significantly enhanced by the addition of iron powder due to its high thermal conductivity, magnetic properties, and microwave absorption capability. The highest healing rate (76%) was achieved at 10% iron powder after the first heating cycle, compared to only 56% in the control mixture. Although 10% iron powder produced the highest initial healing rate, repeated microwave heating caused a decline in healing performance due to overheating and accelerated binder aging. In contrast, the 7.5% mixture showed more stable healing behavior over multiple cycles, indicating better long-term thermal durability. Overall, waste iron powder demonstrated strong potential as a sustainable conductive filler and reinforcing material for AC-WC mixtures. The optimum range of 5–7.5% provided the best balance between mechanical strength, moisture resistance, healing stability, and long-term pavement performance, supporting the development of durable and self-healing asphalt pavements.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to assist with English language editing, grammar correction, sentence restructuring, and improving the clarity and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Statistics Indonesia. Land Transportation Statistics 2019. 2019.

[2] Jeoffroy E, Bouville F, Bueno M, Studart AR, Partl MN. Iron-based particles for the magnetically-triggered crack healing of bituminous materials. Construction and Building Materials 2018;164:775–82. https://doi.org/10.1016/j.conbuildmat.2017.12.223.

[3] Zhu X, Cai Y, Zhong S, Zhu J, Zhao H. Self-healing efficiency of ferrite-filled asphalt mixture after microwave irradiation. Construction and Building Materials 2017;141:12–22. https://doi.org/10.1016/j.conbuildmat.2017.02.145.

[4] Liu Q, Wu S, Schlangen E. Induction heating of mastic asphalt for crack control. Construction and Building Materials 2013;41:345–51. https://doi.org/10.1016/j.conbuildmat.2012.11.075.

[5] Tabaković A, Schlangen E. Self-healing technology for asphalt pavements. Advances in Polymer Science 2016;273:285–306. https://doi.org/10.1007/12_2015_335.

[6] Tajunnisa Y, Pamungkas SB, Wibowo YN, Apsari AK, Masrafat H. AN EXPERIMENTAL ANALYSIS OF COMPRESSIVE STRENGTH AND SHRINKAGE IN HIGH-VOLUME FLY

ASH CONCRETE. Journal of Green Building 2026;21:49–62. https://doi.org/10.3992/jgb.21.3.49.
[7] Masrafat H, Nurfain I, Bayuaji R, Tajunnisa Y, Rifki M, Ash F. Potential of Sandless Geopolymer Concrete Bricks for Soundproof Walls. Rekayasa Sipil 2026;20:231–40. https://doi.org/10.21776/ub.rekayasasipil.2026.020.02.14.
[8] Masrafat H, Almutahir A. Initial Mechanical Performance of Type C Fly Ash-Based Geopolymer Concrete under Sulfate Exposure. Composite Journal 2026;6:30–9. https://doi.org/https://doi.org/10.37905/jc.v6i1.200.
[9] Machsus M, Mawardi AF, Basuki R, Hadi AF, Rosdiana M, Wirawan AF. Asphalt Concrete – Wearing Course (AC-WC) Performance using Gold-Mining Sand Waste as Fine Aggregate in Sustainable Pavements. International Journal of GEOMATE 2025;29:106–17. https://doi.org/https://doi.org/10.21660/2025.133.5039.
[10] Bazin P, Saunier J. Deformability, Fatigue and Healing Properties of Asphalt Mixes. Intl Conf Struct Design Asphalt Pvmts, 1967.
[11] Grant TP. Determination of Asphalt Mixture Healing Rate Using the Superpave Indirect Tensile Test 2001.
[12] Biro S, Gandhi T, Amirkhanian S. Determination of zero shear viscosity of warm asphalt binders. Construction and Building Materials 2009;23:2080–6. https://doi.org/10.1016/j.conbuildmat.2008.08.015.
[13] Chiostri M, Ceseri P. Self-propelled operating apparatus for the regeneration pavement 1984;856.
[14] Xu S, Liu X, Tabaković A, Schlangen E. The prospect of microwave heating: Towards a faster and deeper crack healing in asphalt pavement. Processes 2021;9. https://doi.org/10.3390/pr9030507.
[15] Benedetto A, Calvi A. A pilot study on microwave heating for production and recycling of road pavement materials. Construction and Building Materials 2013;44:351–9. https://doi.org/10.1016/j.conbuildmat.2013.02.082.
[16] Liu W, Miao P, Wang S-Y. Increasing Microwave Heating Efficiency of Asphalt-Coated Aggregates Mixed with Modified Steel Slag Particles. Journal of Materials in Civil Engineering 2017;29:04017171. https://doi.org/10.1061/(asce)mt.1943-5533.0002026.
[17] Qiu J. Self Healing of Asphalt Mixtures. Delft University of Technology 2012.
[18] Zhao H, Zhong S, Zhu X, Chen H. High-Efficiency Heating Characteristics of Ferrite-Filled Asphalt-Based Composites under Microwave Irradiation. Journal of Materials in Civil Engineering 2017;29:04017007. https://doi.org/10.1061/(asce)mt.1943-5533.0001845.
[19] Gallego J, Del Val MA, Contreras V, Páez A. Heating asphalt mixtures with microwaves to promote self-healing. Construction and Building Materials 2013. https://doi.org/10.1016/j.conbuildmat.2012.12.007.
[20] Sun Y, Wu S, Liu Q, Li B, Fang H, Ye Q. The healing properties of asphalt mixtures suffered moisture damage. Construction and Building Materials 2016;127:418–24. https://doi.org/10.1016/j.conbuildmat.2016.10.048.
[21] Sun Y, Wu S, Liu Q, Zeng W, Chen Z, Ye Q, et al. Self-healing performance of asphalt mixtures through heating fibers or aggregate. Construction and Building Materials 2017;150:673–80. https://doi.org/10.1016/j.conbuildmat.2017.06.007.
[22] Zhu X, Ye F, Cai Y, Birgisson B, Yu Y. Digital image correlation-based investigation of self-healing properties of ferrite-filled open-graded friction course asphalt mixture. Construction and Building Materials 2020;234:117378. https://doi.org/10.1016/j.conbuildmat.2019.117378.
[23] Apostolidis P, Liu X, Scarpas A, Kasbergen C, van de Ven MFC. Advanced evaluation of asphalt mortar for induction healing purposes. Construction and Building Materials 2016. https://doi.org/10.1016/j.conbuildmat.2016.09.011.

[24] Al-Tuwayyij H, Sarsam SI. Influence of Iron-filings on marshall and volumetric properties of asphalt concrete. Civil Engineering Journal (Iran) 2020;6:1684–96. https://doi.org/10.28991/cej-2020-03091574.

[25] Tajudin AN, Suparma LB. Effect of Immersion on the Indirect Tensile Strength of AC-BC (Asphalt Concrete – Binder Course) Mixtures with Plastic Waste as Aggregate Substitute 2017;23:166–73.

[26] Directorate General of Highways (Ministry of Public Works). General Specifications for Road and Bridge Construction Works. Indonesia: 2025.

[27] Gulisano F, Crucho J, Gallego J, Picado-Santos L. Microwave healing performance of asphalt mixture containing electric arc furnace (EAF) slag and graphene nanoplatelets (GNPs). Applied Sciences (Switzerland) 2020;10. https://doi.org/10.3390/app10041428.

[28] Ajam H, Gómez-Meijide B, Artamendi I, Garcia A. Mechanical and healing properties of asphalt mixes reinforced with different types of waste and commercial metal particles. Journal of Cleaner Production 2018;192:138–50. https://doi.org/10.1016/j.jclepro.2018.04.262.

[29] Le VP, Phong M, Phuc Q, Lam H. Case Studies in Construction Materials Marshall and Balanced mix design in determining the asphalt content for hot mix asphalt mixture : A comparative study. Case Studies in Construction Materials 2024;21:e03753. https://doi.org/10.1016/j.cscm.2024.e03753.

[30] Xu H, Wu S, Li H, Zhao Y, Lv Y. Study on Recycling of Steel Slags Used as Coarse and Fine Aggregates in Induction Healing. Materials 2020:1–16. https://doi.org/10.3390/ma13040889.

[31] Arabani M, Mirabdolazimi SM. Experimental investigation of the fatigue behaviour of asphalt concrete mixtures containing waste iron powder. Materials Science and Engineering A 2011;528:3866–70. https://doi.org/10.1016/j.msea.2011.01.099.

[32] Chen W, Wei J, Xu X, Zhang X, Han W, Yan X, et al. Study on the Optimum Steel Slag Content of SMA-13 Asphalt Mixes Based on Road Performance. Coatings 2021:1–16. https://doi.org/https://doi.org/10.3390/coatings11121436.

[33] Sarir M, Khan R, Alam M, Tariq M, Waheed K. Performance Evaluation of Asphalt Concrete Mixtures Using Bagasse Ash as Filler. Iranian Journal of Science and Technology, Transactions of Civil Engineering 2022;46:1553–70. https://doi.org/10.1007/s40996-021-00641-8.

[34] Machsus M, Mawardi AF, Basuki R, Hadi AF, Annizza Putri Islamey, Ndruru KS, et al. Utilization of teak wood powder waste as eco-friendly filler in HRS-WC asphalt : a comparative analysis of dry and wet Marshall mix methods. SINERGI 2026;30:263–72. https://doi.org/http://doi.org/10.22441/sinergi.2026.1.024.

[35] Fanggi BAL, Tajunnisa Y, Masrafat H, Rafael JWM. Effect of Sand Type Variation on the Density and Compressive Strength of Lightweight Concrete with Artificial Lightweight Coarse Aggregate. Jurnal Teknik Sipil 2025;14:74–80.

[36] Woszuk A, Bandura L, Franus W. Fly ash as low cost and environmentally friendly filler and its effect on the properties of mix asphalt. Journal of Cleaner Production 2019;235:493–502. https://doi.org/10.1016/j.jclepro.2019.06.353.

[37] Zhang J, Li P, Liang M, Jiang H, Yao Z, Zhang X, et al. Utilization of red mud as an alternative mineral filler in asphalt mastics to replace natural limestone powder. Construction and Building Materials 2020;237:117821. https://doi.org/10.1016/j.conbuildmat.2019.117821.

[38] Wang F, Xiao Y, Cui P, Ma T, Kuang D. Effect of aggregate morphologies and compaction methods on the skeleton structures in asphalt mixtures. Construction and Building Materials 2020;263:120220. https://doi.org/10.1016/j.conbuildmat.2020.120220.

[39] Ullah S, Shah MI, Alqurashi M, Javed MF, Dawood O, Aslam F, et al. Eco-Friendly Incorporation of Crumb Rubber and Waste Bagasse Ash in Bituminous Concrete Mix. Materials 2022:1–13. https://doi.org/https://doi.org/10.3390/ma15072509.

[40] Samuel K, Williams M, Kupolati K, Andre E, Julius B, Ndambuki M, et al. Performance Evaluation and Future Prospects of the Wastewater Sludge Ash as a Filler Material in Asphalt

Mixture. Materials Circular Economy 2025;7:1–17. https://doi.org/10.1007/s42824-025-00177-6.

[41] Mohammed SI. Effect of using waste iron powder as filler on asphalt mixture properties. Journal of University of Duhok 2021;24:10–8. https://doi.org/https://doi.org/10.26682/sjuod.2021.24.1.2.

[42] AASTHO T 283-07. Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage. 2008.

[43] Indonesian National Standards. Test Method for the Resistance of Hot Mix Asphalt to Moisture-Induced Damage. 2015.

[44] Ameri M, Sadeghiavaz M. Microwave healing properties and moisture sensitivity of asphalt mixture containing iron powder filler. Scientific Reports 2024:1–17. https://doi.org/https://doi.org/10.1038/s41598-024-73290-21.

[45] Wang Y, Latief RH, Al-mosawe H, Mohammad HK, Albayati A, Haynes J. Influence of iron filing waste on the performance of warm mix asphalt. Sustainability (Switzerland) 2021;13. https://doi.org/10.3390/su132413828.

[46] Xiao Z, Chen M, Wu S, Xie J, Kong D, Qiao Z. Moisture Susceptibility Evaluation of Asphalt Mixtures Containing Steel Slag Powder as Filler. Materials 2019:1–15. https://doi.org/10.3390/ma12193211.

[47] Dondi G, Mazzotta F, Lantieri C, Cuppi F, Vignali V, Sangiovanni C. Use of Steel Slag as an Alternative to Aggregate and Filler in Road Pavements. Materials 2021:1–13. https://doi.org/https://doi.org/10.3390/ma14020345.

[48] García Á. Self-healing of open cracks in asphalt mastic. Fuel 2011;93:264–72. https://doi.org/10.1016/j.fuel.2011.09.009.

[49] Es-samlali L, El Y, Oudrhiri-hassani F. Performance assessment of sustainable asphalt concrete using steel slag , with an artificial neural network prediction of asphalt concrete behavior. Case Studies in Construction Materials 2024;21:1–16. https://doi.org/10.1016/j.cscm.2024.e03877.

[50] Norambuena-Contreras J, Concha JL, Varela MJ, Trigos L, Poulikakos L, González A, et al. Microwave Heating and Self-Healing Performance of Asphalt Mixtures Containing Metallic Fibres from Recycled Tyres. Materials 2024;17:1–21. https://doi.org/10.3390/ma17235950.

[51] Sun Y, Zhang X, Chen J, Liao J, Shi C. Mixing design and performance of porous asphalt mixtures containing solid waste. Case Studies in Construction Materials 2024;21:e03644. https://doi.org/10.1016/j.cscm.2024.e03644.