



Effect of Bamboo Fiber on the Performance of Stone Matrix Asphalt Using Slag as Aggregate Replacement

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Abstract: The increasing demand for sustainable and durable pavement materials has encouraged the incorporation of natural fibers and industrial by-products in asphalt mixtures. This study investigates the effect of bamboo fiber and steel slag aggregate on the performance of Stone Matrix Asphalt (SMA). Bamboo fiber was incorporated at 0.3% and 0.5% by weight of the total mix, while slag aggregate was used as a partial replacement for natural aggregates at 25% and 50%. Marshall Mix Design methodology was adopted to evaluate the engineering characteristics of the modified SMA mixtures. Performance evaluation included Marshall Stability and Flow, Indirect Tensile Strength (ITS), rutting resistance, and moisture susceptibility tests. The results indicated that the combined use of bamboo fiber and slag significantly improved the stability, tensile strength, and rutting resistance of SMA mixtures compared to the control mix. The highest performance was achieved for the mixture containing 0.5% bamboo fiber and 50% slag replacement, which exhibited maximum tensile strength and minimum rut depth. The study concludes that bamboo fiber and slag aggregate can be effectively utilized in SMA mixtures to produce sustainable, economical, and high-performance asphalt pavements.

Keywords: Stone Matrix Asphalt, Bamboo Fiber, Slag Aggregate, Sustainable Pavement, Marshall Stability, Rutting Resistance



1. Introduction

The rapid increase in traffic volume, axle loads, and environmental stresses has created a growing demand for durable and high-performance pavement materials. Conventional asphalt pavements frequently suffer from premature failures such as rutting, fatigue cracking, raveling, and moisture-induced damage, particularly under heavy traffic and adverse climatic conditions. These deficiencies lead to increased maintenance costs and reduced service life of pavements. To address these challenges, Stone Matrix Asphalt (SMA) has emerged as a superior asphalt mixture because of its gap-graded aggregate structure, high coarse aggregate content, and stone-on-stone contact mechanism, which provide excellent resistance to permanent deformation and rutting (Roberts et al., 1996). SMA mixtures also contain a rich binder mortar that improves flexibility and fatigue resistance, making them suitable for heavily trafficked roads and highways.

Despite its superior engineering performance, SMA mixtures often experience binder drain-down due to the high bitumen content present in the mix. To overcome this issue, stabilizing additives such as fibers are commonly incorporated into the asphalt mixture. In recent years, natural fibers have gained considerable attention in pavement engineering because of their low cost, renewability, biodegradability, and eco-friendly nature. Among various natural fibers, bamboo fiber has shown significant potential due to its high tensile strength, low density, and good compatibility with asphalt binders. Bamboo fibers act as reinforcing agents that improve the tensile strength, fatigue resistance, and moisture susceptibility of asphalt mixtures while reducing binder drain-down during mixing and placement (Li et al., 2010). Furthermore, bamboo is a rapidly renewable resource that grows abundantly in many tropical and subtropical regions, making it an economically viable and environmentally sustainable material for pavement applications.

In addition to natural fibers, the utilization of industrial by-products in pavement construction has become an important strategy for sustainable infrastructure development. Steel slag, a by-product generated during steel manufacturing, has been widely investigated as an alternative aggregate material in asphalt mixtures. Due to its rough texture, angular shape, and high hardness, slag aggregate improves the interlocking characteristics and load-bearing capacity of asphalt mixtures (Ahmedzade & Sengoz, 2009). Previous studies have reported that the incorporation of slag aggregate enhances rutting resistance, abrasion resistance, and skid resistance of asphalt pavements while simultaneously reducing the demand for natural aggregates (Xue et al., 2006). Moreover, the reuse of slag contributes to waste management and supports circular economy principles by minimizing industrial waste disposal.

Although several studies have separately investigated the effects of bamboo fiber and steel slag in asphalt mixtures, limited research has been conducted on their combined influence in Stone Matrix Asphalt. The synergistic interaction between bamboo fiber and slag aggregate may significantly improve the mechanical performance, durability, and sustainability of SMA mixtures. Bamboo fiber can enhance tensile strength and binder stabilization, while slag aggregate can improve stiffness and rutting resistance. Therefore, the present study aims to evaluate the combined effect of bamboo fiber and slag aggregate on the performance characteristics of SMA mixtures through laboratory investigations including Marshall Stability, Indirect Tensile Strength, rutting resistance, and moisture susceptibility analysis. The findings of this study are expected to contribute to the development of sustainable, durable, and high-performance asphalt pavements for modern transportation infrastructure.

2. Materials and Methods

2.1 Materials Used

The materials utilized in this study included VG-30 bitumen, natural coarse and fine aggregates, steel slag aggregate, and bamboo fibers. VG-30 bitumen was selected as the binder material because of its suitability for heavy traffic and high-temperature pavement applications. The aggregates used in the study satisfied the standard requirements for Stone Matrix Asphalt (SMA) mixtures. Steel slag obtained from a local steel manufacturing industry was used as a partial replacement for conventional aggregates due to its high hardness, rough texture, and superior abrasion resistance. Bamboo fibers were incorporated into the SMA mixtures as a natural stabilizing and reinforcing material to improve tensile strength, rutting resistance, and binder stability.

The physical properties of the bitumen were determined according to ASTM standards. The penetration value of the binder was found to be 65, indicating medium hardness suitable for flexible pavements. The softening point and ductility values confirmed the binder's resistance to temperature variations and cracking. The properties of bitumen used in this study are presented in Table 1.

**Table 1 Physical Properties of Bitumen**

Property	Test Method	Value
Penetration (25°C)	ASTM D5	65
Softening Point (°C)	ASTM D36	48
Ductility (cm)	ASTM D113	75
Specific Gravity	ASTM D70	1.01
Flash Point (°C)	ASTM D92	260

Steel slag aggregate was characterized for its engineering properties before use in the asphalt mixtures. The slag exhibited high angularity and abrasion resistance, which are beneficial for improving interlocking and rutting resistance in SMA mixtures. The water absorption and crushing value were within permissible limits specified for pavement aggregates. The physical properties of slag aggregate are presented in Table 2.

Table 2 Physical Properties of Slag Aggregate

Property	Value	Permissible Limit
Specific Gravity	2.75	2.5–3.0
Water Absorption (%)	2.0	≤ 3
Los Angeles Abrasion (%)	22	≤ 30
Crushing Value (%)	20	≤ 30
Angularity (%)	95	≥ 85

2.2 Mix Proportions

Nine SMA mixtures were prepared with varying percentages of bamboo fiber and slag aggregate replacement. The bitumen content was maintained constant at 6% for all mixtures based on the Marshall Mix Design method. Bamboo fiber was incorporated at two levels, namely 0.3% and 0.5% by weight of the total mix, while slag aggregate replaced conventional aggregates at 25% and 50% levels. A control mixture without bamboo fiber and slag was also prepared for comparison purposes.

The selected combinations were intended to evaluate the individual and combined effects of bamboo fiber and slag aggregate on the performance characteristics of SMA mixtures. The detailed mix proportions adopted in this study are presented in Table 3.

Table 3. Mix Proportions

Mix ID	Bitumen Content (%)	Bamboo Fiber Content (%)	Slag Replacement (%)	Description
M0	6.0	0.0	0	Control SMA Mix
M1	6.0	0.3	0	SMA with Bamboo Fiber
M2	6.0	0.5	0	SMA with Higher Bamboo Fiber
M3	6.0	0.0	25	SMA with 25% Slag
M4	6.0	0.0	50	SMA with 50% Slag
M5	6.0	0.3	25	SMA with 0.3% Fiber + 25% Slag
M6	6.0	0.3	50	SMA with 0.3% Fiber + 50% Slag
M7	6.0	0.5	25	SMA with 0.5% Fiber + 25% Slag
M8	6.0	0.5	50	SMA with 0.5% Fiber + 50% Slag

3. Experimental Program

An extensive laboratory experimental program was conducted to evaluate the performance characteristics of the Stone Matrix Asphalt (SMA) mixtures containing bamboo fiber and slag aggregate. The prepared SMA specimens were



subjected to Marshall Stability and Flow tests to determine the load-bearing capacity, stiffness, and deformation characteristics of the mixtures. Indirect Tensile Strength (ITS) tests were performed to evaluate the tensile properties and cracking resistance of the asphalt mixtures under indirect loading conditions. Rutting resistance was assessed using the Wheel Tracking test, which simulated repeated traffic loading to measure the permanent deformation behavior of the mixtures. In addition, moisture susceptibility analysis was carried out through Tensile Strength Ratio (TSR) evaluation to determine the resistance of the SMA mixtures against water-induced damage and stripping. The results obtained from these laboratory investigations were used to analyze the influence of bamboo fiber and slag aggregate on the mechanical performance, durability, and overall stability of SMA mixtures.

4. Results and Discussion

4.1 Marshall Stability and Flow

The Marshall Stability and Flow test results presented in Table 4 indicate that the incorporation of bamboo fiber and slag aggregate significantly improved the performance characteristics of Stone Matrix Asphalt (SMA) mixtures. The control mix (M0) exhibited a Marshall Stability value of 10.5 kN with a flow value of 3.9 mm, whereas the modified mixtures demonstrated higher stability and lower flow values. The stability increased gradually with the addition of bamboo fiber and slag aggregate, reaching a maximum value of 13.2 kN for mix M8 containing 0.5% bamboo fiber and 50% slag replacement. This improvement represents approximately 25.7% enhancement compared to the control mix. The increase in stability can be attributed to the reinforcing action of bamboo fibers, which improved the internal cohesion and tensile resistance of the asphalt matrix, as well as the angular and rough texture of slag aggregates that enhanced aggregate interlocking and load distribution. Moreover, the flow values decreased progressively from 3.9 mm for M0 to 3.2 mm for M8, indicating improved stiffness and resistance to plastic deformation. The lower flow values suggest that the modified SMA mixtures became more resistant to rutting and excessive deformation under heavy traffic loading. Therefore, the results shown in Table 4 confirm that the combined use of bamboo fiber and slag aggregate effectively enhanced the structural stability and deformation resistance of SMA mixtures.

Table 4. Marshall Stability and Flow Values

Mix ID	Fiber Content (%)	Slag Replacement (%)	Marshall Stability (kN)	Flow Value (mm)
M0	0.0	0	10.5	3.9
M1	0.3	0	11.2	3.7
M2	0.5	0	11.8	3.5
M3	0.0	25	11.0	3.8
M4	0.0	50	11.5	3.6
M5	0.3	25	12.1	3.5
M6	0.3	50	12.6	3.4
M7	0.5	25	12.8	3.3
M8	0.5	50	13.2	3.2

4.2 Indirect Tensile Strength (ITS)

The Indirect Tensile Strength (ITS) results summarized in Table 5 demonstrate that the addition of bamboo fiber and slag aggregate substantially improved the tensile properties and cracking resistance of the SMA mixtures. The control mix (M0) recorded the lowest ITS value of 720 kPa, while the highest ITS value of 920 kPa was observed for mix M8 containing 0.5% bamboo fiber and 50% slag replacement. This represents an increase of approximately 27.8% compared to the control mix. The progressive increase in ITS values with increasing fiber and slag content indicates enhanced stress distribution and improved bonding characteristics within the asphalt matrix. Bamboo fibers acted as reinforcing elements that bridged microcracks and restricted crack propagation under tensile loading conditions, thereby improving the fatigue resistance and durability of the mixtures. Simultaneously, slag aggregate contributed to better mechanical interlocking due to its rough surface texture and angularity, resulting in stronger adhesion between the aggregate and bitumen. Mixtures M5, M6, M7, and M8 exhibited particularly high ITS values because of the combined synergistic effect of fiber reinforcement and slag aggregate replacement. The findings presented in Table 5 clearly demonstrate that bamboo fiber and slag aggregate can significantly improve the tensile strength and long-term performance of SMA pavements subjected to repeated traffic loading and environmental stresses.

**Table 5. Indirect Tensile Strength Results**

Mix ID	Fiber Content (%)	Slag Replacement (%)	ITS (kPa)
M0	0.0	0	720
M1	0.3	0	785
M2	0.5	0	825
M3	0.0	25	760
M4	0.0	50	790
M5	0.3	25	860
M6	0.3	50	900
M7	0.5	25	880
M8	0.5	50	920

4.3 Rutting Resistance

The rutting resistance results presented in Table 6 demonstrate that the incorporation of bamboo fiber and slag aggregate significantly improved the resistance of SMA mixtures against permanent deformation under repeated loading. The control mix (M0) exhibited the highest rut depth value of 6.80 mm, indicating greater susceptibility to deformation and rut formation under traffic loading conditions. In contrast, all modified mixtures showed lower rut depth values, confirming the positive influence of bamboo fiber and slag aggregate on the rutting performance of SMA. The rut depth progressively decreased with increasing fiber content and slag replacement level, with the lowest value of 4.80 mm recorded for mix M8 containing 0.5% bamboo fiber and 50% slag replacement. This reduction corresponds to approximately 29.4% improvement in rutting resistance compared to the control mix. The enhanced performance can be attributed to the reinforcing action of bamboo fibers, which improved the stiffness and internal stability of the asphalt matrix by restricting excessive binder movement and deformation. Simultaneously, the angularity, rough texture, and high hardness of slag aggregates enhanced aggregate interlocking and load distribution, thereby reducing permanent deformation under wheel loading. Mixes M5, M6, M7, and M8 exhibited particularly lower rut depths because of the combined synergistic effect of bamboo fiber and slag aggregate. The findings presented in Table 6 clearly indicate that the combined utilization of bamboo fiber and slag aggregate effectively enhances the rutting resistance and structural durability of SMA pavements, making them more suitable for heavy traffic and high-temperature conditions.

Table 6. Rut Depth Results

Mix ID	Fiber Content (%)	Slag Replacement (%)	Rut Depth (mm)
M0	0.0	0	6.80
M1	0.3	0	6.10
M2	0.5	0	5.70
M3	0.0	25	6.20
M4	0.0	50	5.90
M5	0.3	25	5.40
M6	0.3	50	5.00
M7	0.5	25	5.20
M8	0.5	50	4.80

4.4 Moisture Susceptibility

The moisture susceptibility performance of the SMA mixtures was evaluated using the Tensile Strength Ratio (TSR) test to determine the resistance of the mixtures against water-induced damage and stripping. The results indicated that the incorporation of bamboo fiber and slag aggregate significantly improved the moisture resistance characteristics of the asphalt mixtures compared to the control mix. The control mixture (M0) exhibited a TSR value of approximately 78%, indicating relatively lower resistance to moisture damage. In contrast, the modified mixtures showed higher TSR values, with the maximum value of nearly 89% observed for mix M8 containing 0.5% bamboo fiber and 50% slag replacement. The improvement in moisture resistance can be attributed to the ability of bamboo fibers to absorb and stabilize excess binder, thereby reducing binder drain-down and improving adhesion between the binder and aggregate.



surfaces. Furthermore, the rough and angular surface texture of slag aggregates enhanced the mechanical interlocking and bonding characteristics within the asphalt matrix, reducing the possibility of stripping under wet conditions. The combined use of bamboo fiber and slag aggregate also minimized the formation of microvoids and moisture penetration pathways within the SMA mixtures. Consequently, the modified mixtures exhibited better durability and resistance to water-induced deterioration compared to the conventional SMA mixture. These findings confirm that the incorporation of bamboo fiber and slag aggregate can significantly enhance the long-term moisture resistance and service life of SMA pavements exposed to adverse environmental conditions.

5. Discussion

The results obtained from this study clearly demonstrate that the incorporation of bamboo fiber and steel slag aggregate significantly improved the engineering performance of Stone Matrix Asphalt (SMA) mixtures. The enhancement in Marshall Stability values indicates that the modified SMA mixtures possessed greater load-bearing capacity and resistance to deformation compared to the conventional SMA mixture. The increase in stability can primarily be attributed to the reinforcing effect of bamboo fibers and the improved aggregate interlocking provided by slag aggregates. Bamboo fibers acted as stabilizing agents within the asphalt matrix, increasing internal cohesion and restricting excessive movement of the binder under loading conditions. Simultaneously, the angular shape and rough surface texture of slag aggregates enhanced frictional resistance and load transfer efficiency, resulting in improved structural integrity of the pavement mixtures.

The reduction in flow values observed in the modified mixtures further confirms the improvement in stiffness and resistance to permanent deformation. Lower flow values generally indicate better rutting resistance and improved ability of the asphalt mixture to withstand heavy traffic loading without excessive deformation. The rutting resistance analysis demonstrated that the addition of bamboo fiber and slag aggregate effectively reduced rut depth values, particularly in mixtures containing higher fiber and slag contents. The lowest rut depth recorded for mix M8 confirmed that the combined use of 0.5% bamboo fiber and 50% slag replacement produced the most stable and deformation-resistant SMA mixture. The fibers contributed to controlling binder mobility and improving tensile reinforcement, while slag aggregate provided a stronger stone-on-stone skeleton structure capable of resisting repeated wheel loading. The Indirect Tensile Strength (ITS) results also revealed significant improvements in cracking resistance and tensile behavior of the modified SMA mixtures. The increase in ITS values indicates that bamboo fibers enhanced the stress distribution within the asphalt matrix by bridging microcracks and delaying crack propagation under tensile loading. The presence of slag aggregate additionally improved the bonding characteristics between aggregates and bitumen because of its rough and angular surface texture. This combined effect enhanced the fatigue resistance and long-term durability of the asphalt mixtures. Such improvements are particularly important for heavily trafficked roads and highways where pavements are subjected to repeated loading and environmental stresses over long service periods.

The moisture susceptibility results further confirmed the beneficial influence of bamboo fiber and slag aggregate on the durability performance of SMA mixtures. The higher TSR values observed in modified mixtures indicate improved resistance against moisture-induced damage and stripping. Bamboo fibers helped stabilize the asphalt binder and reduced binder drain-down, thereby improving the adhesion between bitumen and aggregates. Moreover, the rough texture of slag aggregates enhanced aggregate-binder bonding and minimized moisture penetration within the mixture. The reduction in microvoids and improvement in internal structure contributed to better resistance against water damage and environmental deterioration. These characteristics are highly desirable for pavements exposed to rainfall, humidity, and freeze-thaw conditions.

From a sustainability perspective, the use of bamboo fiber and steel slag aggregate offers considerable environmental and economic advantages. Bamboo fiber is a renewable, biodegradable, and low-cost natural material that can replace synthetic stabilizing additives in asphalt mixtures. Similarly, steel slag is an industrial by-product that can be effectively utilized as an alternative aggregate material, reducing the demand for natural aggregates and minimizing industrial waste disposal problems. Therefore, the combined utilization of bamboo fiber and slag aggregate supports sustainable pavement construction practices by promoting resource conservation, waste recycling, and reduction in environmental impact. The findings of this study indicate that the incorporation of these materials not only improves pavement performance but also contributes to the development of eco-friendly and durable transportation infrastructure.



6. Conclusions

The following conclusions were drawn from the present investigation on the effect of bamboo fiber and slag aggregate on Stone Matrix Asphalt (SMA) mixtures:

1. The incorporation of bamboo fiber and steel slag aggregate significantly improved the Marshall Stability of SMA mixtures, indicating enhanced load-bearing capacity and structural strength.
2. The maximum Marshall Stability value of 13.2 kN was achieved for mix M8 containing 0.5% bamboo fiber and 50% slag replacement, representing approximately 25.7% improvement compared to the control mixture.
3. The flow values decreased with increasing bamboo fiber and slag content, indicating improved stiffness and resistance to permanent deformation.
4. The Indirect Tensile Strength (ITS) values increased substantially in modified SMA mixtures, confirming improved cracking resistance and tensile behavior due to the reinforcing action of bamboo fibers and improved aggregate interlocking of slag aggregates.
5. The highest ITS value of 920 kPa was recorded for mix M8, which demonstrated approximately 27.8% improvement compared to the conventional SMA mixture.
6. Rutting resistance improved significantly with the addition of bamboo fiber and slag aggregate. The lowest rut depth value of 4.80 mm was obtained for mix M8, corresponding to approximately 29.4% reduction in rutting compared to the control mix.
7. Moisture susceptibility analysis revealed higher Tensile Strength Ratio (TSR) values for modified mixtures, indicating improved resistance against water-induced damage and stripping.
8. Bamboo fibers effectively stabilized the asphalt binder, reduced binder drain-down, and enhanced tensile reinforcement within the asphalt matrix.
9. Steel slag aggregate improved aggregate interlocking, abrasion resistance, and stiffness because of its rough texture and angularity.
10. The combined use of bamboo fiber and steel slag aggregate produced a synergistic improvement in the overall mechanical performance, durability, and sustainability of SMA mixtures.
11. The utilization of bamboo fiber and slag aggregate contributes to sustainable pavement construction by reducing dependence on synthetic additives and natural aggregates while promoting the reuse of industrial by-products.
12. Based on the experimental findings, the mixture containing 0.5% bamboo fiber and 50% slag replacement is recommended as the optimum SMA mixture for high-performance and sustainable pavement applications.

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