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Self-Healing Ability of Steel Fibre Asphalt Mixture Using Microwave Heating and Semi-Circular Bending Test

Ekarizan Shaffie[1,2]*, Fionna Shiong[2], Ahmad Kamil Arshad[2], Mohd Khairul Afzan Mohd Lazi[3], Muhammad Ibrahim Khalili Abd Rahim[4,5], and Ramadhansyah Putra Jaya[6]

[1]Faculty of Civil Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[2]Institute for Infrastructure Engineering and Sustainable Management (IIESM), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[3]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[4]Department of Civil Engineering, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 47500 Bandar Sunway, Selangor, Malaysia
[5]Monash Climate-Resilient Infrastructure Research Hub (M-CRInfra), School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 47500 Bandar Sunway, Selangor, Malaysia
[6]Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, Al-Sultan Abdullah, 26300 Kuantan, Pahang, Malaysia

ABSTRACT

The durability of asphalt pavements is a critical concern in civil engineering due to frequent cracking and deterioration, which often necessitate costly, disruptive maintenance. To address these issues and extend pavement lifespan, the development of self-healing asphalt materials has gained increasing attention. One promising approach involves incorporating steel fibres into asphalt mixtures to enhance both mechanical performance and self-healing capability. However, the relationship between steel fibre content and healing efficiency, particularly under microwave heating, remains insufficiently understood. This study investigates the self-healing performance of Steel Fibre Asphalt Mixture (SFAM) using microwave heating and the Semi-Circular Bending (SCB) test. SFAM samples were prepared with varying steel fibre contents (0%, 0.3%, 0.5%, and 0.7% by total mixture weight) and a bitumen content of 6.0% PEN 60/70. Mechanical properties and healing performance were evaluated using Marshall Stability and Flow, Cantabro Loss, and SCB tests. Results indicate that the inclusion of steel fibres significantly improves mixture stability, flow, and wear resistance compared to conventional asphalt. SFAM also demonstrates

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E-mail address:
eka@uitm.edu.my (Ekarizan Shaffie)
fionnashiong@gmail.com (Fionna Shiong)
drahmadkamil@gmail.com (Ahmad Kamil Arshad)
mohdkhairulafzan@utm.my (Mohd Khairul Afzan Mohd Lazi)
ibrahimkhalii014@gmail.com (Muhammad Ibrahim Khalili Abd Rahim)
ramadhansyah@umpsa.edu.my (Ramadhansyah Putra Jaya)
* Corresponding author

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enhanced crack resistance and load-bearing capacity. Furthermore, self-healing capability is confirmed through observable recovery in SCB measurements after crack initiation. Overall, the incorporation of steel fibres and microwave-assisted healing shows strong potential to reduce pavement deterioration and maintenance needs, thereby supporting the development of more durable infrastructure.

Keywords: Crack healing, microwave heating, semi-circular bending, self-healing, steel fibre, stone mastic asphalt

INTRODUCTION

The implementation of road construction plays a crucial role in facilitating Malaysia's advancement in both society and the economy. The civil sector undergoes constant evolution, adopting dynamic infrastructure developments that prioritise the integration of cost-effective, sustainable, and environmentally friendly technologies. Robust economic growth depends on well-maintained road networks that effectively serve road users. Most Malaysian roads are built on flexible pavements, specifically bituminous hot-mix asphalt. Nevertheless, continuous exposure to traffic-related stress and the surrounding environment can lead to mechanical weakness and durability issues, including ageing, moisture damage, and temperature-induced cracking. Therefore, routine maintenance is crucial to extend the road's lifespan.

Self-healing asphalt pavement is a new concept that is becoming increasingly popular in the effort to achieve durable and environmentally friendly infrastructure. Conventional asphalt mixes largely rely on expensive, labour-intensive maintenance and repair operations to minimise deterioration. In contrast, asphalt mixes enhanced with steel fibres have the remarkable ability to self-repair minor damage and fractures, thereby reducing maintenance needs and prolonging the lifespan of asphalt pavements. The utilisation of fibres has gained significant recognition as an efficient means of enhancing road pavements (Serin et al., 2012; Haikal Mohd Ghazali et al., 2021; Sun et al., 2018; Zhang et al., 2020).

Furthermore, asphalt mixes have the distinct capability to self-repair when they sustain damage, as the bitumen within them flows into cracks in response to higher temperatures (Norambuena-Contreras & Garcia, 2016). The use of steel fibres in pavement engineering materials demonstrates their importance in asphalt, as they improve self-repair and reduce problems such as potholes, ravelling, and sliding in wet conditions (Shiong & Shaffie, 2021). The correlation between the incorporation of steel fibres and the self-healing properties of asphalt mixes using microwave heating remains poorly understood, despite extensive research. The objective of this study is to examine the effect of microwave heating on the ability of fibre asphalt mixtures to self-heal.

Microwave heating is increasingly recognised as an effective method for accelerating the healing of asphalt mixtures containing microwave-absorbing materials (Lou et al.,

2021; Song et al., 2021). Several types of fibres, including carbon fibre, steel fibre, and steel wool, have been utilised in the production of self-healing asphalt mixes. The mechanical characteristics and self-healing abilities of the material were assessed by the Semi-Circular Bending (SCB) test (Loureiro et al., 2023; Haikal Mohd Ghazali et al., 2021).

Recent studies have explored the potential of microwave heating to facilitate the self-healing of cracks in asphalt mixes. Zhang et al. (2023) highlighted the advantages of incorporating coal gangue powder (CGP) and basalt in this method, emphasising that the presence of metal oxides in coal gangue enhances microwave heating efficiency and improves asphalt healing. Another investigation provided evidence of the efficacy of incorporating steel slag aggregates (SSA) and steel wool fibres (SWF) into asphalt mixtures. This resulted in notable enhancements in asphalt's self-healing ability, as well as a substantial 150% increase in the asphalt's lifespan after healing. These findings highlight the considerable potential of these materials in asphalt engineering (Liu et al., 2017; Garcia et al., 2013).

These findings are consistent with prior research demonstrating that appropriate heating methods can facilitate self-healing in asphalt mixtures containing steel fibres or slags. Significantly, specimens subjected to microwave heating exhibited improved healing outcomes compared with those subjected to induction heating (González et al., 2018). The study's findings demonstrated that incorporating steel fibres into the asphalt mixture can improve stability, wear resistance, and self-healing. Overall, incorporating steel fibres into asphalt mixes, especially when combined with microwave heating, has the potential to improve the performance of road pavements. These findings support current initiatives to create durable road infrastructure, thereby promoting sustained economic growth and societal progress.

MATERIALS AND METHODS

Materials

The asphalt mixes were produced using granite aggregates obtained from the Kajang Rocks Quarry. The aggregates undergo careful drying and sieving to ensure they meet the specified 20 mm size range, in accordance with JKR Malaysia's SMA20 standards, as shown in Table 1. To ascertain the appropriateness of the materials for the combinations, a range of tests was carried out on the aggregate materials, following the procedures outlined in the ASTM standards, to establish their physical and mechanical properties.

The asphalt mixtures were produced using a Penetration Grade (PEN 60/70) asphalt binder. The SMA was enhanced by using steel fibres obtained from Gardner Global Enterprise, as shown in Figure 1, in different contents. For this study, two types of SMA20 asphalt mixes were prepared: the steel fibre asphalt mixture (SFAM) and conventional asphalt mixtures, which served as control samples.

The study used Steel Fibre Asphalt Mixture (SFAM) samples with steel fibres at concentrations of 0%, 0.3%, 0.5%, and 0.7% to assess their mechanical properties and healing capacity. The percentages provided are derived from previous research, which demonstrates that a decrease in fibre content (below 1%) improves performance while maintaining the quality of the mixture (Zhao et al., 2020). High percentages may lead to problems with fibre dispersion and mix consistency (Garcia et al., 2013). The chosen percentages are both cost-effective and practicable for large-scale applications, while also enabling an in-depth analysis of the correlation between fibre content and mixture performance (Sun et al., 2017). The characteristics of the steel fibres are specified in Table 2.

Marshall Specimen Preparation

Twelve (12) Marshall specimens were created in accordance with the requirements outlined in ASTM D 1559. The SMA mixes were formed by heating a mixture of 1100 g of aggregate

Table 1
SMA aggregate gradation

Sieve Size (mm)	Lower Gradation	Upper Gradation	Percentage Passing	Percentage Retained	Mass Passing (g)	Mass Retained (g)
19.0	100	100	100	0.0	1200.0	0
12.5	85	95	90	10.0	1080.0	120
9.5	65	75	70	20.0	840.0	360
4.75	20	28	24	46.0	288.0	912
2.36	16	24	20	4.0	240.0	960
0.60	12	16	14	6.0	168.0	1032
0.30	12	15	13.5	0.5	162.0	1038
0.075	8	10	9	4.5	108.0	1092
Pan	-	-	-	9.0	-	108



Table 2
Properties of steel fibres

Description	Straight
Length (mm)	13
Diameter (mm)	0.2
Density (Kg/m^3)	7800
Tensile strength (Mpa)	2600
Aspect Ratio	65

Figure 1. Steel fibre

and filler to 160 °C. The required amount of bitumen was also heated to 160 °C to achieve the acceptable viscosity for the mixture's manufacture. The mixture contained 6.0% bitumen by weight. The steel fibre, at 0%, 0.3%, 0.5%, and 0.7% of the total weight of the mix, was dry-mixed directly into the mix prior to bitumen addition. Each test specimen was subjected to 50 blows per surface using a conventional Marshall compactor. Afterwards, all twelve (12) Marshall specimens underwent additional assessments for Marshall stability, flow test, and Cantabro test in accordance with specific standards.

Marshall Stability and Flow Test

The Marshall stability and flow test was conducted in accordance with the guidelines set by ASTM D 6927. The procedure involved immersing the test specimens in a water bath maintained at 60 °C for 30 minutes. Afterwards, each specimen was removed and immediately placed in the loading head of the Marshall Stability Machine. The flow meter was zeroed by inserting a metal cylinder with a diameter of 101.6 mm into the loading head.

The specimens were subjected to a constant strain rate of 50.8 mm/min until they reached their maximum capacity (peak load). Marshall stability was determined by measuring the maximum load the specimens could withstand before failure. During the stability test, the flowmeter was firmly held above the guide bar and withdrawn as the load started to decrease. The flow value of the specimen was determined based on the deformation observed at the maximum load.

Cantabro Loss Test

This test was conducted in accordance with ASTM D 7064, using specimens produced with steel fibre proportions of 0%, 0.3%, 0.5%, and 0.7% by weight of the mixture. The test specimens were held at 25 °C for 6 hours. Following this, their weight was measured and recorded as the sample's original weight before testing. The recorded weight was then entered into the machine. The drum underwent 300 revolutions at a velocity ranging from 188 to 208 radians per second, with no steel balls present. The Cantabro Loss value is expressed as a percentage, calculated using Equation 1:

$$\text{Cantabro Loss (\%)} = \frac{(M_0 - M_1)}{M_0} \times 100 \quad [1]$$

Where M_0 is denoted as the initial mass of the sample before testing (g), and M1 is the final mass of the sample in grams.

Semi-Circular Bending (SCB)

The Semi-Circular Bend (SCB) test is a laboratory test employed to measure the fracture resistance of asphalt mixes. The test follows the ASTM D8044 criteria for intermediate temperatures. The process involves measuring two important parameters: Strain Energy (kJ) and Peak Load (N). These parameters are crucial for understanding the mechanical properties and carrying capacity of materials, particularly in applications such as pavements, concrete, and other structural elements.

Four sets of cylindrical asphalt specimens were prepared: one control group without steel fibre, and three groups with varying amounts of steel fibre (0.3%, 0.5%, and 0.7% by weight of the total mixture). The asphalt mixtures were prepared using standard procedures and included steel fibres as required for each specific group. The mixes were compacted into cylindrical moulds to produce standardised specimens. The notches for each sample were cut at depths of 25 mm, 32 mm, and 38 mm, as shown in Figure 2.

The tests were performed with a multispeed universal loading testing machine, as depicted in Figure 3. After achieving equilibrium, a preload was applied for 30 seconds to ensure the specimen was securely positioned, while maintaining a constant temperature of 25 °C throughout the operation. Subsequently, the load was released, and the test began in displacement-control mode at a velocity of 0.5 mm/min.

The variables of time, force, and displacement were recorded at a sample frequency of 10 Hz. The test was terminated when the applied load decreased to 25% of the maximum load. Simultaneously, the crack development in the SCB asphalt specimen was continuously monitored. Following cracking, the specimens were subjected to microwave heating for a predetermined duration.



Figure 2. SCB samples



Figure 3. SCB equipment

Microwave Healing Conditions Test

The methodology for assessing the self-healing rate of the asphalt mixture consisted of a sequence of experiments designed to induce and assess the formation and recovery of cracks. The samples were first subjected to the Semi-Circular Bending (SCB) test utilising a Universal Testing Machine (UTM) to induce cracks. The test was conducted on all specimens until a specific deformation length was reached to measure the peak load (kN) and the strain energy required to crack the sample. Each sample was subjected to the SCB test twice: once to assess early cracking and once after receiving microwave-induced healing.

The healing process was accelerated by employing a microwave oven with a power output of 1000 Watts and a frequency of 2.45 GHz. Microwave energy was used to stimulate binder movement and crack closure in damaged samples, thereby promoting self-healing. Following microwave treatment, the specimens were cooled and subsequently retested using the SCB test to evaluate the rate of self-healing. Load-displacement curves were measured, and self-healing efficiency was determined by assessing the recovered stiffness and load-bearing capacity.

The initial SCB test was performed on each specimen under control conditions at 25 °C. The test measured the Peak Load (Fi) and Strain Energy (kJ) required to induce cracking. Following the initial test, the damaged samples were conditioned in a chamber at 20 °C for 2 hours. Subsequently, each conditioned sample was subjected to microwave heating for 40 seconds, with temperature monitored using either a thermocouple or an infrared thermometer. This was done to ensure consistent, controlled heating while preventing an excessive increase in temperature.

After heating, the specimens were allowed to cool to 20 °C in the conditioning chamber. After the specimens cooled, the SCB test was repeated to measure the peak load (Fb) and Strain Energy (kJ) required to induce cracking after the healing process. The self-healing rate was determined by using Equation 2, which accurately represented the recovered mechanical properties of the specimens:

$$Sh = \frac{F_b}{F_i} \times 100 \qquad [2]$$

Where,
Fb is the maximum peak load after heating and
Fi is the maximum peak load before heating.

RESULTS AND DISCUSSIONS

Stability and Flow

Three specimens were produced for each steel fibre proportion category to evaluate stability (kg) and flow (mm). The average values were then calculated. The stability and flow tests are conducted to assess the ability of bituminous materials to withstand deformation, displacement, rutting, and shearing loads. Internal friction and cohesion are the primary variables that contribute to stability. Internal friction refers to the resistance that arises from the interlocking and friction between aggregates, whereas cohesion refers to the binding force exerted by the binder material. The bituminous material must possess high stability and flow characteristics to withstand the substantial traffic loads that bituminous pavement is subjected to.

Figure 4 illustrates the correlation between the stability and flow of the specimens and the different proportions of steel fibres. The results demonstrate that incorporating steel fibres into the asphalt mixture improves stability, as seen by the considerably lower value of the control sample. The improvement in performance can be attributed to the presence of steel fibres in the asphalt mixture, which decreases the internal friction of the asphalt properties (Shaffie et al., 2021).

The specimen with a steel fibre proportion of 0.3% exhibits the highest stability value of 1089.7 kg among all specimens. It is followed by specimens with proportions of 0.5%, 0.7%, and 0%. The stability of the mix decreases progressively as the steel proportion exceeds 0.3%, possibly due to an uneven distribution of steel fibres in the mixture.

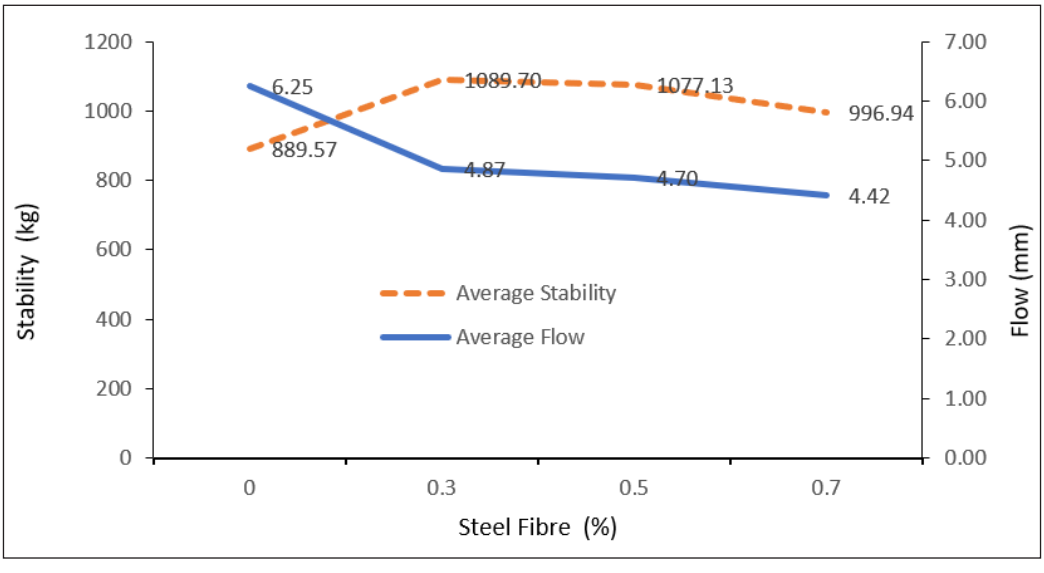

Figure 4. Stability and flow against steel fibre (%)

This uneven distribution can result in voids or weak areas, which negatively affect stability measures.

Conversely, the flow data consistently demonstrates a pattern: as the proportion of steel fibres increases, the flow value decreases. These flow numbers indicate the extent of deformation in the mixture as the load decreases. The sample with a 0% steel fibre proportion exhibits the highest flow value of 6.25 mm, whilst the sample with the highest steel fibre proportion of 0.7% indicates the lowest flow value of 4.42 mm. Introducing steel fibres into the mixture limits the sample's flexibility and free movement, reducing flow values as the amount of steel fibres increases.

Cantabro Loss and Air Voids

According to Figure 5, the air void content decreases as the steel fibre content increases, reaching a maximum at 0.5% of the total asphalt mixture. This occurrence may be attributed to the infiltration of steel fibres into the gaps between the aggregates in the asphalt mixture. The steel fibres used in the experiment were thin strips, allowing them to easily penetrate the spaces between the aggregates (Shiong et al., 2023). Nevertheless, the air void content increases to 7.8% when the steel fibre percentage reaches 0.7%, falling within the desirable range for the specified air void content.

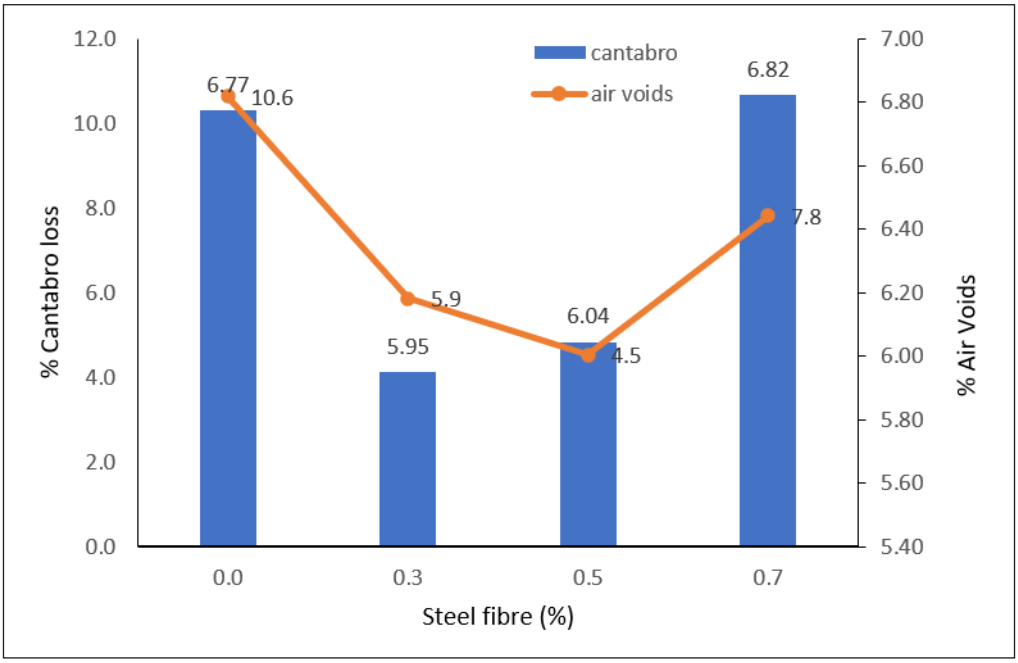

Figure 5. Air voids & cantabro loss values against steel fibre (%)

Figure 5 displays the Cantabro loss data. It is evident that the SMA combination with 0.3% steel fibre content had the lowest abrasion loss percentage, at 5.95%. This was followed by mixtures with steel fibre contents of 0.5%, 0%, and 0.7%. On the other hand, the SMA mixture containing 0.7% steel fibre achieved the highest Cantabro loss of 6.82% compared with the other proportions. The variations in abrasion loss seen for each proportion can be attributed to the abrasion force exerted between the mixture specimens and the drum, resulting in the disintegration of the mixture and a corresponding quantity of abrasion loss.

The inclusion of 0.3% steel fibre in the SMA mixture resulted in a notable decrease of up to 13% in abrasion loss. However, the addition of 0.5% and 0.7% steel fibre later led to an increase in abrasion loss. The addition of 0.7% steel fibre is causing the control mixture's abrasion loss to exceed that of the 0.7% steel fibre mixture. This suggests that using a large quantity of steel fibre does not improve the abrasion resistance of the SMA combination. The changes in the abrasion values may be influenced by several factors, such as the angularity of coarse particles and unequal compaction force. It has been demonstrated that adding steel fibres to SMA is an effective method for minimising abrasion loss when used in appropriate proportions.

The relationship between Cantabro loss and air voids in hot mix asphalt (HMA) is crucial for assessing the long-term resilience of asphalt pavements. Cantabro loss quantifies an asphalt's ability to withstand deterioration from traffic and environmental factors, whilst air voids refer to the empty spaces within the compacted mixture. Experimental data indicate that an increased air-void content typically leads to greater Cantabro loss, as it reduces aggregate interlocking and binder cohesion.

The mix containing 0.3% steel fibre had the lowest abrasion loss, indicating that bitumen quality in this mixture affects the relationship between Cantabro loss and air voids. An excellent binder can reduce Cantabro loss, even when air void levels are within acceptable limits. Adequate compaction and uniform void dispersion are essential for maintaining the long-term durability of asphalt pavement (Ahmad et al., 2020).

Semi-Circular Bending

The Semi-Circular Bending (SCB) test is an important method used in materials testing and engineering, particularly in mechanics and fracture mechanics. This study aimed to assess the self-healing rate of pavement specimens by preparing 12 SCB specimens, with three specimens allocated for each steel fibre proportion.

Figure 6 demonstrates a strong correlation between the addition of steel fibres to asphalt mixtures and the capacity of these mixtures to self-heal when exposed to microwave heating. Before cracking, the asphalt's strength is indicated by its initial peak load. Analysis indicated that specimens containing 0.3% steel fibre exhibited the highest initial peak load, surpassing those of other samples. After inducing cracks and subjecting the specimens to

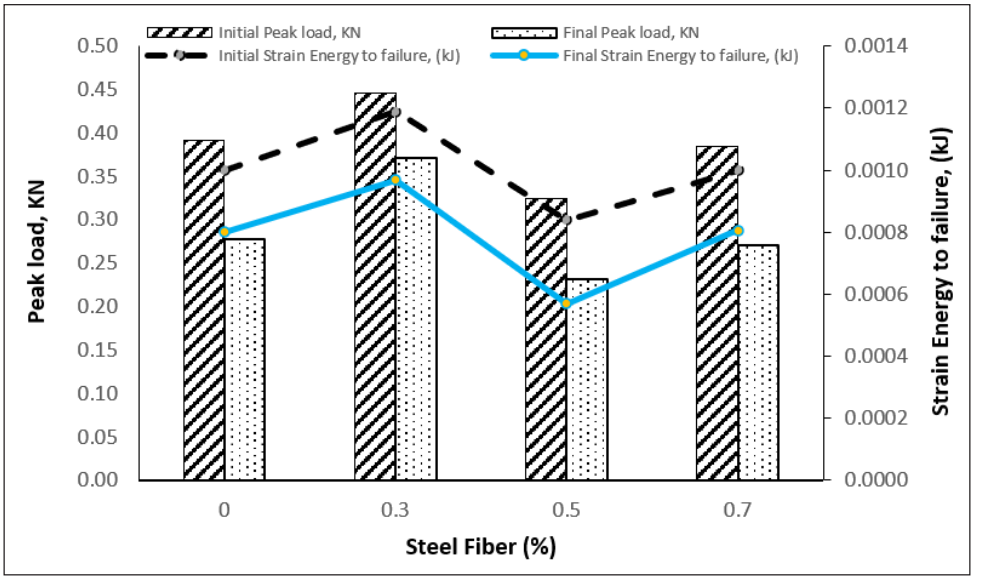

Figure 6. Peak load & strain energy-to-failure values for steel fibre (%)

microwave heating for self-healing, the steel fibre specimens with a 0.3% fibre content exhibited the highest ultimate peak load, indicating excellent self-healing effectiveness.

Steel fibres, particularly at higher concentrations, improve asphalt's ability to return to its original form after cracking. More precisely, the addition of 0.3% steel fibres and the application of microwave treatment enhance the self-healing capability of asphalt pavements, thereby increasing durability.

The results demonstrate a consistent correlation between peak load and strain energy, suggesting their interrelation in assessing a material's mechanical properties. Peak load refers to the maximum amount of force that a material can withstand, which indicates its strength and ability to resist deformation. Strain energy quantifies the energy absorbed during deformation, thereby indicating a material's toughness. A higher peak load indicates superior energy absorption and more resistance to deformation.

The emergence of this tendency can be attributed to the material's inherent mechanical properties, whereby higher strength is associated with stronger molecular bonding and greater structural integrity. The relationship between the maximum load and the energy stored in a material emphasises the balance between its strength and toughness, which is essential for its overall longevity and effectiveness.

Self-Healing Rate of Pavement

The Semi-Circular Bending (SCB) Test measures the Strain Energy and Peak Load of samples, indicating their ability to withstand loads before fracturing. The test exerts

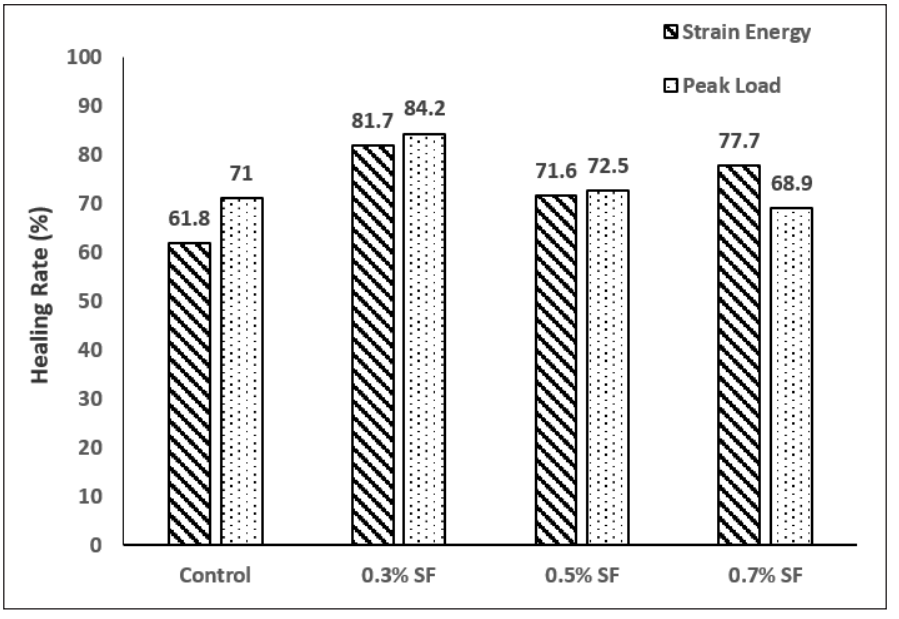

Figure 7. Healing rate of the asphalt mixture

pressure until a predetermined deformation length is achieved. The average healing rate is calculated by comparing the numbers before and after the healing test.

Figure 7 illustrates a percentage comparison of healing rates, showing data for strain energy (kJ) and peak load (N). Data indicate that the inclusion of steel fibre in SMA typically enhances the rate of self-healing. More precisely, a steel fibre content of 0.3% yields the maximum self-healing rate, reaching 81.7% in terms of Strain Energy. In contrast, the control sample with 0% steel fibre has the lowest self-healing rate, measuring 61.8%.

The healing rate varies, suggesting possible anomalies in the mixing or compaction process. The peak load data provide additional evidence of the superiority of the 0.3% steel fibre content, which has a healing rate of 84.2%. In contrast, the steel fibre content of 0.7% has the lowest healing rate at 68.9%.

CONCLUSION

This study examined the impact of adding steel fibre to an asphalt mixture in line with SMA20 requirements. The aim was to identify differences in the mixture's physical properties and its potential for self-healing after performing SCB testing. The following findings are formed based on the outcomes of the experimental work and the extensive analysis:

1. The highest level of stability is attained when the steel fibre percentage is 0.3%, resulting in a weight of 1089.7 kg. Stability decreases beyond this proportion because

of the uneven distribution of fibres. As the steel fibre content increases, the flow values decrease, indicating reduced deformation under load.

2. Air voids decrease with up to 0.5% steel fibre, enhancing density. The 0.3% steel fibre mixture exhibits the lowest abrasion loss, hence enhancing durability. An excessive amount of steel fibre (0.7%) increases abrasion loss and air voids.
3. The 0.3% steel fibre mixture demonstrates the highest initial and ultimate peak loads after self-healing, indicating superior effectiveness. The highest self-healing rates are achieved at a steel fibre content of 0.3%.
4. A steel fibre content of 0.3% maximizes the stability, flow, durability, and self-healing properties of asphalt pavements, leading to improved performance and longevity. Steel fibres, when used in conjunction with microwave heating, greatly enhance the self-healing ability of the asphalt mixture, resulting in stronger and longer-lasting road surfaces.

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