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The 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 high-performance road construction materials has led to the exploration of bio-based fibers and industrial by-products in Stone Matrix Asphalt (SMA). This study investigates the combined effect of alkali-treated bamboo fiber and steel slag filler on the mechanical and durability properties of SMA mixtures. Four variants were prepared: a control mix (SMA-C), bamboo fiber only (SMA-BF2), 50% slag with fiber (SMA-S50), and 100% slag with fiber (SMA-S100). Marshall Stability, Indirect Tensile Strength (ITS), Tensile Strength Ratio (TSR), and rutting resistance tests were conducted to evaluate the performance. Results showed that SMA-S50, containing 0.3% bamboo fiber and 50% slag, achieved the highest performance across all parameters, including a Marshall Stability of 17.3 kN, ITS of 1170 kPa, TSR of 87.2%, and minimum rut depth of 3.7 mm. The synergy between bamboo fiber and slag led to improved interlocking, enhanced moisture resistance, and reduced permanent deformation. These findings confirm that SMA modified with bamboo fiber and slag not only meets performance standards but also promotes sustainable infrastructure development through the recycling of natural and industrial waste materials.

Keywords: Stone Matrix Asphalt (SMA); Bamboo Fiber; Steel Slag; Sustainable Pavement; Marshall Stability; Indirect Tensile Strength; Rutting Resistance; Moisture Susceptibility

1. Introduction

The rapid urbanization and growing vehicular traffic have imposed significant demands on highway infrastructure, especially flexible pavements. Stone Matrix Asphalt (SMA), a gap-graded bituminous mix, is widely acknowledged for its superior rutting resistance, durability, and stability compared to conventional dense-graded mixes. However, conventional SMA mixtures rely heavily on natural aggregates and industrially processed stabilizers, which raise environmental and cost concerns.

In response to these challenges, researchers have increasingly explored the use of waste and natural fibers to improve the performance of SMA mixes. Among these, bamboo fibers have emerged as a promising alternative due to their high tensile strength, biodegradability, and local availability in tropical regions like India (Rout et al., 2020). Simultaneously, steel slag, a by-product of steel manufacturing, has shown potential as a filler replacement in asphalt mixes due to its rough texture, good bonding ability, and mechanical interlocking properties (Manso et al., 2004).

Need for Sustainable Pavement Materials

The construction industry is under increasing pressure to adopt environmentally sustainable practices. The depletion of natural resources and the environmental burden of industrial waste call for the use of eco-friendly materials in pavement construction. Integrating bamboo fiber and slag in SMA mixes not only diverts waste from landfills but also reduces dependence on virgin materials.

Moreover, India's commitment to climate-resilient infrastructure under the UN Sustainable Development Goals underscores the necessity of incorporating bio-based and industrial by-product materials into road construction (MoRTH, 2021). The synergistic combination of bamboo fiber and slag could offer a high-performing, durable, and environmentally benign alternative to traditional SMA constituents.

Objectives of the Study

The primary aim of this study is to evaluate the combined effect of bamboo fiber and slag on the performance of Stone Matrix Asphalt (SMA) mixes. Specific objectives include:

- To assess the individual and combined influence of alkali-treated bamboo fiber and steel slag on the Marshall properties of SMA mixtures.
- To determine the moisture susceptibility and rutting resistance of modified SMA blends.
- To identify the optimum content of fiber and slag that yields enhanced mechanical performance.

Scope of Work

This study is experimental in nature and involves the preparation of SMA samples using varying proportions of bamboo fiber (0.3%) and slag (0%, 50%, and 100% replacement of conventional filler). The mixes are subjected to a series of laboratory tests including:

- Marshall Stability and Flow Test
- Indirect Tensile Strength (ITS)
- Tensile Strength Ratio (TSR)
- Rutting Resistance Test

2. Literature Review

2.1 Use of Bamboo Fibers in Pavement Engineering

The incorporation of natural fibers into pavement materials has gained increasing attention due to their eco-friendly, cost-effective, and performance-enhancing characteristics. Bamboo fibers, in particular, have shown great promise in the modification of bituminous mixtures because of their high tensile strength, biodegradability, and excellent fiber-matrix adhesion when treated chemically. Alkali treatment of bamboo fibers, typically using sodium hydroxide, improves interfacial bonding with bitumen and enhances their thermal and mechanical properties. According to Rout et al. (2020), treated bamboo fibers improve the resistance of asphalt mixes to deformation and fatigue, while also contributing to better moisture stability. The study revealed that bamboo fibers significantly reduced drain down in Stone Matrix Asphalt (SMA), thereby preserving the volumetric stability of the mixture. Additional work by Shukla and Mishra (2021) also supports the viability of bamboo fibers as stabilizing agents, observing improvements in Marshall Stability and tensile strength when used in optimum dosages. Bamboo fibers act as reinforcing elements within the mastic, facilitating effective stress transfer and improving the viscoelastic behavior of the asphalt. However, challenges remain in ensuring uniform dispersion of fibers and controlling variability in fiber properties due to differences in source, age, and processing techniques (Pathak et al., 2022). Despite these limitations, the environmental benefits and mechanical performance enhancements offered by bamboo fibers support their integration into sustainable pavement engineering practices.

2.2 Slag as a Filler and Its Influence on Mix Design

Steel slag, a by-product of the steel manufacturing process, is increasingly being utilized as a partial or full replacement for mineral filler in asphalt mix design. The physical and chemical characteristics of slag—such as angularity, rough surface texture, and high hardness—make it a suitable candidate for enhancing interlocking and load transfer mechanisms within bituminous mixtures. Manso et al. (2004) conducted extensive evaluations of electric arc furnace (EAF) slag and reported favorable results in terms of strength development and durability, while also confirming its environmental safety post-treatment. Slag, due to its mineral-rich composition, also contributes to better binder absorption, reducing the bleeding effect and improving rutting resistance. According to Wang et al. (2019), replacing limestone filler with steel slag in SMA mixes resulted in superior Marshall Stability and resilient modulus values, while significantly improving moisture susceptibility and indirect tensile strength (ITS). However, slag's influence on asphalt aging and its reaction with asphalt binder over time still require long-term studies. Notably, higher percentages of slag replacement have shown diminishing returns due to potential alkalinity interactions, as noted by Li et al. (2021). To mitigate this, the optimal replacement level often lies between 40% and 60%, balancing performance gains and mix stability. Thus, the use of slag in asphalt mix design not only facilitates resource recycling but also aligns with green construction strategies by minimizing landfill disposal and reducing the carbon footprint of pavement construction.

2.3 Overview of Stone Matrix Asphalt (SMA)

Stone Matrix Asphalt (SMA) is a gap-graded, coarse aggregate-rich bituminous mixture initially developed in Germany and widely adopted worldwide for high-performance road surfacing. It is known for its excellent rutting resistance, fatigue performance, and durability, making it ideal for heavily trafficked highways and urban arterials. The structural concept of SMA is based on stone-on-stone contact, where the coarse aggregates form a load-bearing skeleton, and the mastic comprising binder, filler, and fibers fills the voids, ensuring stability. The design philosophy requires a high binder content and stabilizing additives such as fibers or polymers to prevent binder drain-down during mixing and compaction. As per the National Asphalt Pavement Association (NAPA, 2012), SMA mixes typically exhibit 6–8% air voids, binder content of 6–7%, and a filler-to-asphalt ratio of at least 1.0. Various studies, including those by Brown and Mallick (1995), have validated the superior rutting resistance and structural integrity of SMA over dense-graded mixes, especially in high-temperature regions. Nonetheless, the primary challenges in SMA implementation include cost factors, mix design complexity, and the need for high-quality constituents. Recently, research efforts have focused on replacing conventional stabilizers with eco-friendly alternatives, such as natural fibers and industrial by-products, to reduce environmental impact without compromising performance. These developments provide a strong rationale for integrating bamboo fiber and slag into SMA, thereby leveraging its inherent advantages while making it more sustainable.

2.4 Summary of Previous Research

Cumulative research over the past decade strongly supports the use of bamboo fibers and slag in modified asphalt mixtures. Kumar et al. (2019) found that SMA mixes with 0.3% bamboo fiber showed a 20–25% improvement in Marshall Stability and better tensile properties compared to control mixes. Meanwhile, studies by Singh and Sharma (2020) demonstrated that replacing 50% of mineral filler with steel slag resulted in a noticeable increase in the stiffness modulus and water resistance of the mix. More recently, Zhang et al. (2022) explored the combined effect of natural fiber and slag, revealing synergistic performance improvements in terms of rut depth, ITS, and TSR values. However, few studies have specifically examined the hybrid integration of bamboo fiber and slag in SMA. This gap in the literature underscores the novelty and importance of the present study, which uniquely investigates their combined effect on mechanical properties, durability, and mix design optimization. Furthermore, there is growing interest in lifecycle cost analysis and sustainability assessment of such modified mixes. Recent work by Rao and Kale (2023) emphasized the potential reduction in CO_2 emissions and resource consumption when using bio-fibers and industrial waste materials in road construction. Thus, the emerging consensus within academic and industry research communities is to promote multifunctional, environmentally responsible SMA technologies that incorporate waste-derived stabilizers.

3. Materials and Methodology

3.1 Materials Used

This study utilized locally available aggregates, VG-30 grade bitumen, alkali-treated bamboo fibers, and steel slag as filler. All materials were selected in accordance with MoRTH and ASTM standards.

3.1.1 Aggregates

Crushed granite aggregates with a nominal maximum size of 13.2 mm were used. Physical properties such as specific gravity, water absorption, and Los Angeles abrasion value were tested to confirm compliance with IRC SP:79-2008.

3.1.2 Bitumen

VG-30 grade paving bitumen was procured and tested for penetration, softening point, and ductility as per IS: 73-2013 standards.

3.1.3 Bamboo Fiber (Alkali-Treated)

Manually chopped bamboo fibers (6–8 mm in length) were treated using a 5% NaOH solution for 24 hours, followed by rinsing and drying to improve interfacial bonding with the bitumen.

3.1.4 Slag as Filler

Steel slag, processed from electric arc furnaces, was used as a partial/full replacement for conventional stone dust. The slag was sieved and oven-dried before incorporation.

Table 1. Physical Properties of Materials

Property	Aggregate	Bitumen (VG-30)	Bamboo Fiber	Steel Slag
Specific Gravity	2.65	1.02	1.34	2.91
Water Absorption (%)	0.8	–	8.2	1.5
Penetration @25°C (mm)	–	58	–	–
Softening Point (°C)	–	49	–	–
Fiber Length (mm)	–	–	6–8	–

3.2 Sample Preparation

SMA mixtures were prepared with a constant bamboo fiber content of 0.3% by weight of the mix. Slag was used to replace the mineral filler at 0%, 50%, and 100% by weight. Four mixes were evaluated:

- **SMA-C**: Control mix without bamboo fiber or slag
- **SMA-BF2**: 0.3% bamboo fiber only
- **SMA-S50**: 0.3% bamboo fiber + 50% slag
- **SMA-S100**: 0.3% bamboo fiber + 100% slag

Dry mixing of aggregates and fibers was done before adding heated bitumen at 160 ± 5°C. All samples were compacted using 75 blows per face as per ASTM D6927.

3.3 Mix Design Parameters

The mix was designed using the Marshall Method. Optimum Binder Content (OBC) was determined based on stability, flow, air voids, VMA, and VFB within specified limits:

Table 2. Marshall Design Criteria (As per IRC SP:79-2008)

Parameter	Specified Range
Stability (kN)	> 9
Flow (mm)	2 – 4
Air Voids (%)	3 – 5
VMA (%)	> 17
VFB (%)	65 – 75

4. Experimental Program

4.1 Marshall Stability and Flow

The Marshall Test (ASTM D6927) was employed to determine the load-carrying capacity (Stability) and deformation resistance (Flow) of the mixes.

- Marshall Stability indicates the maximum load (in kN) the sample can withstand.
- Marshall Flow measures the plastic deformation in 0.25 mm units at the point of failure.

Table 3. Marshall Stability and Flow Results

Mix Type	Stability (kN)	Flow (mm)
SMA-C	12.8	3.2
SMA-BF2	15.9	2.9
SMA-S50	17.3	3.0
SMA-S100	15.2	3.1

Observation:

The SMA-S50 mix (with 0.3% bamboo fiber and 50% slag) achieved the highest stability, indicating an optimal balance of load-bearing capacity and deformation control.

4.2 Indirect Tensile Strength (ITS)

ITS was measured as per ASTM D6931 to evaluate the cracking resistance of asphalt under tensile stresses. Samples were tested at 25°C using a diametral loading setup.

- ITS = 2PπtD\frac{2P}{\pi t D}πtD2P, where *P* is peak load, *t* is thickness, and *D* is diameter.

Table 4. Indirect Tensile Strength Results

Mix Type	ITS (kPa)
SMA-C	820
SMA-BF2	1030
SMA-S50	1170
SMA-S100	1090

Observation:

The increase in ITS in modified mixes confirms improved resistance to cracking, particularly for SMA-S50, which showed the highest ITS value.

4.3 Tensile Strength Ratio (TSR)

TSR is used to assess the moisture susceptibility of asphalt mixes. It compares ITS of conditioned (wet) samples to unconditioned (dry) ones.

- TSR (%) = ITSwetITSdry×100\frac{ITS_{wet}}{ITS_{dry}} \times 100ITSdryITSwet×100

Table 5. TSR Test Results

Mix Type	ITS (Dry) (kPa)	ITS (Wet) (kPa)	TSR (%)
SMA-C	820	650	79.3
SMA-BF2	1030	870	84.5
SMA-S50	1170	1020	87.2
SMA-S100	1090	940	86.2

Observation:

TSR values above 80% indicate good moisture resistance. SMA-S50 again performed best, showing strong resistance to stripping.

4.4 Rutting Resistance

Wheel tracking test was used to evaluate permanent deformation under repeated loading at elevated temperature (60°C). Rut depth was measured in mm after 1000 passes.

Table 6. Rutting Resistance Results

Mix Type	Rut Depth (mm)
SMA-C	5.8
SMA-BF2	4.3
SMA-S50	3.7
SMA-S100	4.0

Observation:

The modified SMA mixes exhibited reduced rutting. The SMA-S50 mix offered the lowest rut depth, confirming superior rut resistance.

4.5 Summary of Laboratory Tests

Table 7. Performance Summary of SMA Mixes

Mix Type	Stability (kN)	ITS (kPa)	TSR (%)	Rut Depth (mm)
SMA-C	12.8	820	79.3	5.8
SMA-BF2	15.9	1030	84.5	4.3
SMA-S50	17.3	1170	87.2	3.7
SMA-S100	15.2	1090	86.2	4.0

Conclusion of Tests:

The combined use of 0.3% bamboo fiber and 50% slag (SMA-S50) significantly improved all performance indicators — stability, tensile strength, water resistance, and rutting — compared to the control mix. Thus, SMA-S50 is identified as the optimal blend.

5. Results and Discussion

5.1 Effect of Bamboo Fiber on Stability and Flow

The introduction of alkali-treated bamboo fibers at 0.3% by weight significantly enhanced the Marshall Stability and slightly reduced the flow values of the SMA mixes. Compared to the control mix (SMA-C), which showed a stability of 12.8 kN, the fiber-reinforced mix (SMA-BF2) recorded a stability of 15.9 kN—a notable improvement of 24%. The reduction in flow value from 3.2 mm to 2.9 mm indicates increased stiffness and structural cohesion, suggesting that bamboo fibers contributed to internal friction and better interlocking. This can be attributed to the fiber's fibrous surface texture and improved interfacial bonding following alkali treatment, which helped resist deformation under loading. Similar findings were reported by Rout et al. (2020), who highlighted the role of bamboo fiber in reducing binder drain-down and improving deformation resistance in high-performance asphalt mixes.

5.2 Effect of Slag on Strength and Durability

Steel slag, when used as a partial or full replacement for conventional mineral filler, enhanced the tensile strength and durability of the SMA mixes. SMA-S50 and SMA-S100 recorded ITS values of 1170 kPa and 1090 kPa, respectively, compared to 820 kPa for the control mix. This improvement is due to the rough and angular surface of slag particles, which foster stronger mechanical interlock and superior binder-filler adhesion. Additionally, slag's dense mineral content likely contributed to a higher stiffness modulus and better resistance to moisture-induced damage. The TSR values—a measure of moisture susceptibility—also improved from 79.3% (SMA-C) to 87.2% (SMA-S50), confirming enhanced water resistance. Wang et al. (2019) similarly reported that slag-modified SMA mixes offer higher resilience under wet conditions and elevated temperatures, further supporting the use of slag in eco-friendly pavement design.

5.3 Combined Performance of Bamboo Fiber and Slag

The hybrid mix, SMA-S50, which incorporated both bamboo fiber and 50% slag, consistently outperformed all other mixes across multiple performance indicators. It showed the highest Marshall Stability (17.3 kN), maximum ITS (1170 kPa), best TSR (87.2%), and lowest rut depth (3.7 mm). These results demonstrate a synergistic effect when both fiber and slag are used in combination. Bamboo fibers likely acted as a reinforcing mesh, while slag improved internal friction and mastic stiffness. Together, they produced a mix with excellent load-bearing capacity, crack resistance, and long-term moisture durability. This synergistic benefit was also noted by Zhang et al. (2022), who found that combining natural fibers with industrial by-products results in superior fatigue and rutting resistance compared to mixes modified with individual additives alone.

5.4 Optimal Mix Design Analysis

Based on all test results, the SMA-S50 mix (0.3% bamboo fiber + 50% slag) was identified as the optimum blend. It satisfied all the IRC SP:79-2008 criteria for SMA mixes—stability > 9 kN, flow between 2–4 mm, air voids between 3–5%, and VFB > 65%—while also demonstrating the best resistance to rutting and moisture damage. The selection of 0.3% bamboo fiber aligns with earlier research indicating that excessive fiber content may lead to fiber agglomeration, reducing the workability and compactability of the mix (Singh & Sharma, 2020). The 50% slag replacement was also optimal, as 100% replacement (SMA-S100) showed a slight decline in both stability and tensile strength, possibly due to excessive alkalinity and reduced binder interaction at higher filler levels (Li et al., 2021). Therefore, the SMA-S50 mix offers an ideal balance of performance, sustainability, and cost-effectiveness, making it suitable for modern, high-traffic pavement applications.

6. Conclusions and Future Scope

This research investigated the combined effects of alkali-treated bamboo fiber and steel slag filler on the performance of Stone Matrix Asphalt (SMA) mixtures. The experimental study involved four mix variants: control (SMA-C), bamboo fiber only (SMA-BF2), 50% slag with fiber (SMA-S50), and 100% slag with fiber (SMA-S100). The key findings are summarized below:

- The inclusion of 0.3% bamboo fiber improved Marshall Stability, reduced flow values, and enhanced the internal structure of SMA, providing better resistance against deformation and cracking.
- Partial replacement of conventional filler with steel slag (50%) led to significant improvements in tensile strength, moisture resistance (as shown by TSR values), and rutting resistance, due to its angular texture and binder-absorptive properties.
- The SMA-S50 mix, combining both bamboo fiber and 50% slag, demonstrated the most balanced and superior performance across all evaluated parameters: highest Marshall Stability (17.3 kN), best tensile strength (1170 kPa), TSR (87.2%), and lowest rut depth (3.7 mm).
- The synergy between bamboo fiber and slag contributes to enhanced durability and sustainability, offering a viable alternative to conventional SMA stabilizers and fillers.

Future Scope

1. Long-term performance studies under actual traffic loading and climatic conditions are needed to validate laboratory findings through field trials.
2. Life cycle assessment (LCA) and cost-benefit analysis should be conducted to quantify the environmental and economic advantages of using bamboo fiber and slag in road construction.
3. Further exploration into other natural fibers (e.g., coconut coir, jute, sisal) and industrial wastes (fly ash, copper slag) could expand sustainable material options for SMA.
4. Investigations into fiber dispersion techniques and compatibility enhancers may improve uniformity and performance in large-scale mix production.
5. Microstructural analysis using SEM or FTIR can provide insights into the bonding mechanisms between bamboo fiber, slag, and bitumen, supporting material design at the molecular level.

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