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Performance Evaluation of Stone Matrix Asphalt Stabilized with Bamboo Fibre and TOPCEL Cellulose Using Stone and Slag Aggregates

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Abstract: *This study investigates the performance characteristics of Stone Matrix Asphalt (SMA) mixtures stabilized with natural Bamboo fibre and synthetic Topcel cellulose using stone and slag as coarse aggregates. The objective was to assess the Marshall Stability, flow value, air voids (VA), and voids in mineral aggregates (VMA) of various SMA combinations. Marshall tests were conducted on specimens with and without stabilizing fibres. Results showed that the inclusion of Bamboo fibre significantly enhanced the stability and structural performance of SMA, especially when used with slag aggregates. Compared to Topcel cellulose, Bamboo fibre not only improved mechanical properties but also offered a cost-effective and environmentally friendly alternative. The findings suggest the feasibility of using Bamboo fibre as a natural stabilizer in SMA for sustainable road construction.*
Keywords: *Stone Matrix Asphalt (SMA), Bamboo Fibre, Topcel Cellulose, Slag Aggregate, Marshall Stability, Bitumen, Natural Fibre Stabilizer*

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I. Introduction

The rapid expansion of road infrastructure, particularly in developing countries, has necessitated the development of durable, high-performance pavement materials. Among the various types of pavement layers, Stone Matrix Asphalt (SMA) has emerged as a premium surfacing material due to its excellent rutting resistance, durability, and resistance to fatigue and thermal cracking. Originally developed in Germany in the 1960s (Zichner, 1960), SMA is a gap-graded, coarse aggregate-rich asphalt mixture that relies on stone-on-stone contact to provide a strong load-bearing skeleton. The inclusion of a rich mortar of fine aggregates, filler, and binder enhances its performance under heavy traffic and varying climatic conditions (Brown, 1992; Cooley, 1997).

Despite its advantages, SMA is prone to binder drainage during production and transportation due to its high asphalt content. To counter this, stabilizing additives—typically in the form of fibres—are incorporated into the mix to hold the binder in place. Traditionally, cellulose-based fibres such as Topcel have been widely used for this purpose (Shen et al., 2006; Kumar et al., 2007). These fibres help maintain the homogeneity of the mix and prevent binder migration, thereby improving the mixture's stability and service life.

However, the production and processing of synthetic or commercial cellulose fibres are energy-intensive and expensive, raising concerns about sustainability and cost-effectiveness. In response to these concerns, researchers have increasingly turned to natural fibres as alternative stabilizers in asphalt mixtures. Among these, Bamboo fibre has gained attention due to its high tensile strength, biodegradability, and widespread availability in tropical and subtropical regions. Previous studies have demonstrated that bamboo fibres possess desirable mechanical properties, including high flexibility, low density, and good thermal stability, making them suitable for construction applications (Jain et al., 1992; Das, 2002).

Additionally, the environmental benefits of using natural fibres are significant. Bamboo is a fast-growing, renewable resource that sequesters carbon during its lifecycle and produces minimal waste during harvesting and processing. Utilizing bamboo fibres in SMA not only addresses performance requirements but also supports the push toward green and sustainable construction practices (Li & Fang, 2013; Wallenberger, 2002).

The current study investigates the performance of SMA mixtures stabilized with Bamboo fibre and compares it to mixes using Topcel cellulose, using both stone and slag aggregates as the coarse fraction. Slag, an industrial by-product of steel manufacturing, offers angularity and rough texture that improve interlocking and mechanical strength (Xue et al., 2009; Kavussi & Qazizadeh, 2005). By combining natural fibre and industrial waste material, the research aims to evaluate an environmentally sustainable yet mechanically robust asphalt mixture suitable for flexible pavement construction.

This study focuses on evaluating key properties such as Marshall Stability, Flow Value, Voids in Asphalt (VA), and Voids in Mineral Aggregate (VMA) to determine the effectiveness of Bamboo fibre as a stabilizing agent. The results will also help compare the structural and volumetric performance of SMA mixes made with stone and slag aggregates, both with and without fibre stabilizers.

II. Literature Review

Stone Matrix Asphalt (SMA) has been widely adopted globally due to its superior performance in resisting rutting, fatigue, and thermal cracking. First introduced in Germany during the 1960s (Zichner, 1960), SMA quickly gained popularity in Europe and later in the United States for its ability to extend pavement life under heavy traffic. Its performance advantage is primarily due to its coarse aggregate-dominated skeleton and high binder content, which enhance load distribution and durability (Brown, 1992; Brown et al., 1996). However, the higher binder content in SMA can lead to binder drain-down during mixing, transport, and laying, which necessitates the use of stabilizing additives.

To address this, several studies have explored the role of stabilizers in SMA mixtures. Cooley (1997) conducted a comprehensive evaluation of SMA mixes containing different additives—cellulose fibres, mineral fibres, and polymers—and highlighted their effectiveness in controlling drain-down while improving structural integrity. Among these, cellulose fibres like Topcel have become widely accepted due to their ability to absorb binder and create a matrix that minimizes movement during compaction (Shen et al., 2006). Nevertheless, the reliance on synthetic or processed fibres has raised concerns regarding cost and environmental sustainability.

In response, researchers have turned to natural fibres as eco-friendly alternatives. Bamboo fibre has drawn attention for its high tensile strength, flexibility, and biodegradability (Jain et al., 1992). Das (2002) further emphasized its suitability in construction materials by highlighting its strong bonding characteristics and resistance to wear. Li and Fang (2013) studied the mechanical behavior of bamboo fibre-reinforced asphalt and reported improvements in tensile strength and cracking resistance, positioning bamboo as a viable stabilizer in asphalt mixtures.

In terms of commercial comparison, Topcel cellulose is a plant-based but industrially processed product commonly used in SMA for its high absorbency and uniform dispersion. While effective, its environmental and cost implications have motivated a search for alternatives like bamboo, which grows rapidly and is available in abundance in many parts of the world (Wallenberger, 2002). Bamboo's use in SMA could significantly lower the environmental footprint of road construction, aligning with sustainable infrastructure goals.

Beyond fibres, the type of aggregate used in SMA also plays a critical role. Traditional stone aggregates offer high strength and durability, but industrial by-products like slag have been found to provide additional benefits such as enhanced angularity, better interlocking, and environmental savings. Xue et al. (2009) investigated the use of steel slag in SMA and found it effective in improving Marshall Stability and moisture resistance. Similarly, Kavussi and Qazizadeh (2005) reported improved rutting resistance when slag was used as a coarse aggregate in SMA.

The integration of natural fibres and industrial waste materials into SMA aligns with the principles of sustainable pavement design. Combining Bamboo fibre and slag aggregate can yield high-performing asphalt mixes while reducing reliance on virgin materials and non-renewable stabilizers. Despite these promising findings, comparative studies analyzing Bamboo fibre alongside conventional cellulose stabilizers in SMA are still limited, especially under controlled laboratory conditions using standardized methods like the Marshall Stability test.

This study aims to bridge that gap by evaluating SMA mixes incorporating Bamboo fibre and Topcel cellulose, comparing their mechanical and volumetric properties using both stone and slag aggregates. The literature thus supports a hypothesis that natural fibre and industrial by-products can offer a technically sound and environmentally responsible alternative in modern asphalt mix design.

III. Materials and Methods

3.1 Materials Used

This study used two types of coarse aggregates—crushed stone and steel slag—as the primary skeleton for Stone Matrix Asphalt (SMA) mixtures. The stone aggregate is a conventional material widely used in bituminous pavements for its durability and strength. The slag aggregate, an industrial by-product from steel manufacturing, was selected for its rough surface texture and angularity, which improve interlocking and enhance Marshall Stability (Xue et al., 2009). In all cases, stone dust was used as the fine aggregate, and ordinary Portland cement (OPC) was used as the filler.

The binder selected for the study was VG-30 grade bitumen (equivalent to 60/70 penetration grade), which is commonly used in India for heavy-duty pavements due to its balance of stiffness and workability. The binder content was varied in increments (4%, 5%, 5.5%, 6%, and 7%) to determine the optimum binder content (OBC) for each mix type.

Two different stabilizers were employed: Bamboo fibre, a naturally occurring plant fibre, and Topcel cellulose, a commercially available processed fibre product. Bamboo fibres were manually processed to required lengths and dried to remove moisture before use. Their natural tensile strength, flexibility, and biodegradability make them ideal candidates for sustainable pavement applications (Das, 2002; Jain et al., 1992). Topcel cellulose fibres are well-established stabilizers used in SMA for their high absorbency and ease of dispersion during mixing (Cooley, 1997; Shen et al., 2006).

3.2 Mix Design Procedure

The mix design for SMA was carried out following the IRC:SP-79:2008 specifications, which provide guidelines for 13 mm nominal maximum aggregate size. A gap-graded aggregate structure was adopted to ensure stone-on-stone contact and enhance load-carrying capacity. The stabilizing fibres (Bamboo or Topcel) were added at 0.3–0.5% by weight of the total mix.

The dry aggregates and filler were heated to 155–160°C to simulate plant conditions. Bitumen was heated separately to 170–190°C to ensure proper mixing without excessive aging. The stabilizer was dry-mixed with the aggregates before the hot bitumen was added. The entire mixture was then thoroughly hand-mixed until uniform coating and distribution of fibres and binder were achieved.

3.3 Preparation of Samples

Approximately 1200 grams of hot mix was weighed and placed into Marshall moulds (101.6 mm diameter, 76.2 mm height). Compaction was done using a Marshall compaction hammer with 75 blows on each face of the specimen. The compacted samples were then allowed to cool at room temperature for 24 hours.

After cooling, the specimens were coated with paraffin wax to seal the surface and prevent moisture ingress during water bath conditioning. Each sample was then weighed in air and water to determine bulk specific gravity, which was used to calculate void-related properties like VA and VMA.

3.4 Testing Procedures

The prepared specimens were conditioned in a water bath at 60°C for 30 minutes before testing. The Marshall Stability and Flow test was conducted using a standard Marshall testing machine applying a deformation rate of 5 mm/min. The maximum load at failure was recorded as the Marshall Stability, while the total deformation at failure was noted as the Flow Value.

To evaluate volumetric characteristics, Voids in Asphalt (VA) and Voids in Mineral Aggregate (VMA) were calculated using standard formulas based on bulk specific gravity (Gmb), maximum theoretical specific gravity (Gmm), and aggregate properties (Gsb). These metrics are critical in determining the durability, flexibility, and resistance to moisture damage of the SMA mix.

IV. Results and Discussion

4.1 Summary of Experimental Results

The experimental results for five different SMA mix types are summarized in Table 1. The performance was evaluated using four key parameters: Marshall Stability (kN), Flow Value (mm), Voids in Asphalt (VA %), and Voids in Mineral Aggregate (VMA %).

Table 1: SMA Mix Performance Summary reveals that the mix using slag aggregate with bamboo fibre achieved the highest Marshall Stability of 15.3 kN, indicating superior load-bearing capacity. The next best-performing mix was stone + bamboo fibre with 14.8 kN. In contrast, the control mix (stone aggregate without any fibre) recorded the lowest stability value of 10.5 kN, emphasizing the stabilizing effect of fibre additives.

Flow values ranged from 2.8 mm to 3.7 mm, with fibre-reinforced mixes generally showing higher flow, indicating improved ductility and flexibility. Slag + bamboo fibre had the highest flow value (3.7 mm), followed by stone + bamboo fibre (3.5 mm). This suggests that bamboo fibre contributes to the plastic deformation capacity of SMA.

Table 1: SMA Mix Performance Summary

Mix Type	Marshall Stability (kN)	Flow Value (mm)	VA (%)	VMA (%)
Stone Aggregate (No Fibre)	10.5	2.8	4.8	16.5
Stone + Bamboo Fibre	14.8	3.5	4.3	17.2
Stone + Topcel Cellulose	13.2	3.2	4.5	16.8
Slag Aggregate (No Fibre)	11.7	3.0	4.6	17.0
Slag + Bamboo Fibre	15.3	3.7	4.1	17.4

4.2 Marshall Stability and Flow Analysis

A focused comparison of stability and flow for all mixes is shown in Table 2. The addition of bamboo fibre led to the highest gains in Marshall Stability for both stone and slag aggregates. Specifically, stability improved by:

- 4.3 kN (from 10.5 to 14.8) in stone aggregate mixes, and
- 3.6 kN (from 11.7 to 15.3) in slag aggregate mixes.

Topcel cellulose also enhanced stability, but less significantly than bamboo fibre, reaching 13.2 kN with stone aggregates.

Flow values, which indicate the deformation before failure, increased slightly with fibre addition. While higher flow generally signals better flexibility, values exceeding limits may risk rutting. However, all values remained within acceptable IRC guidelines.

Figure 1 visually supports these findings, clearly showing that slag + bamboo fibre performed the best in terms of Marshall Stability, followed closely by stone + bamboo fibre. Fibre-free mixes lagged behind, emphasizing the structural benefit of using fibre stabilizers.

Table 2: Stability and Flow Comparison

Mix Type	Marshall Stability (kN)	Flow Value (mm)
Stone (No Fibre)	10.5	2.8
Stone + Bamboo Fibre	14.8	3.5
Stone + Topcel Cellulose	13.2	3.2
Slag (No Fibre)	11.7	3.0
Slag + Bamboo Fibre	15.3	3.7

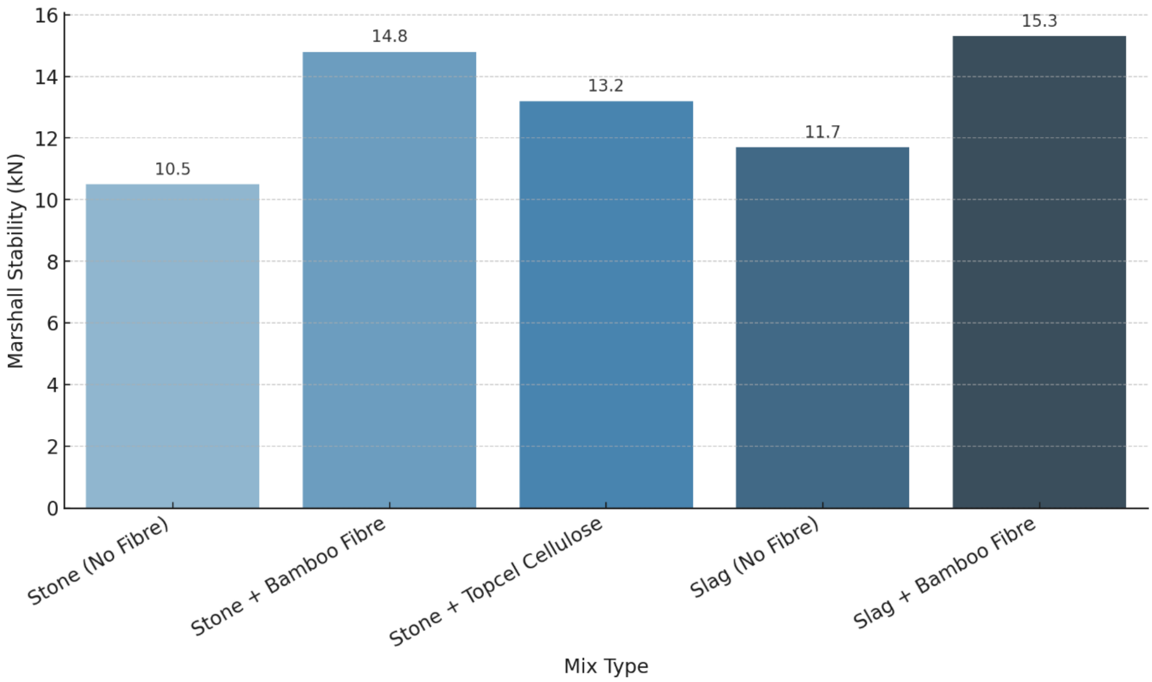

Figure 1: Marshall Stability Across Mixes

4.3 Volumetric Properties (VA and VMA)

Volumetric analysis is critical for understanding the internal structure and durability of SMA mixes. As presented in Table 3, all mixes with bamboo fibre showed reduced VA values, indicating better compaction and less air voids, which minimizes moisture intrusion and oxidation risk.

- The lowest VA (4.1%) was observed in slag + bamboo fibre, followed by stone + bamboo fibre (4.3%).
- Fibre-free mixes had higher VA values (4.6–4.8%), suggesting poorer compaction and durability.

Similarly, VMA increased in all fibre-stabilized mixes, with slag + bamboo fibre again recording the highest (17.4%). This indicates more space for binder retention, essential for resisting fatigue and maintaining binder film thickness.

Figure 2 illustrates that flow values were slightly elevated in fibre-reinforced mixes, especially with bamboo fibre, supporting its role in enhancing workability and resilience under load.

Table 3: Air Voids and VMA Summary

Mix Type	VA (%)	VMA (%)
Stone (No Fibre)	4.8	16.5
Stone + Bamboo Fibre	4.3	17.2
Stone + Topcel Cellulose	4.5	16.8
Slag (No Fibre)	4.6	17.0
Slag + Bamboo Fibre	4.1	17.4

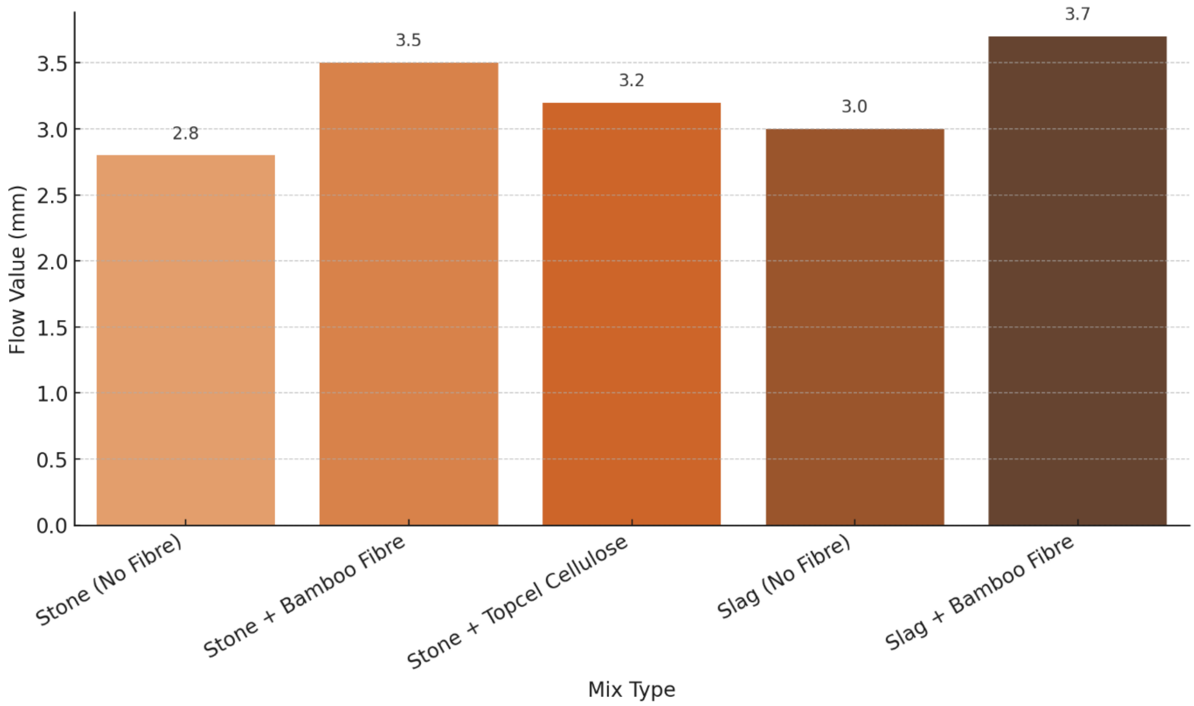

Figure 2: Flow Values Across Mixes

4.4 Comparison of Bamboo Fibre vs. Topcel Cellulose

The performance evaluation between Bamboo fibre and Topcel cellulose as stabilizers reveals that bamboo fibre consistently outperforms Topcel in both mechanical and volumetric properties of SMA mixes.

In terms of Marshall Stability, mixes with bamboo fibre recorded higher values (14.8 kN for stone and 15.3 kN for slag) compared to Topcel cellulose (13.2 kN for stone). This improvement is attributed to the higher tensile strength, better bonding ability, and structural rigidity provided by the bamboo fibres, which improve interlocking and reduce binder drain-down.

Bamboo fibre also contributed to improved compaction, as evidenced by lower Voids in Asphalt (VA) percentages. A VA of 4.3% for stone + bamboo and 4.1% for slag + bamboo indicates efficient space filling and enhanced binder retention. The Topcel-stabilized mix had a slightly higher VA of 4.5%.

Furthermore, bamboo-enhanced mixes demonstrated higher VMA, ensuring better binder accommodation and resistance to cracking and fatigue over the pavement's life cycle. This superior performance, combined with the sustainable and economic advantages of bamboo, makes it a promising alternative to synthetic stabilizers like Topcel.

4.5 Effect of Aggregate Type (Stone vs. Slag)

The type of coarse aggregate used in SMA significantly influenced the mix performance. Comparisons across the data indicate that slag aggregates outperformed stone aggregates in nearly all aspects, regardless of the stabilizer used.

- In fibre-free conditions, slag showed higher stability (11.7 kN vs. 10.5 kN) and slightly better flow and VMA characteristics.
- When combined with bamboo fibre, slag again provided the highest Marshall Stability (15.3 kN), suggesting a synergistic effect due to its angular shape and rough surface texture, which promotes stronger mechanical interlock.

Slag also contributed to higher VMA values, indicating a well-developed aggregate skeleton and greater bitumen film thickness. These results confirm the suitability of slag as a substitute for natural stone aggregates in SMA, especially when aiming for improved strength and sustainability.

4.6 Environmental and Economic Considerations

The environmental impact and economic feasibility of materials are vital in pavement engineering. Both bamboo fibre and slag aggregate offer significant advantages over their conventional counterparts.

- Bamboo fibre is a natural, rapidly renewable resource. It requires minimal processing, is biodegradable, and is widely available in many tropical and subtropical regions. Its use reduces dependency on synthetic fibres like Topcel, lowering costs and environmental impact.
- Slag aggregate, as an industrial by-product, offers a sustainable alternative to quarried stone. Utilizing slag reduces landfill waste and the need for virgin aggregate mining, aligning with principles of the circular economy.

Cost-wise, bamboo fibre is often less expensive than Topcel, particularly in regions where bamboo grows abundantly. Similarly, slag is often provided at reduced costs by steel plants as a waste material, making it both an economically and environmentally preferable option.

The integration of bamboo fibre and slag aggregate into SMA mixes demonstrates not only enhanced mechanical performance but also supports the shift toward sustainable pavement materials in road construction.

V. Conclusion

This study evaluated the mechanical and volumetric performance of Stone Matrix Asphalt (SMA) mixes using Bamboo fibre and Topcel cellulose as stabilizers, with both stone and slag aggregates as coarse fractions. Based on laboratory testing and analysis, several key conclusions were drawn:

1. Bamboo fibre outperformed Topcel cellulose in enhancing Marshall Stability, reducing VA, and increasing VMA, thereby improving both structural strength and durability of SMA mixes.
2. Slag aggregates provided superior performance compared to stone aggregates, particularly in terms of stability and interlocking capability. The combination of slag and bamboo fibre yielded the best-performing mix.
3. Volumetric analysis confirmed that fibre-stabilized mixes achieved better compaction and binder retention, which are critical for long-term performance and resistance to moisture damage.
4. From a sustainability perspective, the use of natural bamboo fibre and industrial slag promotes environmental responsibility, cost-effectiveness, and the adoption of circular construction practices.

Overall, the study confirms that Bamboo fibre is a viable, eco-friendly, and efficient alternative to synthetic stabilizers like Topcel cellulose in SMA. Combined with slag aggregates, it offers a high-performance mix suitable for flexible pavement layers. Further research can expand into fatigue life analysis, field performance validation, and life-cycle cost assessments for broader implementation.

References

[1]. Asi, I. M. (2006). Laboratory comparison study for the use of stone matrix asphalt in hot weather climates. *Construction and Building Materials, 20*(10), 982–989. https://doi.org/10.1016/j.conbuildmat.2005.07.007

[2]. Brown, E. R. (1992). *Experience with stone matrix asphalt in the United States*. National Center for Asphalt Technology, Auburn University.

[3]. Brown, E. R., Haddock, J. E., & Crawford, C. (1996). Investigation of stone matrix asphalt mortars. *Transportation Research Record, 1530*, 95–102.

[4]. Bose, S., Kamaraj, C., & Nanda, P. K. (2006). Stone mastic asphalt (SMA): A long-life pavement surface. In *International Seminar on Innovations in Construction and Maintenance of Flexible Pavements* (Vol. 1, pp. 169–177).

[5]. Cooley, L. A. (1997). Evaluation of stone matrix asphalt (SMA) mixtures containing different stabilizing additives. *Journal of the Association of Asphalt Paving Technologists, 66*, 368–392.

[6]. Das, S. (2002). Mechanical behavior of bamboo fibre reinforced composites. *Indian Concrete Journal, 76*(3), 180–184.

[7]. Jain, S., Jindal, U. C., & Kumar, R. (1992). Development and study of bamboo composite. *Journal of Materials Science, 27*(17), 4598–4604. https://doi.org/10.1007/BF01166334

[8]. IRC:SP:79-2008. (2008). *Tentative specifications for stone matrix asphalt*. Indian Roads Congress.

[9]. Kamraj, C., Sood, V. K., Jain, P. K., & Sikdar, P. K. (2006). Design of stone matrix asphalt by using different stabilizing additives. *Journal of the Indian Roads Congress, 67*(1), 107–114.

[10]. Kennedy, T. W., & Jones, D. R. (1994). *The asphalt model: The results of SHRP asphalt research program*. University of Texas, Austin.

[11]. Kumar, P., Bose, S., & Chandra, S. (2007). Laboratory investigations on SMA mixes with different additives. *International Journal of Pavement Engineering, 8*(1), 11–18.

[12]. Kumar, P., Sikdar, P. K., Bose, S., & Chandra, S. (2004). Use of jute fibre in SMA for road materials and pavement design. *Road Materials and Pavement Design, 5*(2), 239–249.

[13]. Wallenberger, F. T. (2002). *Natural fibers for plastic reinforcement: Properties and processes*. Kluwer Academic Publishers.

[14]. Zichner, F. (1960). *Development of stone matrix asphalt*. Straubag-Bau AG Central Laboratory, Germany.

[15]. Krzysztof, B. (2005). Practical application of SMA mix using modified bitumen. *Polish Road and Bridge Institute Journal, 4*, 37–44.

[16]. National Asphalt Pavement Association. (1994). *Guidelines for materials, production, and placement of SMA* (IS-118).

[17]. Shen, J., Amirkhanian, S., & Tang, B. (2006). Influence of additives on the properties of stone matrix asphalt mixtures. *Construction and Building Materials, 20*(9), 913–921. https://doi.org/10.1016/j.conbuildmat.2005.06.012

[18]. Wang, H., & Wu, S. (2010). Laboratory evaluation on high-temperature properties of fiber-reinforced asphalt binder. *Construction and Building Materials, 24*(3), 384–389.

[19]. Airey, G. D. (2003). Rheological evaluation of ethylene vinyl acetate polymer modified bitumens. *Construction and Building Materials, 17*(4), 247–254.

[20]. Xue, Y., Hou, H., Zhu, S., & Zha, J. (2009). Utilization of municipal solid waste incineration ash in stone matrix asphalt mixture. *Waste Management, 29*(10), 2071–2076.

[21]. Li, X., & Fang, C. (2013). Study of bamboo fiber's mechanical behavior and application in asphalt concrete. *Materials & Design, 52*, 1074–1080.

[22]. Xu, Q., & Huang, B. (2009). Effect of fiber types on high temperature performance of fiber-modified asphalt binders. *Construction and Building Materials, 23*(6), 1998–2003.