Microwave-Induced Self-Healing Performance of Asphalt Concrete Wearing Course (AC-WC) Mixtures Incorporating Beach Sand as Fine Aggregate

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Received: 22 December 2025 | Revised: 17 January 2026 | Accepted: 25 January 2026

ABSTRACT

This study investigates the microwave-induced self-healing performance of AC-WC mixtures incorporating beach sand as a partial replacement for fine aggregate. Beach sand was substituted at levels

of 0%, 10%, 15%, and 25% by weight of fine aggregate. Marshall tests were conducted to evaluate the mechanical and volumetric properties of the mixtures, while self-healing performance was assessed through repeated fracture and microwave heating cycles with heating durations of 40 s, 60 s, and 80 s. The results show that increasing beach sand content leads to a gradual reduction in Marshall stability and mixture stiffness, accompanied by an increase in flow values. Nevertheless, all mixtures satisfied the Marshall and volumetric requirements specified in the 2018 Bina Marga General Specifications. The self-healing evaluation indicates that the Healing Ratio (HR) improves with increasing beach sand content and longer microwave heating durations. The highest final HR of 35% was achieved at a beach sand content of 25% with heating durations of 60 s and 80 s. Among the evaluated heating durations, 60 s provided the most stable healing performance over repeated cycles, indicating an optimal balance between heat transfer and material integrity. Overall, the incorporation of beach sand as fine aggregate combined with microwave activation enhances the self-healing capability of AC-WC mixtures while maintaining acceptable mechanical performance.

Keywords-microwave-induced self-healing; beach sand aggregate; asphalt concrete wearing course; marshall properties; healing ratio

I. INTRODUCTION

Asphalt concrete pavements are extensively applied in road infrastructure due to their favorable structural performance, construction efficiency, and adaptability to various traffic and environmental conditions. Nevertheless, asphalt mixtures are inherently susceptible to progressive deterioration caused by repetitive traffic loading, temperature fluctuations, moisture infiltration, and oxidative aging of the asphalt binder, which collectively lead to cracking and premature pavement failure [1, 2]. Microcracks initiated during early service stages may gradually propagate into macrocracks, significantly reducing pavement durability and increasing maintenance demands, particularly under heavy traffic and harsh environmental conditions [3]. This progressive deterioration is fundamentally associated with reductions in elastic and dynamic modulus, changes in viscoelastic response, and increased temperature–frequency dependency, which collectively govern fatigue degradation and rutting susceptibility of asphalt pavements [4, 5]. These mechanistic degradations not only reduce the load-bearing capacity but also accelerate damage accumulation under repeated traffic and environmental loading. Consequently, innovative damage-mitigation strategies, particularly thermally activated self-healing approaches such as microwave-induced healing, are increasingly explored to restore mechanical performance and extend pavement service life. Self-healing asphalt technology is an effective strategy to mitigate crack development and extend pavement service life by enabling partial recovery of mechanical properties during rest periods [6]. The healing capability of asphalt mixtures is primarily governed by the rheological behavior of the asphalt binder, including viscous flow, surface wetting, and molecular diffusion across crack interfaces [6, 7]. In addition to thermal activation, the incorporation of functional materials and additives has also been reported to improve self-healing performance by enhancing binder elasticity and recovery behavior [9]. However, under normal service temperatures, the natural healing process remains relatively slow and limited, which has encouraged the application of external energy sources to accelerate healing and improve damage recovery efficiency [10].

Among various activation techniques, thermal-based methods, such as induction heating and microwave heating, have attracted research interest due to their ability to rapidly increase internal temperature and enhance binder mobility [10, 11]. Microwave heating is particularly advantageous because it enables volumetric heat generation within asphalt mixtures without direct contact, resulting in a rapid and uniform temperature rise and improved healing efficiency [12, 13]. Microwave-assisted healing can effectively restore the stiffness and strength of cracked asphalt specimens when appropriate heating durations and mixture compositions are applied [14-16]. Nevertheless, excessive or non-uniform heating may adversely affect material integrity and long-term healing stability, highlighting the importance of optimizing both mixture design and heating parameters [17, 18].

The heating efficiency and self-healing effectiveness of asphalt mixtures under microwave exposure are strongly influenced by the physical, thermal, and electromagnetic properties of their constituent materials, particularly aggregates [19, 20]. Aggregates containing mineral components with higher dielectric properties or enhanced heat absorption capacity can significantly improve microwave responsiveness, leading to more efficient heat distribution and improved healing behavior [21, 22]. The incorporation of mineral-rich or conductive materials, such as steel slag, carbonyl iron powder, or metal-containing aggregates, can significantly enhance microwave-induced self-healing performance of asphalt mixtures [13, 15, 23, 24]. Furthermore, the combined use of material modification strategies and thermal activation techniques has been shown to improve the functional performance and durability of asphalt-based materials under repeated loading conditions [15, 25, 26]. Natural beach sand is an abundant material in many coastal regions and has been investigated as a potential partial replacement for conventional fine aggregate in asphalt mixtures [27, 28]. Beach sand can be used within certain replacement limits while still satisfying Marshall and volumetric requirements. However, reductions in mixture stability and stiffness may occur at higher substitution levels due to differences in particle shape and surface texture compared with conventional crushed aggregates [27-29]. The properties of beach sand, including gradation, angularity, surface texture, and mineral composition, vary depending on its geological origin and can significantly influence asphalt mixture performance [28, 30, 31]. Beach sand originating from iron-rich coastal areas may exhibit enhanced heat absorption under microwave exposure, which suggests a potential contribution to improving the microwave-induced self-healing capability of asphalt mixtures [24, 30, 32]. Research on iron-bearing coastal sands and black sands has reported that such materials commonly contain minerals like magnetite, ilmenite, and titanomagnetite, which exhibit favorable electromagnetic and thermal response characteristics under external energy exposure [33-35]. These mineralogical features suggest a plausible mechanism by which iron-rich beach sand may enhance microwave energy absorption and internal heat generation in asphalt mixtures. Although direct mineralogical or dielectric characterization was not conducted in the present study, the potential role of iron-rich beach sand in enhancing microwave-induced healing is discussed based on observed healing trends and relevant literature.

Despite the growing body of research on self-healing asphalt and alternative fine aggregates, limited studies have systematically examined the combined effects of beach sand substitution and microwave activation on the self-healing behavior of AC-WC mixtures, particularly under repeated fracture-healing cycles. Unlike previous studies that primarily focused on microwave self-healing or alternative aggregates separately, this study explicitly investigates the combined influence of beach sand content and microwave heating duration on both mechanical performance and self-healing efficiency. Therefore, this study aims to evaluate the microwave-induced self-healing performance of AC-WC mixtures incorporating beach sand as a partial replacement for fine aggregate. The influence of beach sand substitution levels and microwave heating durations on Marshall properties and healing efficiency is investigated to provide insights into the feasibility of integrating locally available materials with advanced self-healing techniques for more durable and sustainable pavement systems.

II. MATERIALS AND METHODS CHARACTERIZATION

A. Material Characterization

1) Asphalt Binder

The asphalt binder used in this study was penetration grade 60/70, which is commonly applied for wearing course mixtures in tropical regions. The binder was selected in accordance with the requirements specified in the 2018 Bina Marga General Specifications for AC-WC mixtures. Before mixture preparation, standard physical tests were conducted to verify that the binder satisfied the required performance criteria for paving applications. The physical properties of the asphalt binder, including penetration, softening point, flash point, ductility, and loss on heating, are summarized in Table I. All measured parameters were within the specified limits, confirming the suitability of the binder for use in the experimental program.

TABLE I. PHYSICAL PROPERTIES OF ASPHALT BINDER

Property	Test result	Specification requirement
Penetration (0.1 mm) 63.5	63.5	60-70
Softening point (°c)	52	≥ 48
Flash point (°c)	272	≥ 232
Ductility (cm)	113.5	≥ 100
Loss on heating (%)	0.41	≤ 0.8

2) Coarse Aggregate

Crushed stone coarse aggregate was obtained from a local quarry and used as the primary load-bearing component of the asphalt mixture. The aggregate exhibited angular particle shape and rough surface texture, which are essential characteristics for achieving adequate interlocking, shear resistance, and mechanical stability in AC-WC mixtures.

TABLE II. PHYSICAL PROPERTIES OF AGGREGATES AND BEACH SAND

Property	Coarse aggregate	Fine aggregate	Beach sand
Bulk specific gravity	2.609	2.570	2.563
Water absorption (%)	2.359	1.574	2.801
Los Angeles abrasion (%)	27.42	-	-
Material passing no. 200 (%)	0.27	9.49	-
Clay lumps (%)	-	0.96	-
Angularity (%)	-	46.12	-
Salt content (%)	-	-	0.01

The physical properties of the coarse aggregate, including bulk specific gravity, water absorption, and Los Angeles abrasion value, were evaluated in accordance with relevant testing standards. As presented in Table II, all properties complied with the requirements of the 2018 Bina Marga General Specifications, indicating that the coarse aggregate was suitable for use in the mixture design. Compared with conventional fine aggregate, beach sand exhibits higher water absorption and smoother particle surfaces, both of which have important implications for asphalt mixture behavior. Increased water absorption can raise asphalt binder demand and may weaken asphalt–aggregate adhesion if not adequately considered during mixture design. In addition, the smoother and more rounded particle morphology of beach sand reduces internal friction and aggregate interlocking during compaction, which can result in lower mixture stiffness and stability. These characteristics help explain the observed reductions in Marshall stability and Marshall Quotient (MQ), as well as the increase in flow values reported in the Results and Discussion section. Therefore, although beach sand satisfies basic physical requirements, its surface morphology and absorption characteristics play a critical role in governing compaction behavior, bonding efficiency, and the overall mechanical performance of AC-WC mixtures.

3) Fine Aggregate

Conventional fine aggregate sourced from the same quarry was used as the control fine material in the asphalt mixtures. The fine aggregate consisted of crushed particles with sufficient angularity to contribute to mixture stiffness, internal friction, and resistance to permanent deformation. Laboratory tests were conducted to determine bulk specific gravity, water absorption, material passing the No. 200 sieve, clay lump content, and angularity. As shown in Table II, all measured properties satisfied the specification limits for AC-WC applications.

4) Beach Sand

Natural beach sand was employed as a partial replacement for conventional fine aggregate in this study. The beach sand was collected from a coastal area in Cilacap, Indonesia, a region recognized for its iron-rich sand deposits. Before use, the sand was thoroughly washed with clean water to remove impurities and salt residues and subsequently oven-dried to a constant mass. The material was then sieved to ensure compatibility with the gradation requirements of AC-WC mixtures. The physical characteristics of the beach sand, including bulk specific gravity, water absorption, and salt content, are summarized in Table II. Compared with conventional fine aggregate, the beach sand exhibited slightly higher water absorption and smoother particle surfaces. These characteristics may influence asphalt-aggregate bonding, mixture workability, and mechanical performance, particularly through reduced aggregate interlocking. In addition, although direct mineralogical or dielectric characterization was not conducted in this study, the iron-rich nature of the beach sand is expected to enhance heat absorption under microwave exposure, potentially contributing to improved self-healing performance.

B. *Mixture Design and Specimen Preparation*

The AC-WC mixture was designed in accordance with the 2018 Bina Marga General Specifications using the Marshall mix design method [36]. The Optimum Asphalt Content (OAC) was first determined based on conventional Marshall parameters, including Marshall stability, flow, Air Voids (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA). The selected OAC satisfied all specification requirements for wearing course mixtures. After determining the OAC, modified asphalt mixtures were prepared by partially replacing conventional fine aggregate with beach sand at substitution levels of 0%, 10%, 15%, and 25% by weight of the fine aggregate. To isolate the effects of beach sand substitution and microwave heating duration, all mixtures were produced using the same asphalt content corresponding to the OAC. The mixture variations and microwave heating parameters adopted in the experimental program are outlined in Table III. Beach sand was incorporated at different substitution levels, and three microwave heating durations (40 s, 60 s, and 80 s) were applied to evaluate the self-healing performance under repeated fracture-healing cycles.

TABLE III. MIXTURE VARIATIONS AND MICROWAVE HEATING PARAMETERS

Mixture code	Beach sand content (% of fine aggregate)	Asphalt content (%)	Heating duration (s)	Number of healing cycles
BS0	0	6.6	40, 60, 80	4
BS10	10	6.6	40, 60, 80	4
BS15	15	6.6	40, 60, 80	4
BS25	25	6.6	40, 60, 80	4

Marshall specimens were prepared following standard compaction procedures specified for AC-WC mixtures using a Marshall hammer to ensure uniform density and reproducibility. For self-healing evaluation, semi-circular specimens were produced from the same mixture compositions to maintain consistency between mechanical performance testing and microwave-induced self-healing assessment.

C. *Marshall Properties Testing*

Marshall tests were conducted to evaluate the mechanical and volumetric properties of the AC-WC mixtures incorporating beach sand. The evaluated parameters included Marshall stability, flow, MQ, VIM, VMA, and VFA. All tests were conducted in accordance with the standard Marshall testing procedure [31]. The test results were then compared with the requirements of the 2018 Bina Marga General Specifications to evaluate the compliance and suitability of each mixture variation for wearing course applications.

D. *Self-Healing Test Procedure*

The self-healing performance of the asphalt mixtures was evaluated using a microwave-induced healing method, following procedures commonly reported in previous studies [15, 37]. Semi-circular specimens were first conditioned at low temperature to ensure consistent crack initiation and then subjected to controlled fracture loading to induce a single central crack. The fracture loading configuration and the resulting cracked specimen are depicted in Figures 1(a) and 1(b), respectively. After fracture, the specimens were carefully reassembled to restore their original geometry and subsequently subjected to microwave heating to activate the healing process. Microwave heating durations of 40 s, 60 s, and 80 s were applied to examine the influence of heating time on healing efficiency. The microwave heating stage and the arrangement of specimens inside the microwave oven during the healing process are presented in Figures 1(c) and 1(d).


(a) (b) (c) (d)

Fig. 1. The microwave-induced self-healing test procedure. (a) Fracture loading, (b) cracked semi-circular specimen, (c) microwave heating stage, (d) specimen arrangement during healing cycles.

The microwave oven operated at a fixed power level (domestic microwave configuration). Internal specimen temperature was not directly monitored during heating; therefore, heating duration was used as the primary control parameter. The potential influence of temperature variation among different mixtures is acknowledged as an experimental limitation and is discussed in the Results and Discussion section. Following microwave heating, the specimens were allowed to heal under ambient laboratory conditions before being reloaded to failure. The sequence consisting of fracture loading, crack formation, microwave heating, healing, and re-fracture constituted one complete self-healing cycle. This fracture-healing process was repeated for multiple cycles to evaluate the durability and repeatability of the healing capability. The overall microwave-induced self-healing test cycle is schematically illustrated in Figure 2.

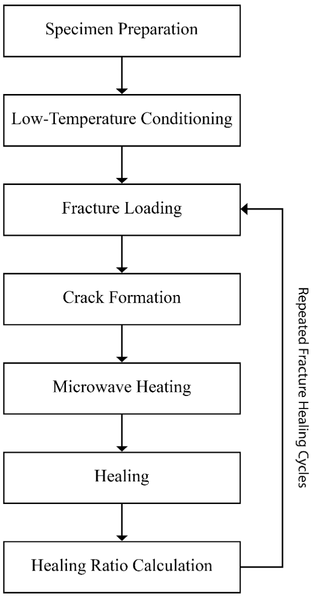

Fig. 2. Schematic illustration of the microwave-induced self-healing test cycle.

HR was calculated using:

$$HR\ (\%) = \frac{P_h}{P_0} \times 100 \qquad (1)$$

where P_h is the recovered fracture load after a given healing cycle and P_0 is the initial fracture load before healing. This parameter quantitatively represents the healing efficiency and allows the evaluation of its evolution under repeated damage–healing cycles.

E. Data Analysis

The effects of beach sand substitution level and microwave heating duration on the Marshall properties and self-healing performance of the asphalt mixtures were evaluated through systematic comparative analysis of all mixture variations. Marshall parameters, including stability, flow, MQ, VIM, VMA, and VFA, were analyzed to assess the influence of fine aggregate substitution on the mechanical and volumetric behavior of the mixtures. For the self-healing assessment, the HR obtained from repeated fracture-healing cycles was used as the primary performance indicator. The HR evolution with respect to beach sand content, microwave heating duration, and number of healing cycles was examined to evaluate both the effectiveness and durability of the healing mechanism. All experimental results were analyzed using a comparative, trend-based approach without applying statistical hypothesis testing. This approach was adopted due to the exploratory nature of the study and its emphasis on identifying relative performance trends, response consistency, and practical implications for mixture design and microwave activation. The analysis enabled the identification of mixture configurations and microwave heating conditions that achieved a favorable balance between mechanical performance and microwave-induced self-healing capability.

III. RESULTS AND DISCUSSION

A. Marshall Properties of AC-WC Mixtures

The Marshall test results indicate that the partial replacement of fine aggregate with beach sand significantly influences the mechanical performance of AC-WC mixtures. As the beach sand content increased from 0% to 25%, Marshall stability decreased from 901.9 kg to 802.32 kg, corresponding to an approximate reduction of 11%. This decline reflects a reduced resistance to load-induced deformation and is primarily attributed to the smoother surface texture and more rounded particle shape of beach sand, which weakens aggregate interlocking compared with conventional crushed fine aggregate. Similar reductions in stability and stiffness have been reported in asphalt mixtures incorporating natural sands, recycled concrete aggregates, or other alternative fine materials with lower angularity and surface roughness [28, 31, 38]. The diminished mechanical interlocking limits the ability of the aggregate skeleton to effectively transfer and resist applied loads, resulting in lower stability values. Nevertheless, all mixtures exhibited Marshall stability values exceeding the minimum requirements of the 2018 Bina Marga General Specifications, confirming their structural suitability for wearing course applications. The corresponding Marshall properties and volumetric parameters are presented in Table IV.

TABLE IV. MARSHALL PROPERTIES AND VOLUMETRIC PARAMETERS OF AC-WC MIXTURES INCORPORATING BEACH SAND

Beach sand content (% of fine aggregate)	**Stability (kg)**	**Flow (mm)**	**MQ (kg/mm)**	**VIM (%)**	**VMA (%)**	**VFA (%)**
0	901.90	3.43	264.27	4.02	18.83	78.69
10	835.33	3.67	227.68	4.07	18.86	78.48
15	817.11	3.67	222.58	4.13	18.88	78.10
25	802.32	3.86	207.68	4.81	19.25	75.04

As portrayed in Figure 3, Marshall stability decreased progressively with increasing beach sand content. The observed trend confirms that the reduction in stability is closely related to diminished aggregate interlocking caused by smoother particle morphology. Nevertheless, the stability values of all mixtures exceeded the specification threshold, confirming the feasibility of beach sand substitution up to the investigated levels.

The variation of Marshall flow with beach sand content is presented in Figure 4. Flow values increased from 3.43 mm for the control mixture to 3.86 mm at 25% beach sand content, representing an increase of approximately 13%. This increase indicates enhanced mixture deformability and is associated with reduced internal friction resulting from the replacement of angular crushed fine aggregate with natural sand. Comparable increases in flow values have been reported in asphalt mixtures incorporating alternative fine aggregates or recycled materials with smoother surface characteristics [38, 39].

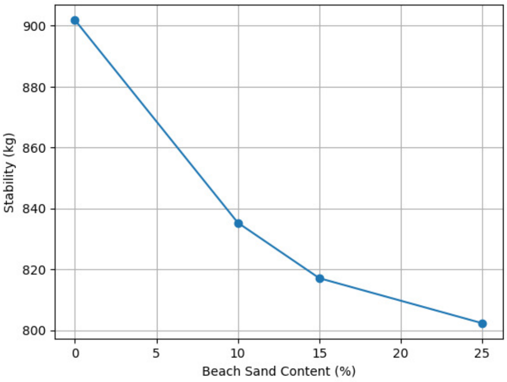

Fig. 3. Effect of beach sand content on Marshall stability of AC-WC mixtures.

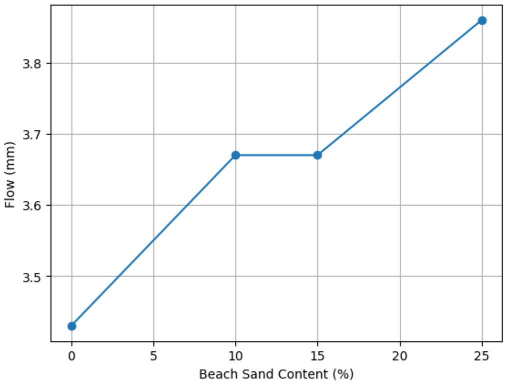

Fig. 4. Effect of beach sand content on Marshall flow of AC-WC mixtures.

The combined effect of decreasing stability and increasing flow resulted in a reduction of the MQ, as illustrated in Figure 5. The MQ decreased from 264.27 kg/mm to 207.68 kg/mm as beach sand content increased from 0% to 25%, corresponding to a reduction of approximately 21%. This trend indicates a decrease in mixture stiffness and a transition toward more flexible mechanical behavior. While increased flexibility may enhance crack accommodation capability, excessive stiffness reduction could increase susceptibility to permanent deformation under traffic loading. Similar stiffness-flexibility trade-offs have been widely discussed in studies on modified asphalt mixtures and alternative aggregate incorporation [40, 41].

The decreasing MQ indicates a reduction in mixture stiffness, suggesting a transition toward a more flexible mechanical response as the beach sand content increases. It has been further confirmed that modifying mixture stiffness through material incorporation can significantly influence both healing efficiency and durability under thermal activation [42]. Regarding volumetric properties, the VIM, VMA, and VFA values remained within the specified limits for all mixture variations, as summarized in Table IV. The relatively stable volumetric behavior indicates that the substitution of beach sand up to 25% did not significantly disrupt the internal structure of the mixtures. Consequently, the observed changes in mechanical performance were primarily governed by aggregate surface characteristics and particle morphology rather than volumetric deficiencies. Overall, the Marshall test results demonstrate that beach sand can be used as a partial replacement for fine aggregate in AC-WC mixtures at substitution levels of up to 25% without violating standard mechanical and volumetric requirements. However, the observed gradual reductions in stability and stiffness with increasing beach sand content emphasize the need to carefully balance mixture strength and flexibility, particularly for wearing course applications exposed to traffic loading and environmental stresses.

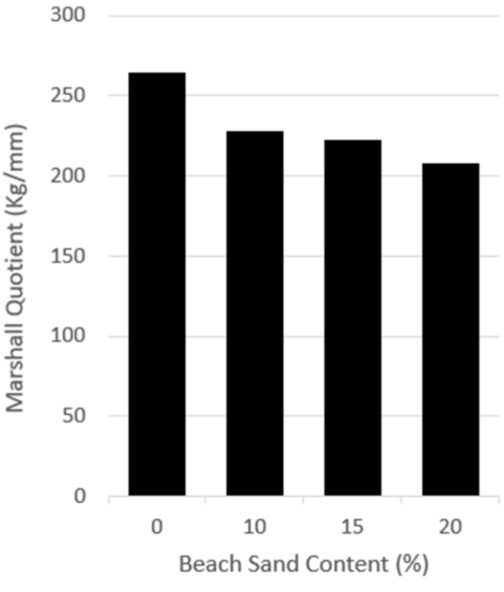

Fig. 5. Effect of beach sand content on MQ of AC-WC mixtures.

B. *Microwave-Induced Self-Healing Performance*

The self-healing test results demonstrate that both beach sand substitution level and microwave heating duration significantly influenced the healing behavior of AC-WC mixtures. For all mixture variations, HR decreased with increasing fracture-healing cycles, indicating cumulative damage and incomplete recovery of mechanical integrity under repeated loading. A similar decline in healing efficiency with repeated cycles has been reported in [18, 43]. At a given microwave heating duration, mixtures incorporating beach sand consistently exhibited higher HRs than the control mixture, with the improvement becoming more pronounced as beach sand content increased. This behavior can be attributed to enhanced microwave energy absorption and more effective heat distribution within the mixture, which promotes greater asphalt binder mobility and improved crack closure at the fracture interface. Variations in microwave heating efficiency associated with material composition and internal structure have also been observed in reclaimed asphalt pavement systems [20].

It has been demonstrated that aggregates with favorable thermal or mineralogical characteristics can significantly enhance microwave-induced self-healing efficiency in asphalt mixtures [44, 45]. In addition, the use of functional aggregates and waste-derived materials can further improve microwave heating efficiency and healing effectiveness in asphalt concrete [22]. Similar improvements in microwave-induced healing efficiency have also been reported in asphalt mixtures incorporating thermally responsive fibers or functional inclusions that enhance heat transfer and binder flow [13]. Microwave heating duration also played a critical role in determining healing efficiency and stability. Increasing the heating duration from 40 s to 60 s resulted in a substantial improvement in HRs for all mixtures. However, further increasing the heating duration to 80 s led to higher initial HRs but a more pronounced reduction in healing efficiency with increasing cycles. This behavior suggests that excessive thermal exposure may negatively affect long-term healing stability, potentially due to accelerated binder aging or microstructural degradation. Similar effects of excessive microwave heating have been reported in [18, 38]. In addition, thermal activation via microwave heating has been shown to simultaneously improve self-healing and thermal-related functionalities, such as deicing efficiency in asphalt concrete [32]. The final HRs obtained after repeated fracture–healing cycles under different microwave heating durations are outlined in Table V. The highest final HR of 35% was achieved for mixtures incorporating 25% beach sand at heating durations of 60 s and 80 s. It has been highlighted that microwave heating duration plays a critical role in controlling both the effectiveness and long-term stability of the self-healing response in asphalt mixtures [17].

TABLE V. FINAL HR OF AC-WC MIXTURES UNDER DIFFERENT MICROWAVE HEATING DURATIONS

Beach sand content (% of fine aggregate)	**HR (%) 40 s**	**HR (%) 60 s**	**HR (%) 80 s**
0	6	8	16
10	13	22	25
15	16	22	29
25	20	35	35

Figures 6-Figure 8 exhibit the HR evolution over repeated fracture–healing cycles under microwave heating durations of 40 s, 60 s, and 80 s, respectively. Under 40 s of heating, all mixtures exhibited a gradual decline in HR with increasing cycles, although mixtures containing beach sand consistently achieved higher HRs than the control mixture. At a heating duration of 60 s, the mixtures showed higher HRs and a more stable healing response across successive cycles, indicating an optimal balance between thermal activation and preservation of material integrity. In contrast, heating for 80 s produced higher initial HRs; however, a more rapid decline in healing efficiency was observed with repeated cycles, suggesting reduced durability of the healing mechanism due to excessive thermal exposure.

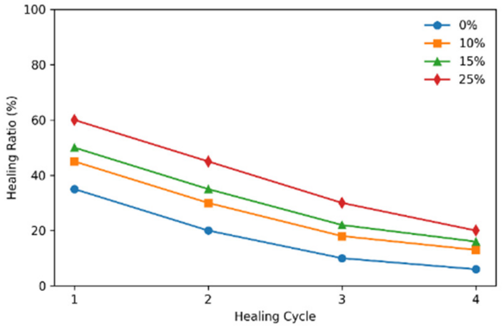

Fig. 6. HR evolution over repeated fracture-healing cycles under 40 s microwave heating.

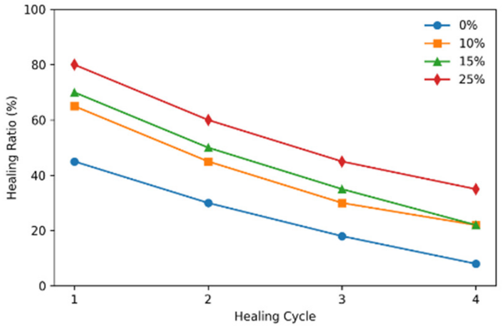

Fig. 7. HR evolution over repeated fracture-healing cycles under 60 s microwave heating.

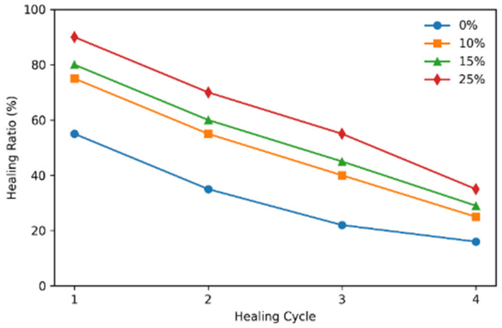

Fig. 8. HR evolution over repeated fracture-healing cycles under 80 s microwave heating.

The gradual reduction in HR with increasing cycles is consistent with previous findings on microwave-healed asphalt mixtures subjected to repeated damage or environmental conditioning [46]. These results demonstrate a strong interaction between the level of beach sand substitution and microwave heating duration in determining healing efficiency and durability. While higher beach sand contents enhance microwave energy absorption and promote binder mobility, the effectiveness of the healing process is strongly dependent on the applied heating duration. From a practical perspective, these results indicate that the incorporation of beach sand as a partial replacement for fine aggregate can significantly enhance the self-healing capability of AC-WC mixtures when combined with appropriate microwave heating. Moderate heating durations provide sufficient thermal activation to promote asphalt binder mobility and crack closure without causing excessive thermal damage, thereby offering a promising approach to improving pavement durability while making effective use of locally available materials.

C. Interaction Between Mechanical Properties and Self-Healing Behavior

The experimental results revealed an interaction between the mechanical characteristics of the mixtures and their microwave-induced self-healing performance. Mixtures exhibiting lower stiffness and higher deformability, as reflected by reduced MQ values, generally demonstrated higher HRs under repeated fracture-healing cycles. In contrast, mixtures with higher stiffness showed comparatively lower healing efficiency. This inverse relationship indicates that increased mixture flexibility facilitates asphalt binder flow and crack closure during thermal activation, whereas excessive stiffness restricts binder mobility at the crack interface. Similar interactions between stiffness reduction and enhanced healing efficiency have been reported in [35, 47]. The observed interaction highlights an important design consideration for self-healing asphalt mixtures, namely the need to balance load-bearing capacity and healing potential. While reduced stiffness may enhance healing efficiency, excessive loss of mechanical strength could compromise resistance to permanent deformation and rutting. In this study, mixtures incorporating beach sand achieved this balance by maintaining compliance with Marshall specification requirements while exhibiting improved self-healing performance under microwave activation. From a practical standpoint, these findings suggest that incorporating beach sand as a partial replacement for fine aggregate, combined with optimized microwave heating duration, can enhance the self-healing capacity of AC-WC mixtures without compromising essential mechanical performance. This integrated approach provides a viable pathway for improving pavement durability and functional performance using locally available materials and advanced self-healing techniques.

IV. CONCLUSIONS

This study investigated the mechanical characteristics and microwave-induced self-healing performance of AC-WC mixtures incorporating beach sand as a partial replacement for fine aggregate. Based on the experimental results, the following conclusions can be drawn:

- The substitution of conventional fine aggregate with beach sand resulted in a gradual reduction in Marshall stability and mixture stiffness. At a beach sand substitution level of 25%, Marshall stability decreased by approximately 11%, while the MQ decreased by about 21% compared to the control mixture. Despite these reductions, all mixtures satisfied the Marshall and volumetric requirements specified in the 2018 Bina Marga General Specifications.
- Microwave activation effectively enhanced the self-healing capability of the asphalt mixtures by increasing asphalt binder mobility and facilitating crack closure at the fracture interface. For the control mixture, microwave heating at 60 s increased the final Healing Ratio (HR) from 8% to 22%, demonstrating the effectiveness of thermal activation.
- Mixtures incorporating beach sand consistently exhibited higher HRs than the unmodified mixture. At a beach sand content of 25% and a microwave heating duration of 60 s, the final HR reached 35%, representing an improvement of approximately 27% compared with the unmodified mixture under the same heating conditions.
- Increasing the microwave heating duration from 40 s to 60 s significantly improved healing efficiency and provided a more stable healing response over repeated fracture-healing cycles. However, further increasing the heating duration to 80 s resulted in reduced healing stability, suggesting that excessive thermal exposure may adversely affect long-term healing durability.
- The results demonstrate that beach sand can be feasibly utilized as a partial fine aggregate substitute in AC-WC mixtures to enhance microwave-induced self-healing performance while maintaining acceptable mechanical and volumetric properties. An optimal balance between healing efficiency and durability was achieved at a beach sand substitution level of 25% and a moderate microwave heating duration of 60 s.

ACKNOWLEDGMENT

This research was supported by Universitas Muhammadiyah Surakarta, Universitas Muhammadiyah Aceh, and the Ministry of Higher Education, Science, and Technology under Grant Nos. 299/SPK/C.C4/PPK.DHK/IX/2025; 003/LL6/AL.04/AI-SINERGI/2025; and 124.8/A.3-III/DRPPS/IX/2025. The authors gratefully acknowledge the financial and technical support that made this study possible.

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