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ARTICLE

Effect of Steel Wool Fibre Addition on Self-Healing Capability and Marshall Characteristics of Rehabilitated Asphalt Concrete Wearing Course (AC–WC)

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ABSTRACT

This study investigates the effect of steel wool fibre addition on the self-healing capability and Marshall performance of Asphalt Concrete Wearing Course (AC–WC). The concept of induction-activated self-healing is introduced to prolong pavement service life by restoring mechanical integrity after microcracking. Four fibre dosages (0%, 1%, 1.5%, and 2%) were evaluated through Marshall testing and controlled induction-healing cycles. The Marshall results revealed a decreasing stability trend with increasing fibre content, from 1870 kg at 0 % to 1717 kg, 1367 kg, and 1038 kg at 1%, 1.5%, and 2%, respectively. Flow increased to 4.3 mm at 1.5% before slightly decreasing at 2%, while VIM rose significantly from 3.82% to 13.85% with increasing fibre dosage. The Marshall Quotient declined from 558 kg/mm at 0% to 276 kg/mm at 2%, indicating reduced stiffness at high fibre contents. Healing performance, assessed via three-point bending before and after induction, showed the highest recovery at 1–1.5% fibre content, confirming the role of conductive fibres in enabling localized binder regeneration. These findings demonstrate that a 1% fibre dosage offers a practical balance between structural stability and healing capability. The results support the potential use of conductive-fibre-modified asphalt as a cost-effective smart pavement strategy in tropical regions while highlighting the need for further field validation and standardization before large-scale implementation.

Keywords: Self-Healing Asphalt; Steel Wool Fibre; Induction Heating; AC–WC; Marshall Test; Pavement Durability

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1. Introduction

1.1. Background and Research Context

Asphalt pavements remain the most widely used material in road infrastructure due to their ease of construction, cost efficiency, and adaptability to different climatic and loading conditions. However, one persistent limitation of asphalt concrete is its susceptibility to microcracking caused by environmental aging, fatigue loading, and oxidation. These microcracks, when left unrepaired, propagate into more severe forms of distress such as rutting and potholes, ultimately shortening pavement service life and increasing maintenance costs [1]. In recent decades, researchers have explored advanced materials and technologies to address this limitation, among which the self-healing asphalt concept has emerged as a promising solution [2].

Self-healing asphalt is designed to autonomously restore its internal structure after damage, either through intrinsic mechanisms or external activation such as induction or microwave heating [3,4]. The use of conductive additives—particularly steel wool fibres—enables localized heating under electromagnetic fields, softening the binder and promoting crack closure through bitumen flow [5]. This method not only extends pavement lifespan but also supports the transition toward sustainable and low-maintenance infrastructure [6]. Several laboratory-based studies have confirmed that the integration of steel fibres or conductive particles enhances the recovery of stiffness and tensile strength after controlled cracking and induction heating cycles [7,8].

Recent advances have further optimized this concept by investigating the effects of heating parameters, coil configuration, and fibre dosage. For instance, Penalva-Salinas et al. (2024) demonstrated that induction efficiency can be significantly improved through optimized frequency and current control, leading to more uniform temperature distribution [9]. Similarly, Jian et al. (2023) applied statistical modelling using the Partial Least Squares (PLS) method to identify parameter combinations that maximize healing performance [10]. Complementary studies have shown that moderate fibre contents (typically 1–1.5%) achieve a desirable balance between structural stability and healing effectiveness, while excessive dosages may reduce mixture compactability and create excessive voids [4,11].

Beyond the mechanical advantages, self-healing technology also presents environmental benefits. According to Karimi et al. (2021), induction-based self-healing systems offer a sustainable alternative to conventional maintenance practices by reducing material waste and energy consumption [12]. Other studies such as Joenck et al. (2022) and Dovom et al. (2024) expanded this concept by incorporating industrial by-products (e.g., steel slag, graphite) alongside steel fibres to improve both conductivity and sustainability [13,14]. These developments align with the global movement toward circular construction materials and smart pavement systems, which integrate sensing, energy recovery, and self-repair capabilities [15].

In Indonesia and other tropical countries, the potential of conductive-fibre-modified asphalt is particularly relevant. High rainfall, temperature variation, and rapid traffic loading intensify cracking and oxidation rates. Prior works by Silitonga et al. (2018) have pioneered experimental evaluations of AC–WC mixtures with steel wool modification under local environmental conditions, showing that the approach is technically feasible and compliant with national specifications [16,17]. However, the optimal fibre content balancing self-healing efficiency and mechanical stability remains underexplored, especially within the framework of Indonesian road design standards such as SNI 06-2489-1991 and Bina Marga 2018 [18,19].

Therefore, this study aims to evaluate the mechanical and self-healing performance of AC–WC mixtures modified with varying steel wool fibre dosages (0%, 1%, 1.5%, and 2%) under induction heating. The objective is to determine the most effective composition that satisfies both structural and functional requirements. This research contributes to the advancement of smart pavement technologies by providing empirical data on healing performance and establishing a foundation for future field implementation in tropical climates.

1.2. Self-Healing Asphalt and Induction Heating Technology

Self-healing asphalt refers to the ability of asphalt mixtures to restore part of their mechanical integrity after damage by promoting the flow and reconnection of asphalt binder within microcracks [8]. This recovery process may occur naturally at elevated temperatures or be enhanced through external stimuli such as microwave heating, induction heating, and encapsulated rejuvenating agents [9,10].

Among these techniques, induction heating has attracted significant attention due to its rapid heating capability, controllability, and compatibility with existing pavement structures [4].

Induction-based self-healing relies on the presence of conductive materials embedded within the asphalt mixture. When subjected to an alternating electromagnetic field, these conductive elements generate heat through eddy current losses and magnetic hysteresis, resulting in localized temperature increases within the mixture [11]. The generated heat softens the surrounding asphalt binder, enabling it to flow into microcracks and partially restore structural continuity. Compared to conventional surface heating methods, induction heating is more energy-efficient, as heat is generated internally rather than transferred from the pavement surface [12].

1.3. Role of Steel Wool Fibre in Conductive Asphalt Mixtures

Steel wool fibres are among the most widely investigated conductive additives for induction-healable asphalt mixtures due to their high electrical conductivity, magnetic permeability, and fibrous geometry [13]. These properties enable the formation of interconnected conductive networks within the asphalt matrix, enhancing electromagnetic energy absorption and heat distribution during induction heating [14].

However, the incorporation of steel wool fibres also alters the mechanical and volumetric properties of asphalt mixtures. Fibres occupy space within the aggregate framework, potentially disrupting aggregate interlocking and increasing air void content [15]. While moderate fibre contents may improve mixture flexibility and crack resistance, excessive fibre inclusion can reduce stability and compactability [16]. Previous studies have reported that fibre contents in the range of 1–1.5% by total mix weight provide an effective balance between heating efficiency and mechanical performance, whereas higher dosages may lead to fibre agglomeration and reduced structural integrity [17,18].

1.4. Research Gap and Motivation

Despite substantial advances in induction-based self-healing asphalt technology, several research gaps remain. First, many studies focus primarily on heating efficiency or healing performance without sufficiently addressing compliance with standard mechanical and volumetric requirements, which are critical for surface layers such as Asphalt Concrete Wearing Course (AC–WC) [19]. Second, most experimental investigations have been conducted under temperate climatic conditions, with limited attention given to tropical environments characterized by high temperatures, intense rainfall, and accelerated aging processes [20].

Furthermore, there is a lack of integrated experimental frameworks that simultaneously evaluate Marshall characteristics, volumetric properties, and fracture-based healing performance. Such integrated assessments are necessary to identify fibre dosages that achieve a balanced performance rather than optimizing a single parameter at the expense of others [21].

1.5. Objectives and Contributions of the Study

In response to the identified research gaps, this study evaluates the effect of steel wool fibre addition on the mechanical performance and self-healing capability of Asphalt Concrete Wearing Course (AC–WC) mixtures. Four fibre dosages (0%, 1%, 1.5%, and 2% by total mix weight) were investigated using Marshall testing, volumetric analysis, and fracture-based healing evaluation under induction heating [22].

The main contributions of this study are threefold. First, it provides a comprehensive assessment of the influence of steel wool fibre content on Marshall characteristics and volumetric properties of AC–WC mixtures in accordance with Indonesian road specifications [23]. Second, it quantifies the self-healing performance of fibre-modified asphalt through fracture strength recovery under controlled induction heating conditions [24]. Third, it identifies an optimal fibre dosage that balances structural integrity and functional self-healing performance, with particular relevance to tropical climatic conditions [25].

2. Materials and Methods

This study was designed to evaluate the effect of steel wool fibre addition on the self-healing capability and mechanical characteristics of Asphalt Concrete Wearing

Course (AC–WC) mixtures through induction heating. The methodology consisted of four primary stages: material selection, specimen preparation, mechanical and healing performance testing, and data interpretation. All procedures were conducted following national and international asphalt testing standards, ensuring reproducibility and reliability of results [20].

2.1. Materials

The base asphalt mixture used was the Asphalt Concrete–Wearing Course (AC–WC), which serves as the surface layer in flexible pavement structures. Aggregates were sourced from a certified quarry and consisted of coarse aggregates, fine aggregates, and filler, each meeting the gradation and quality criteria specified in the Indonesian National Standard, SNI 06-2489-1991 [21]. The asphalt binder was Penetration Grade 60/70, selected for its proven balance between flexibility and durability, particularly under tropical environmental conditions [22–24].

Steel wool fibres were employed as the conductive additive responsible for enabling induction-based self-healing. These fibres were selected based on their high magnetic permeability and thermal conductivity, which promote efficient heat generation under electromagnetic exposure. The fibres used in this study had an average length of 10–15 mm and a nominal diameter of 0.25 mm. Four dosage levels—0%, 1%, 1.5%, and 2% by total mix weight—were investigated. Similar dosage ranges have been reported to effectively balance the structural and self-healing performance of conductive asphalt mixtures [4,9,25].

The material configuration was designed with reference to the recommendations of Silitonga et al. [16] and Liu et al. [26], who suggested that moderate fibre content (1–1.5%) enhances binder connectivity and improves induction response without significantly reducing compactability. **Figure 1** illustrates the conceptual framework of the induction-healing mechanism adopted in this study, adapted from recent studies [9,27].

2.2. Sample Preparation

Sample preparation followed the Marshall Mix Design Method, as outlined in SNI 06-2489-1991 [21], with adaptations for fibre inclusion. Aggregates and filler were first oven-dried at 170 °C, then blended according to the target gradation. Steel wool fibres were gradually introduced into the heated aggregates to ensure uniform dispersion prior to binder addition. The mixture was manually stirred until a homogeneous composition was achieved.

The blended material was compacted using a Marshall compactor with 75 blows per side, representing heavy-traffic conditions per Bina Marga specifications [28]. Twelve samples were produced for each mixture variation, resulting in a total of 48 specimens for complete analysis. Compacted samples were allowed to cool to room temperature for at least 24 h before testing to ensure proper binder stabilization and to minimize internal stress development.

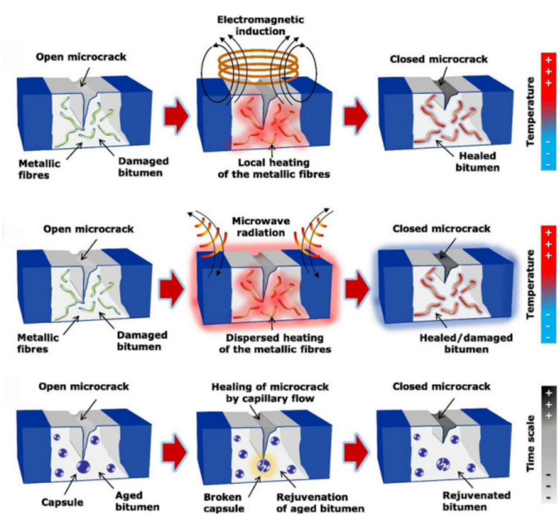

Figure 1. Schematic illustration of induction-based self-healing mechanism in steel wool fibre-modified AC–WC.

2.3. Induction Heating Mechanism and Experimental Configuration

The self-healing mechanism investigated in this study is based on electromagnetic induction heating, which enables localized and controlled thermal activation within the asphalt mixture. As schematically illustrated in **Figure 1**, steel wool fibres dispersed throughout the Asphalt Concrete Wearing Course (AC–WC) act as conductive elements when exposed to an alternating electromagnetic field generated by an induction coil positioned above the pavement surface. The interaction between the electromagnetic field and the conductive fibres induces eddy currents within the fibres, resulting in rapid localized heat generation inside the asphalt matrix.

The generated heat increases the temperature of the surrounding asphalt binder, causing it to soften and regain flowability. This thermal activation allows the binder to migrate toward microcracks and damaged interfaces, promoting crack closure and partial restoration of mechanical integrity [27,29,30]. Compared to conventional external heating methods, induction heating offers a more efficient and targeted approach, as heat is generated internally within the mixture rather than transferred from the surface. This mechanism is particularly effective for asphalt mixtures containing conductive fibres, where thermal energy can be concentrated around damaged zones without excessive surface overheating.

The effectiveness of the induction-based self-healing process strongly depends on the presence, distribution, and dosage of steel wool fibres within the asphalt matrix. At moderate fibre contents, a continuous conductive network can be formed, enabling efficient heat transfer and relatively uniform temperature distribution across the specimen. This condition enhances healing efficiency while maintaining acceptable mechanical performance. However, excessive fibre content may lead to fibre agglomeration, increased air voids, and disruption of aggregate interlocking, which can reduce both structural stability and heating uniformity. Therefore, the fibre dosages investigated in this study (0%, 1%, 1.5%, and 2% by total mix weight) were selected to evaluate the balance between mechanical performance and self-healing capability.

The induction heating system employed in this research utilized a laboratory-scale induction coil designed to generate a stable electromagnetic field over the asphalt specimen surface, as shown in **Figure 2**. The coil geometry was selected to ensure sufficient magnetic coupling with the embedded steel wool fibres while maintaining a safe and consistent distance from the specimen surface. This configuration allowed effective energy transfer without direct contact between the coil and the asphalt, minimizing the risk of surface damage or binder burning.

Figure 2. Induction heating coil geometry.

The distance between the induction coil and the specimen was carefully controlled to achieve localized heating within the mixture rather than uniform surface heating. This approach reflects the practical application of induction-healing technology in pavement maintenance, where heating efficiency and energy concentration are critical factors. The coil configuration adopted in this study ensured that thermal activation occurred primarily around the conductive fibres, thereby enhancing the self-healing mechanism while limiting unnecessary thermal exposure to the surrounding material.

The overall laboratory setup for the induction-healing test is presented in **Figure 3**. Asphalt specimens were positioned directly beneath the induction coil and subjected to controlled heating cycles using an induction power supply operating at 800 W and a frequency of 55 kHz. Each heating cycle was applied for 60 s, followed by a cooling period of 24 h at room temperature to allow the asphalt binder to stabilize before subsequent testing. This heating–cooling sequence was designed to simulate realistic maintenance conditions, in which induction heating may be applied periodically to restore pavement performance.

The experimental configuration ensured repeatability and consistency across all specimens and fibre dosage variations. By maintaining identical induction parameters for each test, the influence of steel wool fibre content on heating efficiency and healing performance could be isolated and evaluated systematically. This setup also supports the reproducibility of the experimental procedure for future studies and potential field-scale applications.

To evaluate the self-healing efficiency, selected specimens were initially subjected to controlled pre-cracking using a three-point bending test. The experimental sequence, illustrated in **Figure 4**, consisted of pre-cracking, induction heating, cooling, and post-healing mechanical testing. Healing efficiency was quantified by comparing the mechanical strength before and after induction heating, allowing the recovery ratio to be calculated. This approach enabled a direct assessment of the ability of conductive fibres to facilitate repeated healing cycles under controlled laboratory conditions.

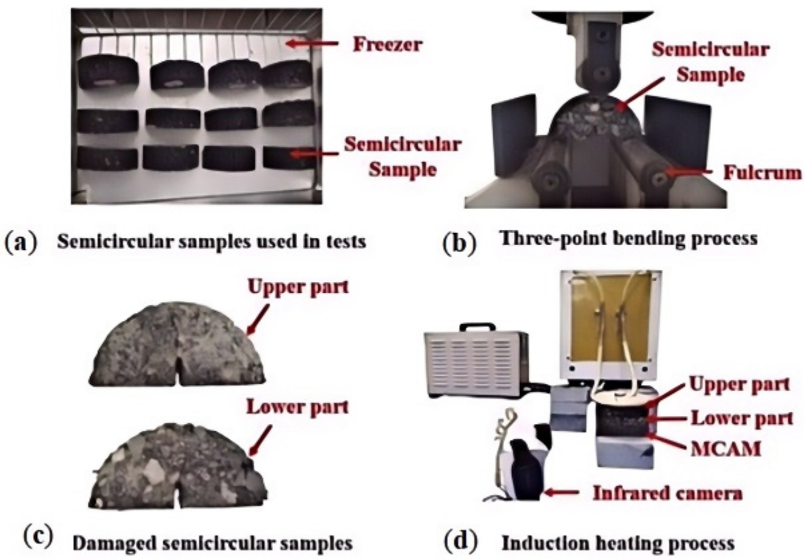

Figure 3. Laboratory setup for induction-healing testing of AC–WC specimens.

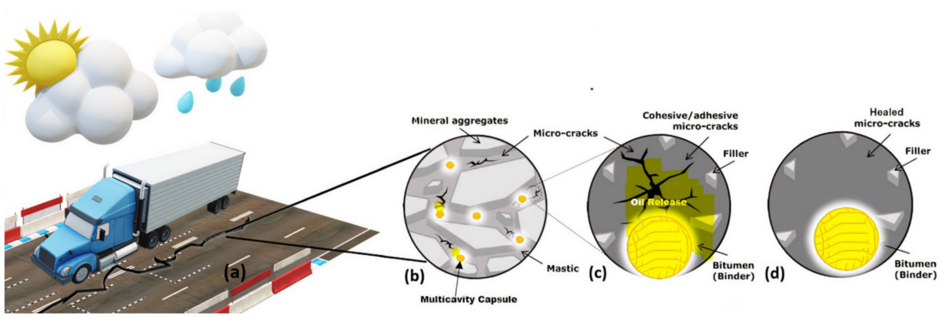

Figure 4. Experimental sequence of induction-healing evaluation using three-point bending and induction heating cycles.

2.4. Testing Procedure

Mechanical performance was evaluated using Marshall Stability and Flow tests, in accordance with Bina Marga and ASTM D1559 standards [24,25]. Key parameters measured included stability, flow, Voids in Mix (VIM), Voids Filled with Asphalt (VFA), Voids in Mineral Aggregate (VMA), and the Marshall Quotient (MQ). These parameters collectively represent the mixture's strength, deformation resistance, and durability [28].

To assess healing performance, selected specimens were subjected to controlled pre-cracking using a three-point bending apparatus. The cracked specimens were then placed beneath an induction heating coil operating at 800 W and 55 kHz frequency. Each sample underwent five heating–cooling cycles, with 60 s of heating followed by 24 h of cooling between cycles, simulating realistic environmental conditions. The induction parameters were selected based on the optimized ranges suggested by Jian et al. [10] and Karimi et al. [12] to ensure effective energy transfer and consistent temperature distribution.

Healing efficiency was quantified using the recovery ratio formula:

$$Sh = Fa/F_0 \quad (1)$$

where S_h is the healing ratio, F_a is the strength after heating, and F_0 is the initial strength. This approach aligns with the evaluation techniques used by Liu et al. [26] and Joenck et al. [13], who employed comparative strength measurements to assess induction-based recovery efficiency.

2.5. Data Analysis

The experimental data were analysed using descriptive and comparative statistical methods. For each fibre dosage, mean and standard deviation values were computed for all Marshall parameters and healing ratios. The data were compared against the minimum performance thresholds established in Bina Marga 2018 [24] to determine compliance. The relationship between fibre dosage and performance parameters was further interpreted in the context of prior studies, highlighting the trade-off between stiffness reduction and healing enhancement [9,10,14].

All results were synthesized to determine the optimal fibre dosage that achieves the most efficient balance between mechanical stability and self-healing capacity. The outcomes are expected to serve as a basis for developing smart pavement designs in tropical regions, where environmental stressors accelerate asphalt deterioration.

3. Results and Analysis

The mechanical and healing performance results of fibre-modified asphalt mixtures are presented in this section. The findings are divided into subsections covering each key parameter: stability, flow, voids, Marshall Quotient, and density. Trends were analysed relative to fibre dosage and compared to relevant findings in the literature to validate the observed behaviour.

3.1. Stability

Figure 5 shows that Marshall stability decreased consistently with increasing steel wool fibre content. The control mixture exhibited the highest stability, indicating optimal aggregate interlocking and binder cohesion. A moderate reduction in stability was observed at 1% fibre content, while a more pronounced decrease occurred at fibre contents of 1.5% and 2%. This trend suggests that excessive fibre inclusion disrupts aggregate contact and increases internal voids, thereby reducing load-bearing capacity. However, the mixture containing 1% fibre remained within acceptable stability limits, indicating that moderate fibre addition does not critically compromise structural performance. Similar findings were reported by Liu et al. (2024) and Joenck et al. (2022), who observed that mixtures containing more than 1.5% conductive fibres tended to show diminished structural strength due to fibre agglomeration and poor dispersion [13,26]. The slight decrease in stability at moderate fibre content (1–1.5%) indicates a transitional phase where the benefits of fibre reinforcement begin to be offset by internal void formation.

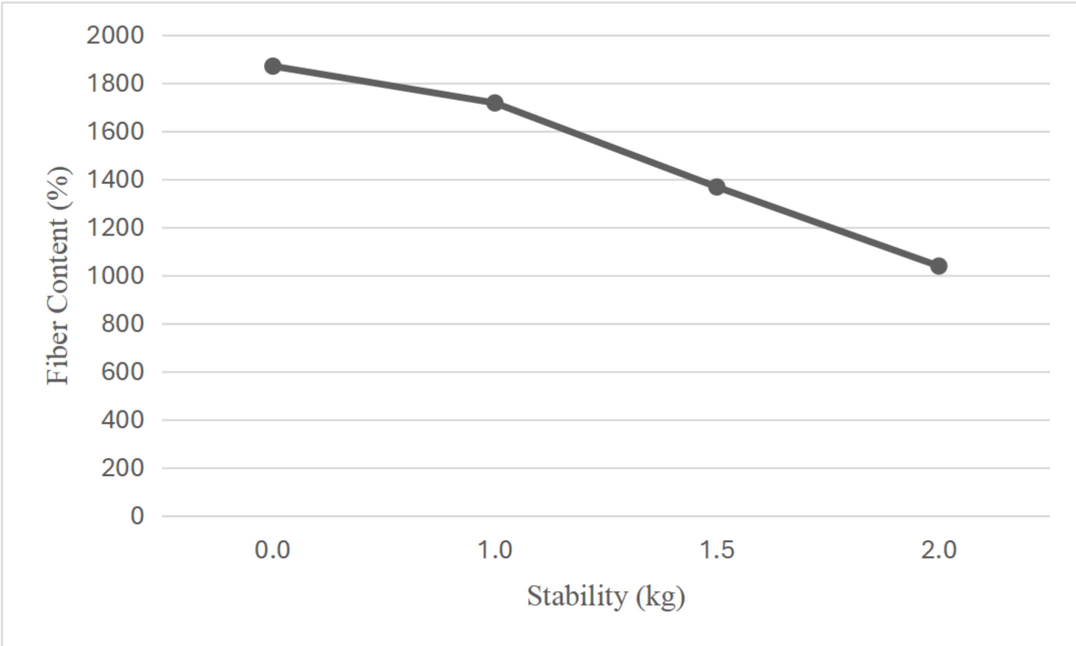

Figure 5. Stability vs. Fiber Content.

3.2. Flow

As presented in **Figure 6**, flow values increased with fibre addition up to 1.5%, indicating enhanced mixture flexibility due to reduced stiffness. At 2% fibre content, a slight reduction in flow was observed, possibly caused by fibre clustering that restricted binder mobility. From a performance perspective, the 1% fibre mixture exhibited a balanced deformation behaviour, remaining within specification limits while providing improved ductility. A similar pattern was observed by Karimi et al. (2021), who reported increased ductility in conductive asphalt mixtures after induction cycles because of localized binder softening [12].

3.3. Voids in Mineral Aggregate (VMA)

Figure 7 indicates that VMA increased consistently with increasing fibre content. The presence of steel wool fibres tends to push aggregates apart, reducing packing efficiency. While a moderate increase in VMA may enhance binder accommodation, excessive values observed at higher fibre contents indicate a less compact internal structure, which correlates with reduced stability.

These results are consistent with Jian et al. (2023), who found that high fibre contents generate additional voids that hinder effective binder coating and densification during compaction [10].

3.4. Voids in the Mix (VIM)

As shown in **Figure 8**, VIM increased sharply with fibre content. The control mixture exhibited air voids within the recommended range, whereas mixtures containing more than 1% fibre showed excessive air voids. High VIM values may facilitate moisture intrusion and accelerate oxidative aging, potentially reducing long-term pavement durability.

The sharp rise at higher fibre levels corroborates the observations of Penalva-Salinas et al. (2024), who noted that excessive conductive fibres disrupt aggregate packing and create micro-voids that hinder binder mobility [9].

3.5. Voids Filled with Asphalt (VFA)

Figure 9 shows a decreasing trend in VFA with increasing fibre content. This reduction indicates that fibres occupy part of the internal void space and limit effective binder distribution. Lower VFA values at higher fibre contents may compromise durability due to insufficient binder coating.

These results support earlier conclusions that higher fibre content tends to lower binder coating efficiency due vto competition for internal void space [11,13].

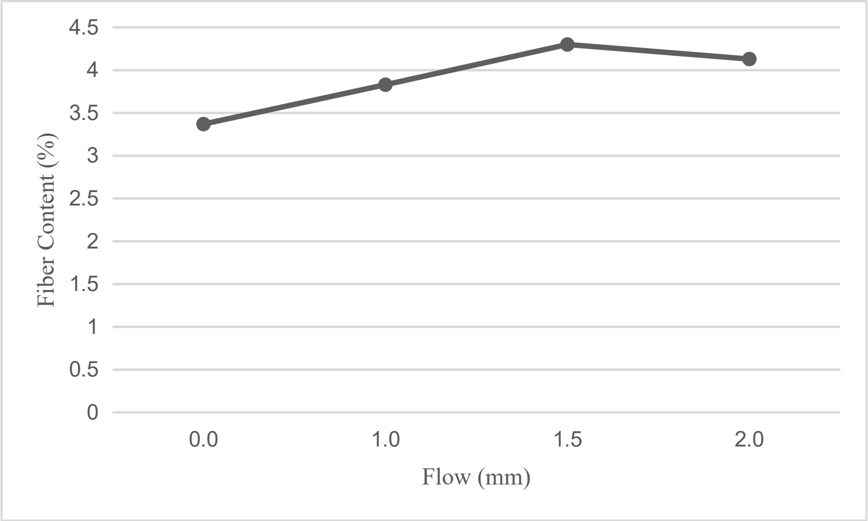

Figure 6. Flow vs. Fiber Content.

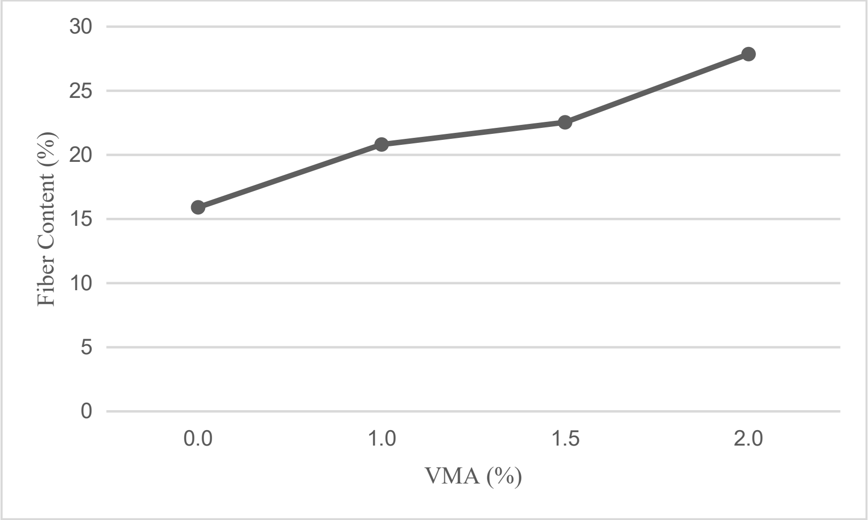

Figure 7. VMA vs. Fiber Content.

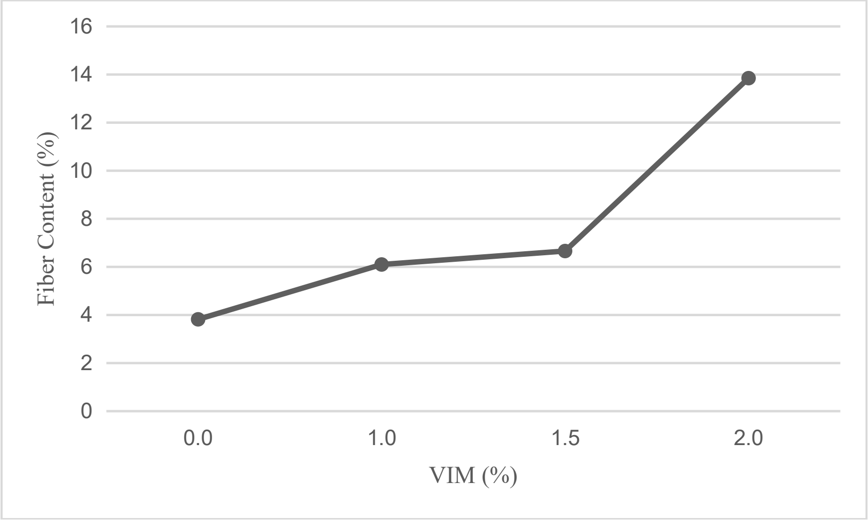

Figure 8. VIM vs. Fiber Content.

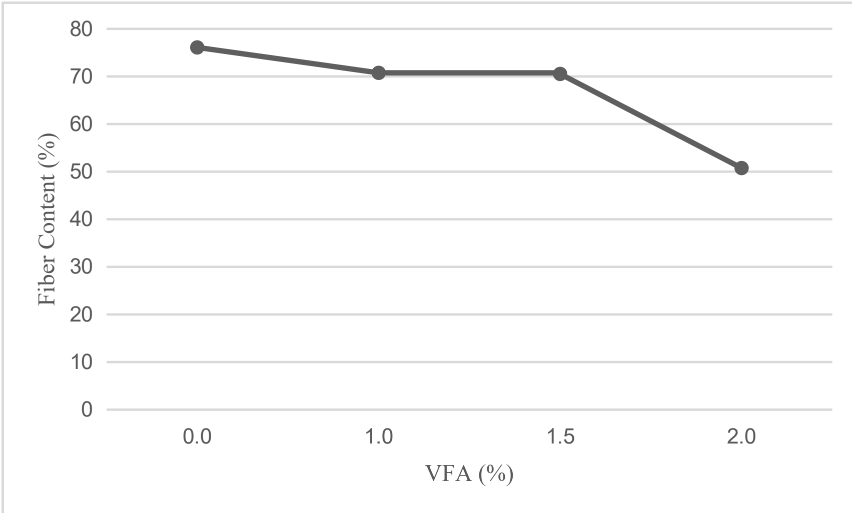

Figure 9. VFA vs. Fiber Content.

3.6. Marshall Quotient (MQ)

The Marshall Quotient values presented in **Figure 10** decreased steadily with increasing fibre content, indicating a reduction in mixture stiffness. Moderate MQ reduction at 1% fibre content suggests improved fatigue resistance, whereas excessive reduction at higher fibre contents may increase rutting susceptibility.

Although a moderate decrease is desirable for improving fatigue resistance, excessive loss of stiffness could lead to rutting under repeated traffic loads [24]. The MQ trend in this study aligns with that of Fakhri et al. (2021), who found that polymer-modified and fibre-reinforced asphalt mixtures exhibited lower MQ but improved healing and deformation resistance after electromagnetic activation [25].

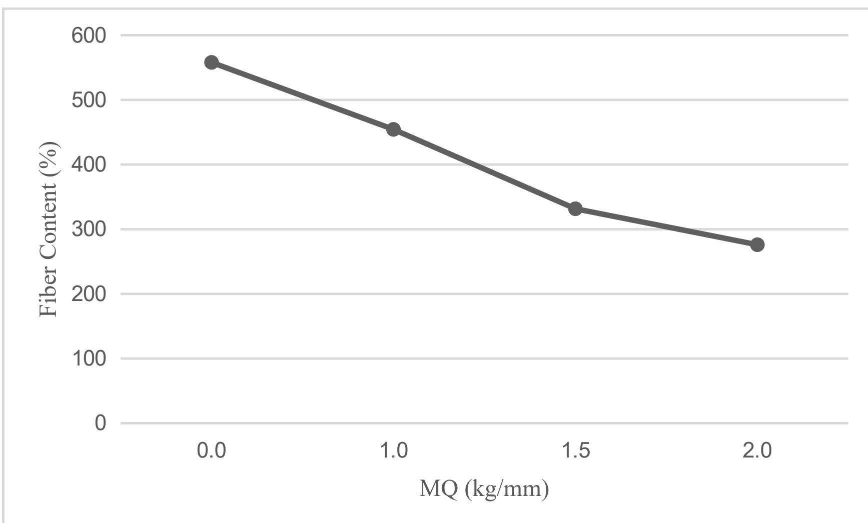

Figure 10. MQ vs. Fiber Content.

4. Discussion

The experimental findings clearly demonstrate that the addition of steel wool fibres significantly affects the mechanical characteristics and self-healing performance of Asphalt Concrete Wearing Course (AC–WC). Each measured parameter, including stability, flow, voids, Marshall Quotient, and density, showed distinctive behavioural trends as the fibre dosage increased. These variations highlight the existence of an optimum fibre content that provides the most efficient balance between strength, flexibility, and self-healing capability.

4.1. Interpretation of Mechanical Performance Trends

The results of this study demonstrate a clear influence of steel wool fibre content on the mechanical behaviour of Asphalt Concrete Wearing Course (AC–WC) mixtures. The gradual reduction in Marshall stability with increasing fibre dosage indicates that the introduction of conductive fibres alters the internal structure of the asphalt mixture. At low fibre content (1%), the reduction in stability remains moderate, suggesting that the aggregate skeleton is still able to maintain sufficient interlocking and load transfer. However, at higher fibre contents (≥1.5%), the decline in stability becomes more pronounced, indicating that excessive fibres interfere with aggregate contact and reduce the effectiveness of binder–aggregate bonding.

This behaviour can be explained by the physical role of steel wool fibres within the mixture. While fibres contribute to conductivity and heating efficiency, they also occupy volume within the aggregate framework. When fibre content increases beyond an optimal threshold, fibres tend to disrupt aggregate packing, leading to higher air void content and reduced compactability. As a result, the mixture becomes less resistant to deformation under load, which is reflected in the reduced Marshall stability values. This finding confirms that conductive fibre addition must be carefully controlled to avoid compromising the fundamental structural performance of AC–WC.

The observed changes in flow values further support this interpretation. The increase in flow at moderate fibre contents reflects a reduction in mixture stiffness and an increase in ductility, which can be beneficial for accommodating traffic-induced strains. However, excessive flow values at higher fibre dosages may indicate a tendency toward plastic deformation, particularly under high service temperatures. Therefore, the mechanical performance results highlight the existence of a critical balance between stiffness and flexibility when incorporating steel wool fibres into asphalt mixtures.

4.2. Influence of Fibre Content on Volumetric Properties

The volumetric properties of the mixtures, including VMA, VIM, and VFA, provide important insight into the internal structure changes induced by fibre addition. The consistent increase in VMA and VIM with increasing fibre content indicates that steel wool fibres reduce aggregate packing efficiency and create additional void spaces within the mixture. While a moderate increase in VMA can improve binder accommodation and enhance fatigue resistance, excessive voids may negatively affect durability by increasing permeability and susceptibility to moisture damage.

The reduction in VFA observed at higher fibre contents further suggests that the effective binder coating of aggregates becomes less efficient when fibres occupy a significant portion of the void structure. This condition may lead to weaker binder–aggregate adhesion and reduced resistance to stripping under environmental and traffic loading. These findings emphasize that volumetric control is particularly critical when modifying asphalt mixtures with non-traditional additives such as conductive fibres.

From a pavement engineering perspective, the volumetric trends observed in this study indicate that fibre contents above 1% may introduce excessive voids that outweigh the potential benefits of enhanced self-healing. Consequently, mixture design for conductive asphalt should prioritize compliance with volumetric specifications to ensure long-term durability, especially in surface layers such as AC–WC that are directly exposed to environmental stressors.

4.3. Relationship between Mechanical Performance and Self-Healing Capability

One of the key contributions of this study is the identification of a trade-off between mechanical performance and self-healing capability. The fracture strength and healing ratio results demonstrate that mixtures containing steel wool fibres exhibit improved recovery after induction heating compared to the control mixture. This improvement confirms the essential role of conductive fibres in facilitating electromagnetic energy transfer and localized heating within the asphalt matrix.

However, the relatively low healing ratios obtained in this study indicate that self-healing efficiency is highly dependent on multiple factors beyond fibre content alone. Heating duration, fibre distribution, initial damage severity, and binder properties all influence the extent of strength recovery. While the inclusion of 1% fibre resulted in a noticeable increase in healing ratio, the recovery remained partial, suggesting that induction heating primarily promotes microcrack closure rather than full restoration of fracture resistance.

These results are consistent with previous studies reporting that induction-based healing is most effective when damage levels are limited and when heating parameters are optimized. Therefore, self-healing asphalt should be viewed as a preventive or maintenance-oriented technology rather than a complete replacement for conventional rehabilitation methods. In this context, the improved healing observed at moderate fibre contents supports the application of induction heating as a supplementary strategy to delay crack propagation and extend pavement service life.

4.4. Engineering Implications for Smart Pavement Design

The findings of this research have important implications for the design and implementation of smart pavement systems. The results indicate that a steel wool fibre content of approximately 1% provides the most balanced performance, maintaining acceptable mechanical properties while enabling measurable self-healing capability. This balance is particularly critical for AC–WC layers, where both load-bearing capacity and surface durability are essential.

In practical applications, the use of conductive-fibre-modified asphalt may offer significant advantages in terms of maintenance efficiency and lifecycle cost reduction. Induction heating can be applied selectively to damaged pavement sections, reducing the need for material removal and reconstruction. However, the effectiveness of this approach depends on careful mixture design, appropriate induction equipment, and well-defined maintenance protocols.

For tropical regions, where high temperatures, heavy rainfall, and traffic loading accelerate pavement deterioration, the integration of self-healing technology may be especially beneficial. The ability to restore microcracks before they develop into severe distress can help mitigate the effects of environmental aging and reduce the frequency of major rehabilitation works. Nevertheless, the application of this technology must be supported by field validation to confirm laboratory findings under real service conditions.

4.5. Limitations and Future Research Directions

Despite the valuable insights provided by this study, several limitations should be acknowledged. First, the experiments were conducted under laboratory conditions using a limited number of heating cycles and fibre dosage variations. Field-scale behaviour may differ due to factors such as traffic loading, temperature gradients, and environmental exposure. Second, the healing performance was evaluated based on fracture strength recovery, which represents only one aspect of self-healing behaviour. Other performance indicators, such as fatigue resistance and moisture damage recovery, should be investigated in future studies.

Future research should focus on optimizing induction heating parameters, including power, frequency, and heating duration, to maximize healing efficiency without inducing thermal damage. The influence of fibre geometry, orientation, and hybrid conductive additives also warrants further investigation. Additionally, large-scale field trials are essential to assess the long-term durability, energy efficiency, and economic feasibility of induction-based self-healing asphalt pavements.

4.6. Overall Discussion Summary

Overall, the discussion confirms that steel wool fibre modification enhances the functional performance of AC–WC mixtures by enabling induction-based self-healing, but at the cost of reduced mechanical strength when fibre content becomes excessive. The results highlight the importance of identifying an optimal fibre dosage that balances structural integrity and healing capability. The 1% fibre mixture emerged as the most promising configuration in this study, offering a practical compromise suitable for smart pavement applications.

5. Conclusions

This study evaluated the influence of steel wool fibre addition on the mechanical and self-healing performance of Asphalt Concrete Wearing Course (AC–WC) mixtures. Four different fibre dosages—0%, 1%, 1.5%, and 2%—were analysed using the Marshall method and controlled induction-healing cycles to determine the optimal mixture composition.

The experimental results revealed that the inclusion of steel wool fibres significantly affected all key performance parameters. Marshall stability decreased consistently with increasing fibre content, from 1870 kg at 0% to 1038 kg at 2%, indicating that excessive fibres reduced load-bearing capacity. Flow values increased from 3.37 mm to 4.3 mm, reflecting improved flexibility but also suggesting a potential loss of stiffness at higher dosages. Voids in the mix (VIM) and voids in mineral aggregate (VMA) increased with fibre addition, confirming that the internal structure became more open and less compact. Meanwhile, the Marshall Quotient and density both declined, indicating a softer and less dense mixture at elevated fibre contents.

The self-healing evaluation showed that the highest recovery ratio was achieved at 1%–1.5% fibre dosage. At these levels, the mixture exhibited sufficient conductivity to enable efficient induction heating and binder flow without compromising its mechanical stability. The 1% fibre mixture demonstrated the most balanced performance, maintaining structural integrity while providing notable healing capability.

Based on these findings, the optimal fibre dosage for conductive-fibre-modified AC–WC is 1% by total mix weight. This configuration offers an effective compromise between stability, flexibility, and healing performance, making it suitable for tropical regions where high temperatures and traffic loads accelerate pavement deterioration.

Recommendations

For practical implementation, future research should include large-scale field trials to evaluate the long-term durability and energy efficiency of the induction-healing process under real traffic conditions. Further studies may also explore the integration of alternative conductive materials or hybrid fibre systems to improve cost-effectiveness and environmental sustainability. The development of national standards that accommodate self-healing asphalt technology is recommended to support its application in modern pavement design.

Abbreviations

AC–WC	Asphalt Concrete – Wearing Course
CEB-FIP	Comité Euro-International du Béton – Fédération Internationale de la Précontrainte
CTM	Compression Testing Machine
ISO	International Organization for Standardization
D	Dead Load
EL	Earthquake Load
F_a	Compressive strength after healing
F_0	Compressive strength before healing
LL	Live Load
MQ	Marshall Quotient
RC	Reinforced Concrete
SAP 2000	Structural Analysis Program 2000
SDL	Superimposed Dead Load
Sh	Healing Ratio
SLS	Serviceability Limit State
SNI	Standar Nasional Indonesia
ULS	Ultimate Limit State
VFA	Voids Filled with Asphalt
VIM	Voids in Mix
WL	Wind Load

Author Contributions

Conceptualization, E.S. and M.Q.; methodology, E.S.; software, S.A.; validation, E.S., M.Q. and H.B.; formal analysis, E.S.; investigation, E.S. and H.B.; resources, D.S.; data curation, E.S.; writing—original draft preparation, E.S.; writing—review and editing, E.S., M.Q., and D.S.; visualization, S.A.; supervision, M.Q. and H.B.; project administration, M.Q.; funding acquisition, M.Q. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest. During the preparation of this manuscript, AI-generated language assistance (ChatGPT, OpenAI) was used solely to improve grammar, sentence structure, and clarity of expression. All scientific content, including ideas, data, analyses, and conclusions, was fully developed and verified by the authors, who take full responsibility for the work.

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