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Original Article

Self-healing crack of steel fibre asphalt mixture using heating method with non-destructive test- ultrasonic pulse velocity (UPV)

Fionna Shiong[1], Ekarizan Shaffie[1, 2*], Muhammad Syafiq Iqbal Din[1], Nuryantizapura Mohamad Rais[3], and Noor Azreena Kamaluddin[1]

[1] *School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, 40450 Malaysia*

[2] *Institute for Infrastructure Engineering and Sustainability Management (IIESM), Universiti Teknologi MARA, Shah Alam, Selangor, 40450 Malaysia*

[3] *Malaysia Institute of Transport (MITRANS), Universiti Teknologi MARA, Shah Alam, Selangor, 40450 Malaysia*

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Abstract

Asphalt pavements are durable and cost-effective but are prone to issues like rutting and surface cracking, especially under heavy traffic. Traditional asphalt mixtures often necessitate expensive and frequent maintenance to resolve these issues, leading to traffic disruptions and raising the overall lifetime costs of road infrastructure. Developing self-healing techniques for asphalt pavements is crucial to reducing maintenance requirements and extending their lifespan. Stone Mastic Asphalt (SMA) is valued for resisting these issues, and the addition of steel fibers can enhance its self-healing capability. The inclusion of steel fibers also helps improve the low tensile strength of SMA mixtures. This study evaluates the effects of adding steel fibers to SMA on its physical properties and self-healing abilities, using tests like Ultrasonic Pulse Velocity (UPV) and heating. The research shows that 0.3% was the optimum percentage of steel fibre content to be used as modification of SMA, and this improves the stability, density, and durability of SMA, enhancing its resistance to traffic loads and its ability to self-heal. The findings suggest that steel fiber reinforced SMA is a superior, longer-lasting alternative for high-traffic areas.

Keywords: stone mastic asphalt, steel fibre, self-healing, ultrasonic pulse velocity, heating method

1. Introduction

Road construction in Malaysia is very important when it comes to economic and social development. Mix design and the use of appropriate materials are the first steps in improving road performance (Panda, Das, & Sahoo, 2017). Flexible, rigid, and composite pavements are the three primary types of pavements available today. Commonly, flexible pavement is utilised on most Malaysian roads.

Asphalt is the primary material used in flexible pavement construction. It is a composite material consisting of aggregates and bitumen, commonly employed in road construction. Asphalt is extensively utilized worldwide in the paving industry due to its durability, versatility, and cost-effectiveness. The mechanical resistance and durability of asphalt mixes can be lowered because of their constant exposure to traffic loading and environmental conditions, with damage due to ageing, moisture, and thermal cracking (Norambuena-Contreras, & Gonzalez-Torre, 2017). Thus, from time to time, pavement needs maintenance in order to increase the lifespan of the road.

In response to that need, the application of road pavement can be strengthened using fibres (Serin, Morova,

*Corresponding author
Email address: eka@uitm.edu.my

Saltan, & Terzi, 2012). Other than that, asphalt mixture can repair itself when damaged, whereby bitumen can flow through asphalt cracks when the temperature rises beyond the threshold for bitumen flow (Norambuena-Contreras, & Garcia, 2016). The use of steel fibre in pavement engineering materials shows the importance of their use in asphalt, as it improves the self-healing process and helps minimize issues with potholes, ravelling, slippage when driving in the rain, and other similar issues (Shiong, & Shaffie, 2021). These statements are the same as from other studies that said it is found that with the proper heating techniques, asphalt mixes containing steel fibres or slags may be healed. Additionally, it appears that samples heated by microwave had somewhat better healing results than those heated by induction (Sun *et al.*, 2017). As a result, steel fibre is employed in this research as an addition to asphalt mixture to see if the employment of heating technology will increase self-healing performance.

Many studies have been done on self-healing of asphalt mixture with addition of steel fibre, but it remains unclear what is the relationship between steel fibre with the self-healing of asphalt mixture. In this study, the effect of microwave heating on the self-healing capabilities of fibre asphalt mixes is investigated. To achieve this, varying concentrations of steel fibres were added into an asphalt mixture and heated in a microwave. The results of this study demonstrate that the addition of steel fibre can potentially improve the stability and self-healing of asphalt mixture.

2. Materials and Methods

The test conducted was volumetric properties and healing test which includes bulk specific gravity test (G_{mb}), theoretical maximum specific gravity test (G_{mm}), Marshall stability and flow test, indirect tensile strength test and Ultrasonic Pulse Velocity (UPV) test (before and after the healing effect) in this research study. The modification of SMA was enhanced by incorporating a modifier, specifically steel fibers, into the mixture. Figure 1 shows the research flowchart of this study.

2.1 Preparation of marshall samples

During the preparation of Marshall samples, proportions of steel fibre were mixed with the asphalt mixture at levels 0.3%, 0.5% and 0.7% by the total weight of mixture. The percentages tested were chosen based on the previous study done by Shaffie *et al.* (2022). The mixing process of the aggregates, steel fibre and bitumen were carried out until the mixture reached a temperature from 160°C to 180°C. This precise temperature control ensures optimal blending and coating of the aggregates, promoting uniformity and enhancing the overall quality of the asphalt mixture.

2.2 Volumetric properties

There were four tests conducted which were bulk specific gravity (G_{mb}) test, theoretical maximum specific gravity (G_{mm}) test, Marshall stability and flow test. For G_{mb} test, there were twelve (12) SMA mixture samples with varying steel fibre percentages of 0%, 0.3%, 0.5% and 0.7% being used, while eight (8) SMA mixture samples, also with different steel fibre contents were used for G_{mm} test. G_{mb} test was conducted to determine the specific gravity of well-compacted stone mastic asphalt mixture samples. The specific gravities of all SMA mixture samples were calculated as the ratio of the weight of the sample to the weight of an equal

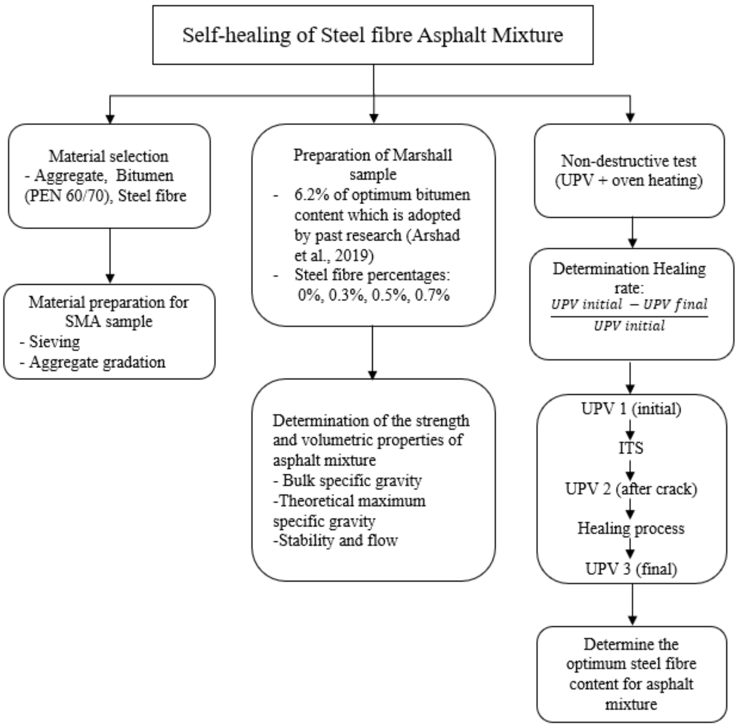

Figure 1. Flowchart of research in this study

water volume. The weight of the tamped SMA mixture samples were evaluated under three (3) varying states which were dry, submerged in water and saturated surface dry.

Regarding the G_{mm} test, it was done to determine the air voids in a well compacted SMA mixture sample. It was also known as the specific gravity without the air voids. Rice method with respect to American Society for Testing and Materials 2041 (ASTM 2041, 2019) and American Association of State Highway and Transportation Officials T 209 (AASHTO T 209, 2019) standards were followed in this laboratory study. The process began with the bitumen content and aggregates being mixed. Following the mixing operation, the SMA mixture was subsequently distributed and loosened on a tray to separate the bitumen-coated aggregates into smaller granules and set them at room temperature. The dry mass of the loosened SMA mixture was recorded and it was sealed in a plastic bag in order to eliminate any entrapped air within the mixture using Corelok vacuum chamber. Following the expulsion of trapped air from the sample-filled plastic bag, the plastic bag with the sample was suspended for about 10 minutes at 25°C in a water bath to determine its constant mass.

2.2.1 Marshall stability and flow test

One particular test has been chosen namely Marshall stability and flow test. In this test, for twelve (12) of SMA mixture samples with varying contents of steel fibre (0%, 0.3%, 0.5% and 0.7%). Based on a study done by Sengul, Oruc, Iskender, and Aksoy (2013), Marshall stability was conducted to evaluate the SMA mixture sample's tensile strength aptitude, and regarding the flow attributes, it was done as it is associated with the resistance of the SMA mixture towards rutting. The Marshall stability and flow test was conducted in line with ASTM D-6927 (2015), and it began with the SMA mixture samples being submerged in a water bath for 30 minutes at a steady temperature of 60°C. After that, one by one, the SMA mixture samples were taken out of the water bath and immediately loaded into the Marshall stability test machine. A metal cylinder with a diameter of 101.6 mm was inserted into the loading head and adjusted to make the flow meter become **'**zero**'**. Up until the testing load reached its maximum strength or top resistance load, the testing load was applied to the SMA mixture samples at a continuous rate of 4 deformation of 50.8 mm/minute. The Marshall stability value was obtained by recording the maximum load that the SMA mixture samples are able to withstand before failure. The flow meter was kept securely in place above the guide rod during the stability test and was withdrawn when the load started to diminish. The deformation at the maximal load determines the flow value for the sample.

2.3 Microwave healing condition test

All the samples were subjected to an Indirect Tensile Test (ITS) only to create cracks in the samples. After that, the samples were left at room temperature until they reached 25ºC before they underwent the healing phase. The samples were then placed in a microwave (Figure 2) in order to apply heat to the samples. The samples were heated for 120 minutes at 60ºC (Sarsam, & Kadium, 2020) to see how temperature affected the healing efficiency. When the treatment reached the specified time, the SMA mixture sample was taken out of the microwave and the cracks in the sample were observed and analyzed. The samples were then taken for the next step of this laboratory study.

2.4 Ultrasonic pulse velocity (UPV) test

A total of twelve (12) SMA samples were tested by a UPV test to determine the healing rate for this research, with three (3) samples for each steel fibre percentage of 0%, 0.3%, 0.5%, and 0.7%. Each sample was subjected to UPV several times before and after going through microcrack healing process. The first and second UPV test were before and after going through ITS process to create crack. The third test was after going through microcrack healing process. The last test was after repeated ITS test. The UPV data that only have been considered in this research was the first (initial), second and the third (final) UPV values. The collected data were averaged for further analysis on determining optimum steel fibre content in asphalt mixture in terms of healing rate following Equation 1 (Abo-Qudais & Suleiman, 2005; Liang *et al.*, 2021; Norambuena-Contreras & Garcia, 2016; Sarsam & Kadium, 2020). Figure 3 shows the equipment of UPV test used and Figure 4 indicates the measurement setup on the sample.

$$\text{Healing rate} = \frac{(\text{UPV initial-UPV final})}{(\text{UPV initial}) \times 100\%} \quad (1)$$

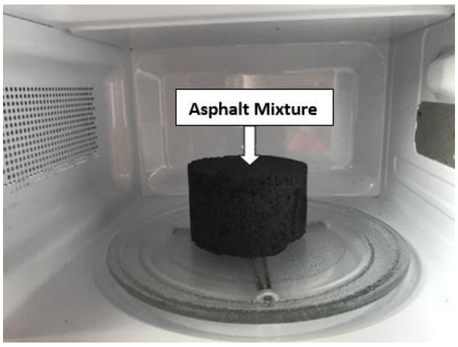

Figure 2. Stone mastic asphalt mixture sample in microwave

Figure 3. Ultrasonic Pulse Velocity (UPV) equipment used

Figure 4. Ultrasound pulse velocity measurement setup

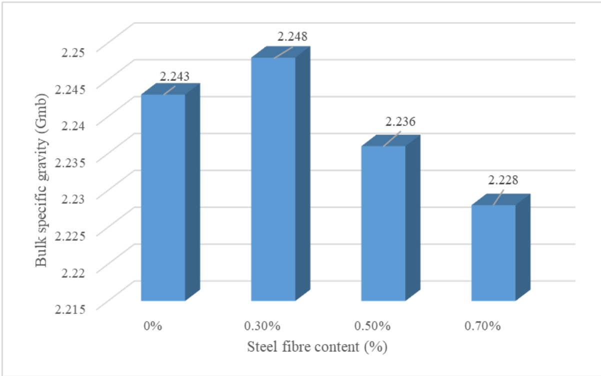

Figure 5. Bulk specific gravity with different steel fibre contents

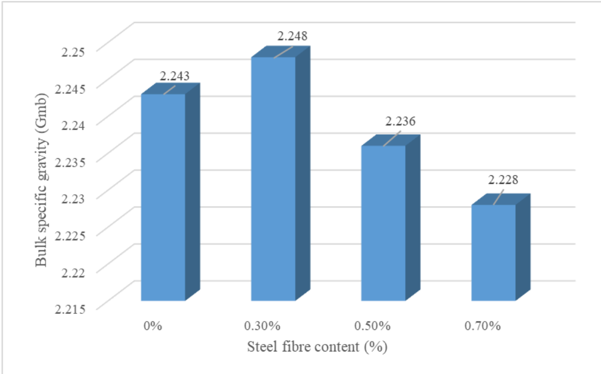

Figure 6. Theoretical maximum gravity with different steel fibre contents

3. Results and Discussion

3.1 Volumetric properties test of steel fibre modified asphalt mixture

According to Figure 5, 0.3% steel fibre content has the maximum bulk specific gravity (G_{mb}), 2.248. It was then followed by 0%, 0.5% and 0.7% steel fibre content. The results in the graph show that by adding the steel fibre at an optimum percentage, the G_{mb} of the asphalt mixture will increase and then decrease after its reach optimum, which is 0.3% steel fibre content. G_{mb} properties are principally related to the air void content of the asphalt mixture. The higher the G_{mb}, the less there are air voids in the asphalt mixture. Excessive air void content in a mixture may increase the probability of cracking due to a lack of binder to coat aggregates, whereas too low air void content may contribute to increased rutting and bleeding problems.

Based on the given description of Figure 6, the variation in theoretical maximum specific gravity (G_{mm}) with different steel fibre contents exhibits a nonlinear trend. Initially, as the steel fibre content increases from 0% to 0.3%, G_{mm} decreases, indicating that the addition of steel fibres initially leads to a reduction in G_{mm}. This could be due to the steel fibres' impact on the mixture's density or void structure.

However, when the steel fibre content increases further to 0.5% and 0.7%, the G_{mm} starts to increase again. This nonlinear behavior suggests that the relationship between steel fibre content and G_{mm} is not straightforward and may involve complex interactions between the fibres and the asphalt mixture (Ajam, 2019).

The nonlinear trend observed in G_{mm} against varying steel fibre content indicates that the relationship between steel fibre addition and specific gravity is complex and influenced by multiple factors related to fibre distribution, interaction, compaction, and matrix saturation (Almutairi, 2023). At lower steel fibre contents (0% to 0.3%), fibres may be more uniformly distributed, which leads to a consistent reduction in G_{mm}. As the fibre content increases, however, the dispersion of fibres might become less uniform, leading to localized effects that could alter the overall density.

3.2 Marshall stability and flow test

The average stability of 0.3% of steel fibre obtained the maximum value 1089.7kg, as shown in Figure 7. The graph also shows that the control mixture has the lowest average stability of 889.57 kg. Also on the opposite side, the stability of the mixture began to decrease gradually with the addition of 0.5% and 0.7% steel fibre. This situation occurred because of an excessive amount of steel fibres that did not disperse uniformly throughout the mixture and finally formed weak areas as a result of coagulation.

In contrast, the stability of mixture started to reveal a gradual decrease with the addition of 0.5% and 0.7% steel fibre. This trend is similar to the research done by Jasni *et al.* (2020), which found that the stability increases with 0.2% steel fibre and decreases when fibre content is increased up to 0.6%. As a result, the stability drops with increasing steel fibre content. The study also found that asphalt mixes containing 0.1 % and 0.2 % steel fibre by volume of total mix had greater stability (Al-Ridha, Hameed, & Ibrahim, 2014) at all testing temperatures and compaction.

Additional studies by Shiong *et al.* (2024) and Shaffie *et al.* (2023) corroborate these results, highlighting the benefits of moderate steel fiber content in enhancing tensile strength, crack resistance, fatigue life, and load-bearing capacity. Figure 7 also shows the average flow value with

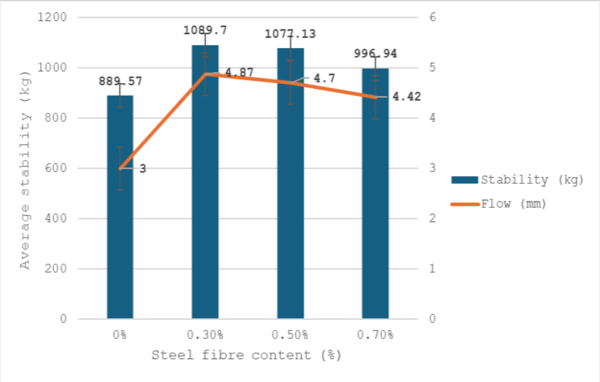

Figure 7. Stability and flow test with different steel fibre contents

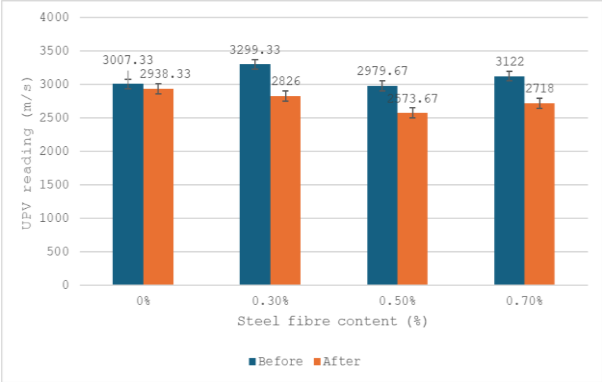

Figure 8. UPV with different steel fibre contents

different steel fibre contents. By analysing flow values obtained for 0%, 0.3%, 0.5%, and 0.7% levels of steel fibre, it is clear that the flow value of asphalt mixture tends to decrease significantly with increasing steel fibre content. The flow values obtained represent the amount of deformation that happens in the mixture when the load is reduced. The results show that increasing the amount of steel fibre resulted in lower flow values owing to the stiffness of steel fibres in asphalt mixture, resulting in a less flexible mixture. This is proof that the steel fibre percentage influences the flow of asphalt mixture.

3.3 Ultrasonic pulse velocity test (UPV) test

According to Figure 8, the lowest value of UPV is at 0.5% level of steel fibre, and this is lower than for the control sample before going through the microwave heating. Furthermore, 0.3% steel fibre content has a maximum UPV of 3299.22 m/s. This was then followed in rank order by 0.7%,0% and 0.5% of steel fibre. As steel fibre was added, the graph shows increased UPV, but it decreases once the asphalt mixtures reach the optimum at 0.3% of steel fibre and increases again after that. Thus 0.3% of steel fibre shows a good result in terms of UPV reading before going through microcrack healing process.

The graph also shows the UPV of samples after going through microcrack healing process. It can be noted that the UPV in all cases decreased on going through microcrack healing. This is because, before the samples went through microcrack healing process, the samples went through ITS test to create cracks and this made the UPV increase rapidly. After the healing process, the UPV of all the asphalt mixtures had increased. This matches past research that said that if the UPV was increased, that means the asphalt mixture is damaged; while if the UPV was decreased, healing may have occurred (Liang *et al.*, 2021). The second finding explains why the ultrasonic pulse velocity increases after the micro-crack healing process (Sarsam & Kadium, 2020).

According to the graph, after microcrack healing process, the difference UPV value was 69 m/s, 473.33 m/s, 406 m/s and 404 m/s for 0%,0.3%,0.5% and 0.7% of steel fibre content. It can be noted that the 0.3% steel fibre content show the highest difference in UPV namely 473.33 m/s, comparing before creating cracks and after going through microcrack healing. It can be observed that specimens constructed at optimum asphalt content are able to sustain higher pulse velocity after load repetition and exhibit minimum damage among other specimens with 0.3% asphalt above or below the optimum content before and after healing process. Such finding agrees well with the work reported by Lao (2021).

Similar studies have reported that the addition of steel fibers increases the tensile strength and durability of asphalt mixtures. For example, studies by Zhao (2023) and Li & Chen (2021) demonstrated that steel fibers enhance the crack resistance and overall durability of asphalt concrete, corroborating the current findings on UPV improvements post-healing process.

3.4 Healing rate

The steel fibre content of 0.3% showed the greatest healing rate of 12.47% and it was followed by 0.5% and 0.7% steel fibre contents, as shown in Figure 9. Healing rate increased with the addition of 0.3% steel fibre but decreased with the addition of 0.5%. However, the healing rates of 0.5% and 0.7% cases were higher than the healing rate with 0% steel fibre content. From these results, the presence of steel fibre is clearly proven to increase the healing rate of asphalt mixtures compared to a conventional mixture that exhibits the lowest healing rate among all proportions of steel fibre.

All the samples with steel fibre had increased UPV after microcrack healing process. This matches past research that said that if the UPV was increased, that means the asphalt mixture is damaged; but if the UPV was decreased, the healing may have occurred (Liang *et al.*, 2021). The second finding explains that the UPV increases after the micro-crack healing process (Sarsam & Kadium, 2020). The increase in pulse velocity indicates that a material's internal structure is excellent and properly compacted (Siddique & Belarbi, 2021). The porosity of the asphalt mixture decreased after microcrack healing meaning the cracks were reduced and thus the UPV increased. The wave path will be reflected due to structural discontinuities (such as cracks) making the UPV decrease (Pacheco-Torgal *et al.*, 2017).

Based on the UPV values, it is revealed that the addition of 0.3% steel fibre in SMA enhances the self-healing of microcracks by up to 37% compared to the conventional SMA, followed by 13% with 0.5% steel fibre, and 2% with 0.7% steel fibre. This is a clear indication that the presence of

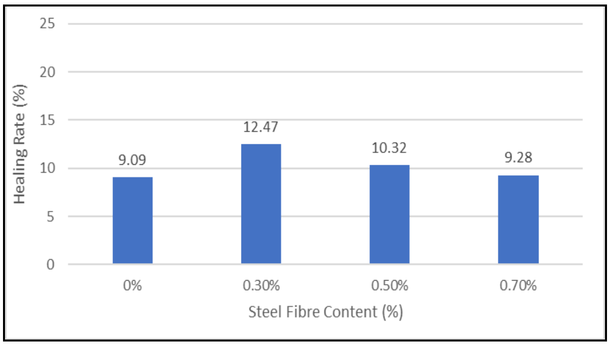

Figure 9. Healing Rate with different steel fibre contents

steel fibre strengthens the interconnecting bonds between the bitumen molecules, enhancing cohesion and adhesion properties of SMA when being exposed to heat to be better than those of conventional SMA.

3.5 Optimum steel fibre content

In comparison to conventional SMA based on Table 1, the addition of steel fibre in SMA demonstrates enhanced mixture performance in terms of specific gravity, stability, flow, and healing rate, according to the findings of the properties and performance tests. Based on the results, it can be concluded that an SMA mixture with 0.3% steel fibre content is the best choice for improving SMA performance in terms of healing rate, as it had the most positive impact on the properties and performance of SMA among the steel fibre proportions studied.

Table 1. Optimum steel fibre content

Steel fibre	G_{mb}	G_{mm}	Stability (kN)	Flow (mm)	Healing rate (%)
0	2.243	2.510	8.116	3	9.09
0.3	2.248	2.388	9.769	4.87	12.47
0.5	2.236	2343	9.827	4.70	10.32
0.7	2.228	2.417	10.832	4.42	9.28

4. Conclusions

This study aimed to evaluate the impact of steel fibers on Stone Mastic Asphalt (SMA) at various percentages, focusing on performance aspects such as self-healing and determining the optimal fiber content for SMA modification. The findings reveal that the inclusion of steel fibers enhances the stability and self-healing properties of SMA. Based on the experimental results and detailed analysis, the following conclusions are drawn:

1. Optimal Stability: The maximum stability is achieved with a steel fiber content of 0.3%, resulting in a weight of 1089.7 kg. Beyond this percentage, stability decreases due to uneven fiber distribution. Increased steel fiber content also leads to lower flow values, indicating reduced deformation under load.
2. Enhanced Self-Healing: Adding steel fibers at 0.3%, 0.5%, and 0.7% improves the self-healing rate of the asphalt mixture by 37%, 13%, and 2%, respectively, compared to conventional SMA.
3. Superior Performance: The 0.3% steel fiber mixture exhibits the highest initial and final Ultrasonic Pulse Velocity (UPV) readings post-healing, demonstrating the greatest effectiveness in self-healing. The highest self-healing rates are observed at a 0.3% steel fiber content.
4. Enhanced Pavement Properties: A 0.3% steel fiber content optimizes SMA's stability, flow, durability, and self-healing characteristics, enhancing performance and extending the pavement's lifespan. When combined with microwave heating, steel fibers significantly improve the asphalt mixture's self-healing capacity, leading to more resilient and durable road surfaces.

The use of ultrasound pulse velocity tests for evaluating asphalt concrete quality after load repetitions and microcrack healing is a reliable and rapid method for quality control in the laboratory. Its application in the field is also recommended.

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