Letters in High Energy Physics
ISSN: 2632-2714
Volume 2024

Advanced Bituminous Mix Designs Incorporating Natural Fibers for Enhanced Performance and Sustainability

Suguna B Rao [1], Akshata Shagoti [2], S PoornaChandra Thejaswi [3], P.Kishore Kumar Reddy [4], C. Raja Gopal Reddy [5] and Prashant Sunagar [6]

[1] Assistant Professor, Department of Civil Engineering, M S Ramaiah Institute of Technology, Bangalore-560054

[2] Assistant Professor, Department of Architecture, M S Ramaiah Institute of Technology, Bangalore-560054

[3] Assistant Professor, Department of Civil Engineering, Bangalore Institute of Technology Bengaluru-560004

[4] Associate Professor, Department of Civil Engineering, Malla Reddy Engineering College Secundrabad, Telangana-500100

[5] Director, Envision Sustainable Engineering Services, Bengaluru

[6] Associate Professor, Department of Civil engineering, Sandip Institute of Technology and Research Centre, Nashik

Corresponding Author: Prashant Sunagar

Email ID: Prashant.sjce@gmail.com

Abstract:

comprehensive study comparing the performance of Bituminous Concrete (BC) and Stone Matrix Asphalt (SMA) mixes, both with and without the addition of natural sisal fibers. The research investigates the effects of varying binder contents (from 4% to 7%) and fiber contents (from 0.3% to 0.5%) on the mechanical properties of the mixes. Using 60/70 penetration grade bitumen as the binder, the work aims to explore how sisal fibers influence the stability, durability, and tensile strength of the mixes. A series of experiments, including Marshall stability, static indirect tensile strength (ITS), static creep tests, and drain down tests, were conducted to evaluate these properties. The study finds that the inclusion of fibers generally enhances stability and reduces deformation in both BC and SMA mixes. Specifically, adding 0.3% sisal fiber to SMA significantly improves its performance, reducing binder drain down and improving tensile strength, making it more suitable for flexible pavements. The research concludes that sisal fibers are effective in improving mix properties, and SMA with fiber offers superior performance over BC. The study also suggests that sisal fiber is a cost-effective, environmentally friendly stabilizing additive, as it reduces industrial waste while offering practical engineering benefits. The work highlights potential areas for future research, including the investigation of other natural and synthetic fibers, fatigue properties, and resistance to rutting.

Keywords: Natural Sisal Fibers, Stone Matrix Asphalt (SMA), Marshall Stability, Tensile Strength.

1 Introduction

The construction of highways is a significant investment requiring careful planning and precise engineering to ensure both economic efficiency and long-term durability. By focusing on an optimal engineering design, significant cost savings can be achieved while simultaneously delivering reliable performance in service. In flexible pavement engineering, two fundamental aspects—pavement design and mix design—are critical. The current study emphasizes the mix design component, which plays a pivotal role in ensuring sustainable and efficient pavement systems.

A well-designed bituminous mix is expected to meet several key criteria: (i) sufficient strength to bear traffic loads, (ii) durability to withstand environmental and mechanical wear, (iii) resistance to fatigue and permanent deformation, (iv) environmental friendliness to support sustainability goals, and (v) cost-effectiveness. These characteristics are essential for designing pavements that align with modern sustainability objectives. Mix designers conduct various tests on different mix compositions, iterating and optimizing to achieve the most suitable mix that addresses these requirements. This research highlights some of the critical challenges in bituminous mix design and explores contemporary research trends focused on enhancing both performance and sustainability in pavement construction.

1.1 Bituminous Mix Design

1.2 Objective of Bituminous Mix Design

Asphaltic or bituminous concrete is a composite material consisting of a carefully graded mix of aggregates, typically smaller than 25 mm in size, and fine fillers that are less than 0.075 mm. Bitumen is added in sufficient quantities to ensure that the compacted mix remains impermeable, durable, and exhibits both dissipative and elastic properties. The overarching goal of bituminous mix design is to optimize the proportions of bitumen, filler, fine aggregates, and coarse aggregates to create a sustainable mix that meets the following objectives:

1. Adequate bitumen content to ensure a durable, weather-resistant pavement.
2. Sufficient strength to resist deformation under traffic loads, particularly at elevated temperatures.
3. Adequate air voids to allow for further compaction under traffic without premature deterioration.
4. High workability to facilitate easy placement without segregation during construction.
5. Strong resistance to fatigue and cracking, especially under repeated traffic loading and bending.
6. Robust performance at low temperatures to prevent shrinkage-induced cracks.
7. Ensuring environmental compatibility and sustainability by incorporating eco-friendly materials and minimizing resource use.

1.3 Constituents of a Sustainable Mix

- **Coarse Aggregates:** Provide compressive and shear strength while enhancing interlocking properties. Granite is a commonly used material.
- **Fine Aggregates:** Fill voids in the coarse aggregates and stiffen the binder, contributing to the mix's overall strength and durability.
- **Filler:** Fills remaining voids, improves binder stiffness, and provides permeability. Materials like rock dust, cement, lime, and fly ash are commonly used, and their recycling contributes to sustainability.
- **Binder:** Provides cohesion by filling voids, adhering particles, and making the mix impermeable. Examples include bitumen, asphalt, and tar, with innovations in eco-friendly binders supporting sustainable construction practices.

1.4 Selection of Sustainable Binder

Innovations in binder selection are crucial for enhancing the sustainability of highway construction. In addition to conventional bitumen grades, modified binders like Polymer Modified Bitumen (PMB), Crumb Rubber Modified Bitumen (CRMB), and Natural Rubber Modified Bitumen (NRMB) are used to enhance durability and environmental performance. Research is also being conducted using high-performance binders like PG 76-22, which, when paired with eco-friendly additives, create more sustainable and durable mixes.

1.5 Selection of Stabilizing Additives for Sustainability

Sustainable stabilizing additives, such as natural fibers (e.g., jute, sisal), recycled materials (e.g., plastic, rubber), and polymers, are increasingly used to enhance the properties of bituminous mixes. In particular, sisal fiber—a naturally available and biodegradable material—shows great promise in reducing environmental impact while improving the mechanical properties of the mix.

1.6 Objectives

- ➢ Conduct a comparative study between **Bituminous Concrete (BC)** and **Stone Matrix Asphalt (SMA)** mixes.
- ➢ Investigate the effect of **varying binder contents** ranging from **4% to 7%**.
- ➢ Examine the impact of **fiber contents** ranging from **0.3% to 0.5%** on the mix properties.
- ➢ Incorporate **sisal fiber**, a natural and sustainable additive, as a stabilizer in both BC and SMA mixes.

- Analyze the **Marshall properties** of BC and SMA mixes, with and without sisal fiber.
- Evaluate the performance of the mixes through tests such as:
- **Drain down test**
- **Static Indirect Tensile Strength test**
- **Static Creep test**

Pavements consist of multiple material layers, supported by the subgrade. Pavements are broadly classified into flexible and rigid types. Flexible pavements are designed to flex under load and are composed of various layers that distribute stress, typically consisting of:

- **Surface course**: The top layer in contact with traffic, usually made of hot mix asphalt (HMA).
- **Base course**: The layer directly below the surface, generally made of aggregates.
- **Sub-base course**: Sometimes included beneath the base course.

1.7 Asphalt Concrete (Bituminous Mixture)

Asphalt concrete is a composite material used for roads and other surfaces. It combines asphalt binder with mineral aggregates. Key types of asphalt concrete include:

- **Hot Mix Asphalt (HMA)**: Produced by heating asphalt to reduce viscosity and drying aggregates before mixing. HMA is commonly used in high-traffic areas.
- **Warm Mix Asphalt (WMA)**: Utilizes additives (zeolites, emulsions) to lower the required mixing temperatures, reducing energy use and emissions. This method enhances sustainability by consuming less fossil fuel and allowing for cold-weather application.
- **Cold Mix Asphalt**: Created by emulsifying asphalt in water, used for lower traffic roads and patching.
- **Cut-Back Asphalt**: Uses a petroleum solvent to dissolve asphalt. Due to pollution concerns, it has been largely replaced by emulsified asphalt.
- **Mastic Asphalt**: A highly viscous form used for surfaces requiring strong durability.

1.8 Hot Mix Asphalt (HMA)

HMA consists of coarse and fine aggregates bound with asphalt. Types of HMA include:

- **Dense-Graded Mixes**: Well-graded to ensure impermeability and good strength, suitable for various pavement layers.
- **Stone Matrix Asphalt (SMA)**: Developed for high traffic areas, SMA's stone skeleton structure resists deformation and improves durability.
- **Open-Graded Mixes**: Designed for water permeability, often used for surface layers to reduce splash and improve skid resistance.

2 Experimental Investigation

2.1 Tests on Materials

Aggregates for Bituminous Concrete (BC) and Stone Matrix Asphalt (SMA) were selected based on MORTH standards, with materials mixed using the Marshall method. The coarse aggregates, with a specific gravity of 2.75, consisted of stone chips passing through the 4.75 mm IS sieve. Fine aggregates, with a specific gravity of 2.6, were obtained from crusher dust and passed through the 0.075 mm IS sieve. Cement, fly ash, and stone dust were used as fillers, with specific gravities of 3.0, 2.2, and 2.7, respectively, and fly ash was included for further comparative analysis. The binder used was 60/70 penetration grade bitumen, with a specific gravity of 1.03, and sisal fiber, a natural and eco-friendly material, was cut into 15-25 mm pieces to ensure uniform distribution within the mix.

2.2 Preparation of Mixes

- Mixes were prepared following the Marshall procedure (ASTM D1559), with varying binder contents (0-7%) and fiber contents (0.3-0.5%). Aggregates, fillers, and fibers were preheated to appropriate temperatures before being mixed with the binder. The prepared samples were compacted with 75 blows per side and allowed to cool before testing.
- **Marshall Test**

The Marshall method was used to determine the optimum binder content (OBC) and fiber content

(OFC), along with key characteristics like stability, flow value, unit weight, and air voids.

- **Drain-Down Test**
The MORTH-specified method evaluated binder drain-down. Heated samples were placed in drainage baskets, and binder loss was measured.

- **Indirect Tensile Strength (ITS) Test**
The ITS test was used to assess the tensile strength of bituminous mixes, using a compressive load applied to cylindrical samples. The tensile strength was calculated using ASTM D6931. The test was conducted at varying temperatures (5℃ to 40℃).

Fig 1.1 Marshall Sample

Fig 1.2 Marshall Test in Progress

3 Analyses of Test Results and Discussions

This chapter provides a detailed analysis of the test results obtained from the experimental investigation. The analysis focuses on different sections, including parameters used, calculations of Optimum Binder Content (OBC) and Optimum Fibre Content (OFC), as well as the results of various tests like drain-down, static indirect tensile stress, and static creep tests. Each section highlights how these results align with sustainable practices and improved material performance.

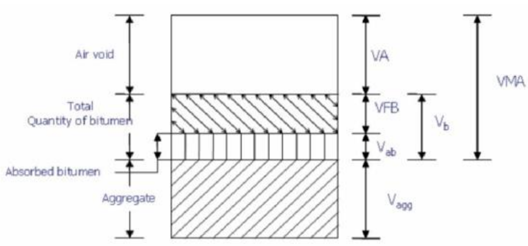

Fig 1.3 Phase Diagram of bituminous mix

3.1 Voids Filled with Bitumen (VFB)

VFB is a critical parameter, reflecting the volume of voids in the mineral aggregate filled with bitumen. A higher VFB ensures better compaction, contributing to the durability of the pavement and minimizing environmental degradation.

3.2 Effect of Different Types of Filler on Bituminous Concrete (BC)

Marshall Stability The stability of BC increases with the binder content up to a certain point, after which it begins to decline. The graph demonstrates the variation in Marshall Stability for BC using different fillers (cement, fly ash, stone dust). Cement, although providing maximum stability, is costly and less sustainable. Fly ash and stone dust, as industrial by-products, offer more environmentally friendly and cost-effective alternatives without compromising stability.

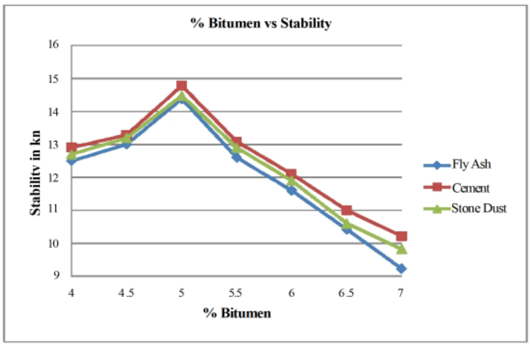

Fig 1.4 Variation of Marshall Stability of BC with different binder content

Table 1. Maximum Marshall Stability values and their corresponding binder content

BC with filler type	Max. Stability (KN)	Corresponding Binder Content (%)
Cement	14.78	5
Stone dust	14.48	5
Fly ash	14.38	5

Flow Value The flow value increases as the binder content rises. For BC, flow values should remain between 2 to 4 mm. This parameter indicates the mix's ability to deform under loads, ensuring that the pavement can adjust to traffic stresses while maintaining its integrity over time.

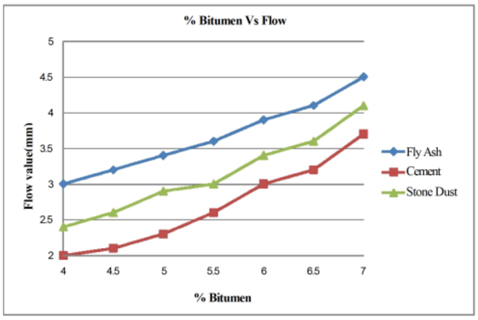

Fig 1.5 Variation of Flow Value of BC with different binder content (With different type of filler)

Unit Weight The unit weight increases with binder content until a peak is reached, after which it decreases. This trend is critical for sustainable construction, as an optimal balance in weight ensures resource efficiency and long-lasting infrastructure.

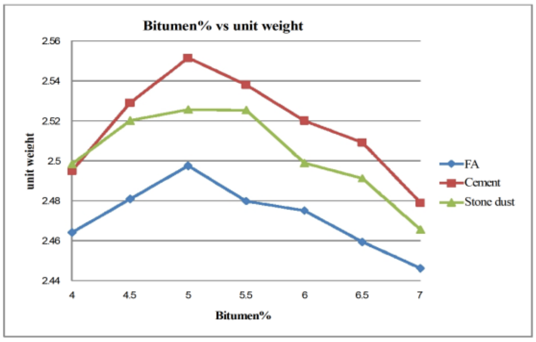

Fig 1.6 Variation of unit weight Value of BC with different binder content

Air Voids Air voids decrease with increasing binder content. Air voids in BC mixes should range between 3-6%, as per MORTH recommendations. Sustainable practices aim to control these voids to reduce oxidation and water infiltration, extending the pavement's lifespan and minimizing maintenance.

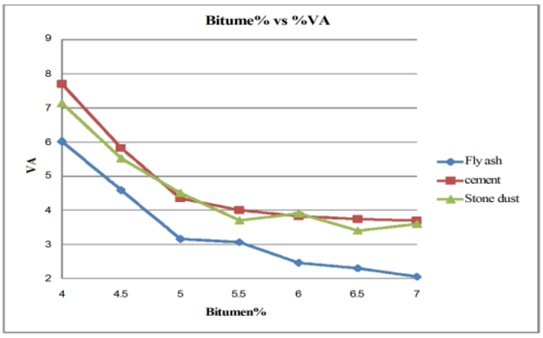

Fig 1.7 Variation of air void of BC with different binder content

Table 2 binder content corresponding to 4.5% of air void

BC with filler type	Air void (%)	Corresponding Binder Content (%)
Cement	4.5	5
Stone dust	4.5	5
Fly ash	4.5	4.8

Voids in Mineral Aggregate (VMA) VMA first decreases and then sharply increases with increasing binder content. VMA represents the void space between aggregate particles and is crucial for allowing bitumen to fill and bind the mix properly, contributing to longer-lasting, sustainable pavements.

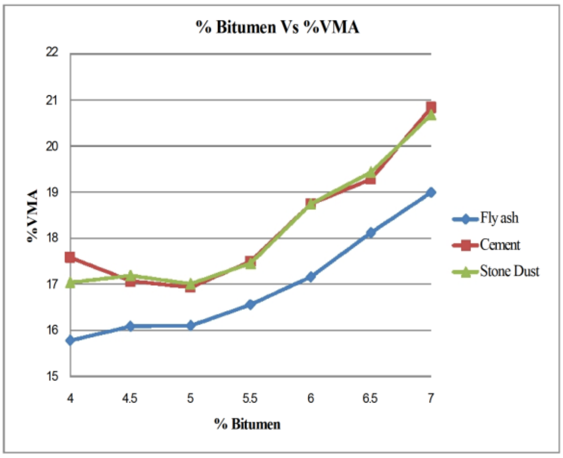

Fig 1.8 Variation of VMA of BC with different binder content

Voids Filled with Bitumen (VFB) VFB increases with the binder content, indicating how effectively the bitumen fills the voids within the aggregate. Higher VFB values result in better compaction and reduced permeability, which are essential for constructing sustainable roads with enhanced durability and lower maintenance needs.

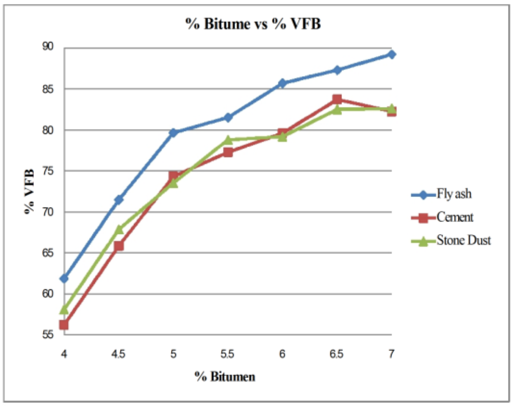

Fig 1.9 Variation of VFB of BC with different binder content

3.3 Optimum Binder Content (OBC) OBC is derived by averaging the bitumen content at three points: maximum stability, maximum unit weight, and the median of air void limits. The OBC for BC with different fillers (cement, fly ash, stone dust) ranges from 4.8% to 5%. Using fly ash as filler contributes to sustainability by recycling industrial waste and reducing costs.

Table 3 OBC of BC with different type of filler

BC With filler type	OBC (%)
Cement	5
Stone dust	5
Fly ash	4.8

3.4 Effect of Fiber on BC

Marshall Stability The stability of BC increases with binder content and fiber content up to a point. The addition of 0.3% fiber optimizes stability, while further increases (e.g., 0.5%) lead to a decrease. This trend highlights the potential of natural fibers like sisal to enhance pavement strength in a sustainable manner by reducing the need for synthetic additives.

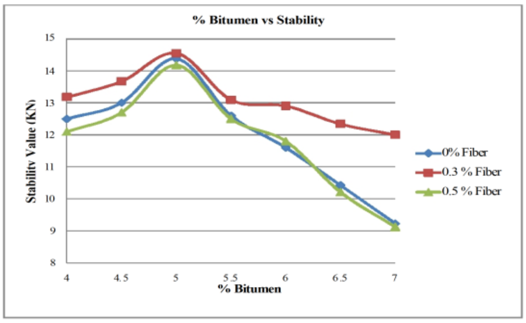

Fig 1.10 Variation of Marshall Stability of BC with different binder content

Flow Value Flow value rises with increasing binder content. The addition of fibers influences this value, contributing to the overall flexibility of the pavement. Optimal fiber content (0.3%) helps control deformation while supporting sustainability through the use of natural materials.

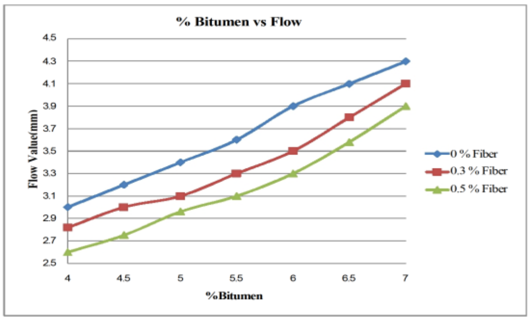

Fig 1.11 Variation of Flow value of BC with different binder content

Unit Weight Unit weight increases with binder content, peaking at specific levels for different fiber contents. By maintaining the right fiber content, the mix can achieve maximum compaction, promoting resource-efficient and sustainable construction practices.

Air Voids Air voids decrease with increasing binder content. Fiber-modified mixes with 0.3% sisal fiber exhibit optimal air voids, ensuring a balance between durability and environmental performance.

Void in Mineral Aggregate (VMA) VMA decreases initially and then increases, emphasizing the importance of fiber content in achieving the right void balance. This helps ensure that the mix is adequately filled with bitumen, enhancing sustainability by preventing premature degradation.

Voids Filled with Bitumen (VFB) VFB increases sharply with binder content, showing the impact of fibers on bitumen distribution. Higher VFB values contribute to better bonding and reduced pavement deterioration, aligning with sustainable infrastructure goals.

3.5 Effect of Fiber on Stone Matrix Asphalt (SMA)

Marshall Stability The stability of SMA increases with binder content and fiber addition up to a limit, after which it declines. Optimal stability is achieved with 0.3% sisal fiber, demonstrating how natural fibers can replace synthetic materials while maintaining high performance.

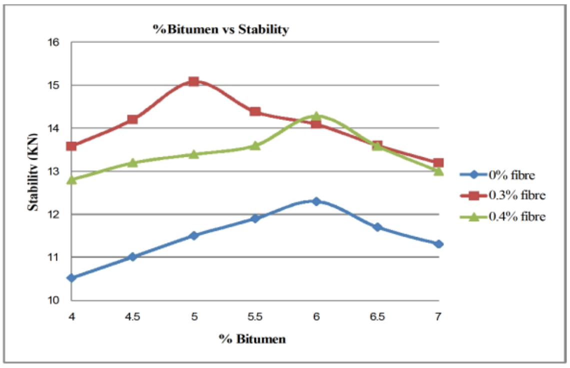

Fig 1.12 Variation of Stability Value of SMA with different binder content

Flow Value SMA flow values follow a similar trend to BC. Fiber content of 0.3% optimizes flexibility, balancing stability and deformation to ensure long-lasting, sustainable pavements.

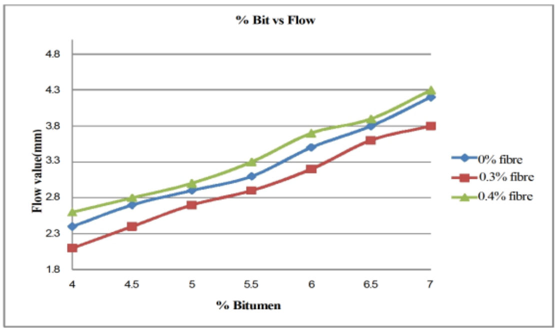

Fig 1.13 Variation of Flow Value of SMA with different binder content

Unit Weight Unit weight increases with binder content and reaches its maximum at 0.3% fiber. This balance contributes to effective material usage, aligning with resource-efficient and sustainable construction practices.

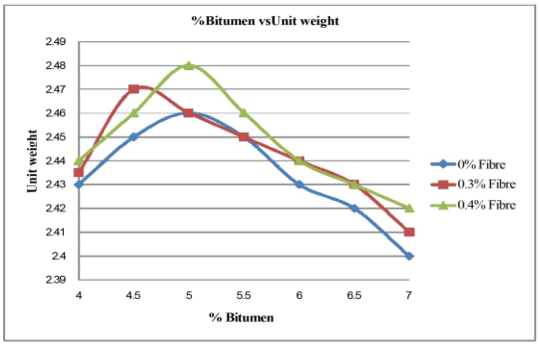

Fig 1.14 Variation of Unit Weight Value of SMA with different binder content

Air Voids Air voids decrease with binder content, and optimal binder and fiber contents ensure the right air void levels for durability. By minimizing voids, the pavement becomes more resistant to environmental factors like moisture infiltration, reducing maintenance needs and resource consumption.

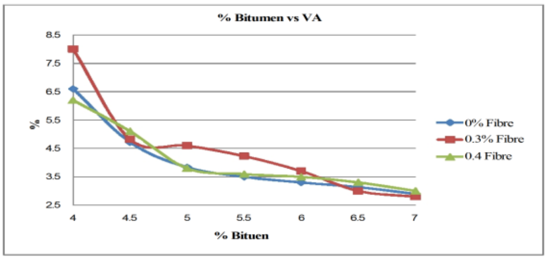

Fig 1.15 Variation of Unit Weight Value of SMA with different binder content

Voids in Mineral Aggregate (VMA) VMA trends similar to BC, indicating that maintaining the right VMA levels is crucial for ensuring the mix's sustainability through proper bitumen bonding and void management.

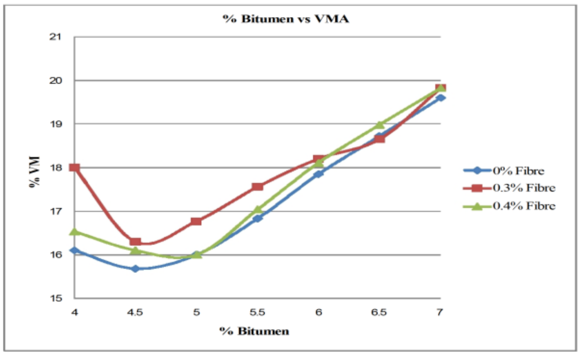

Fig 1.16 Variation of VMA Value of SMA with different binder content

Voids Filled with Bitumen (VFB) VFB increases with binder content, reaching optimal levels at 0.3% fiber content, which helps ensure maximum durability with minimal resource usage.

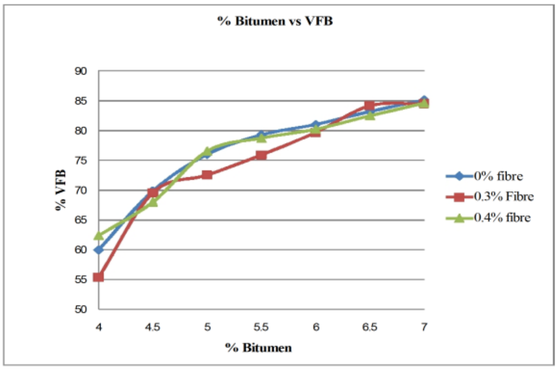

Fig 1.17 Variation of VFB Value of SMA with different binder content

3.6 Drain-Down Characteristics

The drain-down characteristics of SMA and BC mixes were tested with and without fiber. SMA had a higher drain-down rate compared to BC due to its higher bitumen content. However, the addition of sisal fiber significantly reduced drain-down, particularly for SMA. This demonstrates the effectiveness of natural fibers in preventing bitumen loss and promoting sustainability in pavement design.

3.7 Static Indirect Tensile Test

3.7.1 Effect of Fiber on Static Indirect Tensile Strength SMA and BC mixes showed an increase in tensile strength with the addition of fiber, highlighting its role in improving resistance to cracking. Sisal fiber, being a sustainable option, enhances the performance of bituminous mixes while minimizing environmental impact.

3.7.2 Effect of Temperature on Static Indirect Tensile Strength Tensile strength decreases with increasing temperature, with SMA exhibiting higher strength than BC, especially at lower temperatures. The addition of fiber further enhances tensile strength, making it a key component for sustainable road construction in varying climates.

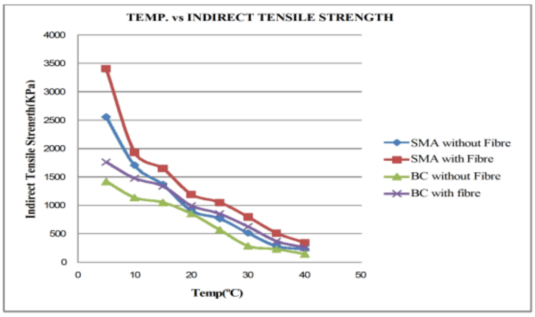

Fig 1.18 Variation of ITS Value of SMA and BC with different Temperatures

3.8 Static Creep Test

The static creep test measures the permanent deformation of bituminous mixes under load. Fiber-modified SMA and BC showed reduced deformation, confirming the role of fibers in improving pavement resistance to rutting. SMA exhibited better performance than BC, particularly when fibers were added, further supporting the use of sustainable natural fibers like sisal in road construction.

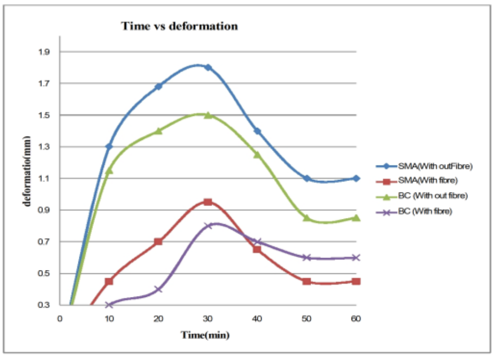

Fig 1.19 Deformation of SMA and BC (with and without fibre

4 Conclusions

The findings from the experimental investigation on Stone Matrix Asphalt (SMA) and Bituminous Concrete (BC) mixes. Both types of mixes were evaluated for their performance, focusing on material properties, filler, and fiber content. The conclusions drawn provide insights into optimizing material use for sustainable road construction.

4.1 BC with Different Types of Filler

1. The design requirements for bituminous mixes, as per MORTH specifications, are outlined in Table 5.1, which includes critical performance metrics such as stability, flow value, air voids, and voids filled with bitumen (VFB).
2. The study confirmed that BC mixes with all three types of fillers—cement, fly ash, and stone dust—meet the MORTH requirements. This demonstrates that multiple filler options can be used without compromising mix quality.
3. While BC with cement filler offers the highest stability, its cost-effectiveness is lower compared to fly ash and stone dust. Hence, for more sustainable and economical solutions, fly ash and stone dust are viable alternatives.
4. The use of **fly ash** contributes to sustainability by minimizing industrial waste, offering a dual benefit of environmental conservation and effective road construction material.

4.2 BC with Different Fiber Content

1. The Optimum Binder Content (OBC) was determined to be 5%, while the Optimum Fiber Content (OFC) was 0.3%.
2. Adding fiber up to 0.3% increased Marshall Stability, but further fiber addition caused stability to decrease. This indicates that 0.3% fiber content is optimal for enhancing the strength of BC. However, stability did not improve as much as in the SMA mixes.
3. The flow value of the mix decreased with the addition of fiber, suggesting better compaction and less deformation. However, at 0.5% fiber content, the flow value increased again, showing the need for balance in fiber usage.

4.3 SMA with Different Fiber Content

1. According to IRC SP-79-2008 specifications, the performance requirements for SMA mixes are shown in Table 5.2, covering aspects such as void percentage, binder requirement, and voids in mineral aggregates (VMA).
2. The binder requirement for SMA without fiber was found to be 5.8%. When 0.3% sisal fiber was added, this reduced to 5.2%, highlighting sisal fiber's ability to decrease binder content. However, exceeding 0.3% fiber led to a rise in binder demand, which resulted in increased drain-down.
3. The addition of 0.3% sisal fiber significantly improved stability, but further fiber additions caused a decline in stability.
4. The flow value decreased with 0.3% fiber addition, indicating improved mix workability and reduced deformation. However, beyond 0.3%, the flow value increased again.
5. One major advantage of incorporating fibers, especially natural ones like sisal, is the reduction in air voids within the mix. This enhances the durability and compaction of the pavement.
6. The binder drain-down was also minimized with the addition of 0.3% fiber, contributing to more efficient and stable pavement design.

4.4 Mix at Optimal Binder Content (OBC) and Fiber Content (OFC)

Several tests, including drain-down, Indirect Tensile Strength (ITS), and static creep tests, were conducted on the mixes at their OBC and OFC to draw the following conclusions:

1. The drain-down in SMA without fiber is higher than in BC. However, when fibers were added, the drain-down significantly decreased, indicating improved binder retention in the mix.
2. The ITS test revealed that SMA has a higher tensile strength than BC, further emphasizing its suitability for high-traffic areas.
3. The static creep test demonstrated that adding fibers to both BC and SMA reduced deformation. The MORTH guideline limits permanent deformation to 0.5 mm. SMA samples with fibers showed a deformation of about 0.45 mm, which is well within acceptable limits, indicating improved performance.

This study evaluated two types of mixes, Stone Matrix Asphalt (SMA) and Bituminous Concrete (BC), using 60/70 penetration grade bitumen as the binder. Additionally, a natural, sustainable fiber, sisal, was incorporated into the mixes at varying concentrations (0-0.5%). Through the Marshall method of mix design, the Optimum Binder Content (OBC) and Optimum Fiber Content (OFC) were determined. The findings indicate that adding 0.3% sisal fiber significantly improved the properties of both SMA and BC mixes.

Tests such as the drain-down, Indirect Tensile Strength (ITS), and static creep tests revealed that the sisal fiber-enhanced SMA performs exceptionally well, making it a suitable choice for flexible pavements. The use of sisal fiber, a renewable and biodegradable resource, not only enhances mix performance but also supports sustainable construction practices by reducing reliance on synthetic materials and addressing waste management challenges. The integration of natural fibers like sisal contributes to environmental sustainability by promoting the use of eco-friendly materials in infrastructure development.

REFERENCES

1) Santos, J., Ferreira, A., & Flintsch, G. (2020). “Life-Cycle Assessment of Pavement: Comparing the Use of Natural Fibers in Bituminous Mixes.” Sustainability, 12(3), 789-812.
2) Rafiq, W, Qureshi, H. J., & Khan, S. (2021). "The Effect of Coir Fiber on the Mechanical Properties of Bituminous Mixes." Construction and Building Materials, 301, 123-134.
3) Rahman, M. M., & Al-Abdul Wahhab, H. I. (2019). "Performance Evaluation of Asphalt Mixtures with Date Palm Fibers." Materials and Structures, 52(5), 1-12.
4) Kar, M., & Maiti, M. (2020). "Use of Jute Fiber in Sustainable Bituminous Mixes for Road Pavements." International Journal of Pavement Research and Technology, 13(6), 790-798.
5) Tarefder, R. A., Islam, M. R., & Anwar, M. A. (2021). "Influence of Coconut Coir Fiber on the Fatigue and Rutting Resistance of Asphalt Mixes." Journal of Materials in Civil Engineering, 33(10), 04021244.
6) Rathore, P., & Jain, S. (2022). "Sustainable Pavement Design with the Incorporation of Natural Fibers in Bituminous Mixtures." Journal of Transportation Engineering, Part B: Pavements, 148(1), 04021093.
7) Saba, N., & Jawaid, M. (2020). "Review on Natural Fiber-Reinforced Asphalt Mixes: Sustainability and Durability Considerations." Journal of Cleaner Production, 263, 121-132.
8) Thakur, M. & Kumar, S. (2021). "Evaluation of Sisal Fiber as a Reinforcing Material in Bituminous Pavement Mixes." Journal of Traffic and Transportation Engineering, 8(4), 405-413.
9) Amin, M. R., & Hasan, M. J. (2019). "Study of Bamboo Fiber Reinforced Asphalt Mixtures for Pavement Sustainability." Journal of Road Materials and Pavement Design, 20(7), 1778-1792.
10) Peng, X., Wu, J., & Luo, H. (2020). "The Impact of Kenaf Fiber on the Thermal and Mechanical Properties of Asphalt Mixtures." Journal of Construction and Building Materials, 239, 1179-1191.
11) Patil, P., & Jain, V. (2019). "Investigation on the Use of Cotton Fiber for Enhancing the Mechanical Properties of Bituminous Pavement Mixes." Journal of Sustainable Construction Materials and Technologies, 5(2), 289-297.
12) Sah, R., & Bhattacharya, M. (2020). "Effect of Pineapple Leaf Fiber on the Durability and Rutting Resistance of Asphalt Pavement

Mixes." International Journal of Pavement Engineering, 23(3), 381-392.

13) Choudhary, A., & Kumar, A. (2021). "Analysis of Tensile Strength and Rutting Behavior of Bituminous Mixtures Reinforced with Flax Fibers." Materials Today: Proceedings, 47(2), 108-117.
14) Jiang, X., Li, Y., & Zhang, Y. (2022). "Eco-Friendly Bituminous Mixes Incorporating Corn Husk Fiber: A Case Study." Journal of Cleaner Production, 348, 131-142.
15) Qasim, A. M., & Mohammed, A. A. (2021). "Influence of Banana Fiber on Mechanical Properties and Performance of Asphalt Concrete." Journal of Materials in Civil Engineering, 33(6), 04021197.
16) Anup, S., & Basu, S. (2020). "Use of Wool Fiber in Bituminous Pavement for Improved Flexural Strength and Sustainability." Journal of Natural Fibers, 17(6), 924-936.
17) Fernando, R., & Williams, C. R. (2020). "Impact of Natural Fiber Additives on the Resistance of Asphalt Mixes to Fatigue and Cracking." Journal of Road Materials and Pavement Design, 21(4), 1021-1034.
18) Naidu, P., & Mahesh, K. (2021). "Mechanical Performance of Asphalt Mixtures Reinforced with Sugarcane Bagasse Fibers." International Journal of Pavement Engineering, 22(5),
19) Islam, R., & Siddique, N. (2019). "Enhancing Rutting and Fatigue Life of Asphalt Mixtures by Incorporating Palm Kernel Fiber." Construction and Building Materials, 217, 56-66.
20) Gupta, A., & Jain, N. (2022). "Investigating the Sustainable Use of Hemp Fiber in Flexible Pavement Design." Journal of Cleaner Production, 375, 134112.