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Research Paper

Effect of Waste Plastic and Fiber Modification on Asphalt Mixture Properties

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ABSTRACT

Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) are widely used in road construction due to their excellent mechanical properties and long-term durability. This study investigates the effect of sisal fiber and waste plastic as modifiers to enhance the performance of SMA and AC mixtures. The Marshall mix design method was employed to determine the optimum bitumen content (OBC) and optimum fiber content (OFC), evaluating parameters such as Marshall stability, flow value, air voids, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB). VG 30 grade bitumen was used as a bitumen, and fly ash was utilized as a filler. Sisal fiber was incorporated to reduce bitumen drain down and improve crack resistance, with the optimal fiber content identified as 0.4% by total mix weight. Simultaneously, waste plastic was added to improve workability and mechanical performance, with 2.5% content enhancing handling characteristics and 3% improving drain-down resistance and tensile strength. Results from drain down and moisture susceptibility tests indicated that the combined use of sisal fiber and waste plastic significantly improved the durability and overall performance of the asphalt mixes.

1 Introduction

The growing demand for sustainable, high-performance pavements has led to considerable interest in modifying conventional asphalt mixtures using waste materials and natural fibers. Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) are commonly used for road construction due to their strength and durability, yet both suffer from challenges such as rutting, moisture susceptibility, and bitumen drain-down [1]. Researchers have introduced stabilizing additives, particularly fibers and polymers, to address these limitations and enhance mechanical and durability properties [2]. Recent studies have investigated natural fibers like Sisal and synthetic materials such as waste plastic (PP) plastic for asphalt modification [3,4]. SMA's gap-graded structure and high bitumen content offer inherent resistance to deformation and cracking; however, it remains prone to moisture damage and drain-down. Sisal fibers have shown promise in reducing these issues by increasing tensile strength and aggregate interlocking while minimizing permanent deformation. Optimization studies using Response

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Surface Methodology (RSM) identified 0.3% Sisal fiber by mix weight as an effective dosage [5]. Parallely, using waste plastics in AC offers a sustainable solution to pavement enhancement and plastic waste disposal. Incorporating waste plastics, especially high-density polyethylene (HDPE) and polyethylene terephthalate (PET), has improved Marshall Stability and reduced deformation. However, limited research has been dedicated to assessing the impact of PP plastic on the stiffness, moisture resistance, and cracking performance of AC mixtures [6]. While prior investigations have independently explored fiber-reinforced SMA and plastic-modified AC, this study compares Sisal fiber and waste PP plastic used as modifiers in SMA and AC, respectively. The research introduces a novel comparative analysis, assessing stability, deformation resistance, and moisture susceptibility across both modified mixtures. Additionally, it explores how these additives influence bitumen-filler interaction, aggregate interlocking, and structural behavior under load.

Sisal fiber enhances load distribution and reduces bitumen drain-down, improving Marshall Stability and tensile strength. Its high tensile strength and elasticity form a reinforcing network that delays rutting and fatigue cracking. On the other hand, waste PP plastic modifies the bitumen's viscoelastic behavior, improving adhesion with aggregates and enhancing resistance to stripping and temperature-induced deformation. This study builds on previous work that explored SMA with 8% shredded waste plastic, achieving performance comparable to polymer-modified bitumen (PMB) [7], and AC modified with PET and Sisal fibers to reduce drain-down and increase stiffness [8,9]. Use of residual plastic fibers in place of virgin bitumen has also shown promising structural results [10]. Research indicates that plastic-modified mixtures show varying optimum bitumen content (OBC) depending on dosage; 4% plastic addition, for example, enhances Marshall Stability significantly [11]. However, performance can decline at higher dosages due to thermal instability and dispersion challenges [12,13], with 6% PET found to be optimal cost and performance in SMA [14,15]. Sisal fiber's benefits in SMA are well-documented in enhancing fatigue life and moisture resistance [16,17], yet a side-by-side comparison with waste plastic-modified AC is largely missing. This gap in comparative analysis under varied environmental and loading conditions justifies the present research.

Objectives

- To compare the mechanical and durability characteristics of SMA modified with Sisal fibers and AC modified with Sisal fibers.
- To evaluate and contrast the performance of waste PP plastic-modified AC with conventional AC, focusing on moisture resistance and deformation behavior.

Research Contribution This study fills a critical research gap by comprehensively analyzing the impact of Sisal fiber in SMA and waste PP plastic in AC. It correlates additive composition with performance outcomes such as stability, moisture resistance, and fatigue performance, offering insights for developing eco-friendly and durable pavement materials that support sustainable road construction practices.

2 Materials

The choice of materials is essential in influencing the performance characteristics of modified Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) mixes. Building on prior research, the selected materials have demonstrated considerable promise in enhancing the strength, longevity, and environmental sustainability of asphalt pavements. This section outlines the specific materials utilized in the present study, which include aggregates, fillers, Sisal fibers, bitumen, and waste plastic (PP).

2.1 Aggregates

Aggregates form the primary load-bearing framework in asphalt mixtures, playing a vital role in determining their strength, stability, and resistance to deformation. This research adopts the aggregate grading system recommended by the Indian Roads Congress (IRC), which combines coarse aggregates, fine aggregates, and mineral filler to ensure proper interlocking and efficient load transfer [18]. According to IRC guidelines, a nominal maximum aggregate size (NMAS) of 12.5 mm was selected. The thickness of the SMA wearing course was kept within the range of 40 to 50 mm. The physical properties of the aggregates used in the study were tested in the Transportation Engineering Laboratory at COEP and are listed in Table 1.

2.2 Stone Dust

Fillers significantly contribute to the cohesion, structural stability, and moisture resistance of asphalt mixtures. Commonly used fillers include fly ash, lime, hydrated lime, stone dust, and cement. In this study, stone dust was chosen as the filler owing to its demonstrated ability to enhance the stability of asphalt mixes. As per IRC: SP:79 [19], the mineral filler must be finely divided, and fly ash is discouraged since it can adversely affect the adhesion characteristics of bitumen.

2.3 Sisal Fiber

Sisal fibers serve as reinforcement in Stone Matrix Asphalt (SMA), helping to control deformation and enhance the mix's structural integrity. Their presence strengthens the bond between bitumen and aggregates, creating a more cohesive and rigid matrix that resists the development and spread of cracks [20]. Moreover, Sisal fibers help minimize bitumen drain-down—an inherent challenge in SMA—by providing additional surface area for bitumen absorption. With a high elastic modulus of 11 GPa and tensile strength of 0.95 GPa, Sisal fibers significantly boost Marshall Stability and Indirect Tensile Strength (ITS), thereby improving resistance to rutting and fatigue. In the study, fibers with an average diameter of 0.21 mm were manually cut to lengths of about 10 mm to ensure uniform dispersion within the mix. Based on preliminary trials to achieve optimal blending with aggregates and bitumen, the fiber content varied by up to 0.8% in total mix weight.

2.4 Bitumen

Bitumen is a key binding agent in asphalt mixtures, providing cohesion among aggregates, flexibility under load, and protection against aging. For this study, viscosity-grade VG-30 bitumen was chosen due to its effectiveness in high-traffic conditions and its resistance to temperature-related softening. The physical characteristics of the VG-30 bitumen were evaluated under IS and ASTM standards [21–28], and the results are presented in Table 1.

2.5 Waste Plastic (PP)

Waste PP plastic alters the rheological behavior of bitumen by enhancing its stiffness and reducing its sensitivity to temperature variations. When integrated into AC, waste PP plastic promotes better interaction between bitumen and aggregates, improving adhesion and minimizing the risk of stripping and moisture damage. It also strengthens the cohesive properties of the mixture, leading to improved Marshall Stability and tensile strength. However, excessive use of plastic can cause the mix to become overly stiff and brittle, which may impair its fatigue performance. Therefore, identifying an optimal plastic content is essential to balance rigidity, durability, and deformation resistance. In this study, the waste PP plastic was sourced from scrap dealers in Pune, primarily from non-recyclable industrial food packaging waste. The material was processed through milling at a rate of 40–45 kg/h, producing flakes sized 8–9.5 mm in length and 1.5–2.5 mm in width. It was supplied by Vishal Bio-Tech Pvt. Ltd., Pune, a firm specializing in processing plastic waste [15]

Table 1. Physical Properties of Materials

Samples	Test	Standards	Vital values IRC: SP: 79	Experiential values (%)
Coarse Aggregate	Impact value	IS 2386	Max 24%	9.54%
	Abrasion value	IS 2386	Max 25%	19.23%
	Water absorption	IS 2386	Max 2%	1.12%
	Elongation and Flakiness index combined	IS 2386	Max 30%	29.7%
Bitumen (VG 30)	Penetration (1/10 th of mm)	IS1203 ASTM D5	50-70	62
	Softening point ring and ball apparatus (°C)	IS1205 ASTM D36	40-55°C	48.7°C
	Ductility test (cm)	IS 1208	>75 cm	80

2.6 Aggregate Blending

Optimizing aggregate gradation is a key aspect of asphalt mix design, as it significantly affects rutting resistance, durability, and the structural performance of pavements. A properly graded aggregate matrix promotes effective particle interlocking, which enhances the load-bearing capacity and overall behavior of both SMA and AC mixtures. In this research, the aggregate gradation was established in accordance with the Ministry of Road Transport and Highways (MoRTH, 2013) [29], Indian Roads Congress (IRC) 29 standards [30], and relevant AASHTO guidelines, including MP 8-05 and PP41-02 [31,32]. A nominal maximum aggregate size (NMAS) of 12.5 mm was chosen to align with typical pavement design practices. The gradation curve, depicted in Figure 1, reflects compliance with the specified particle size distribution criteria necessary for achieving effective mechanical interlocking and optimal bitumen retention [33–36]

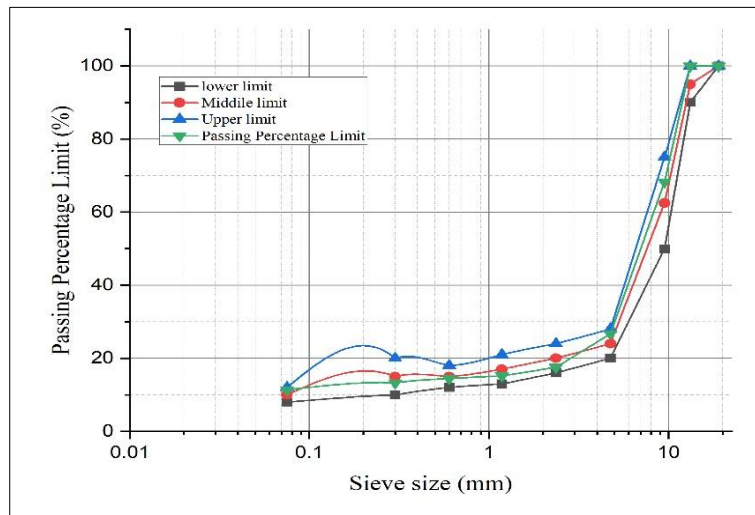


Fig 1. - Aggregate Blending

3 Sample Fabrication and Experimental Methodology

The mix formulation was carried out following the guidelines specified by Brown and Cooley [37] in the National Asphalt Technology Report, along with the provisions in IRC: SP: 79-2008. The compaction strategy for Stone Matrix Asphalt (SMA) adhered to the approach proposed by Brown and Mallick [38], which advocated for rotational compaction to simulate field conditions more accurately. Their research indicated that air void distribution achieved through rotational compaction closely resembled that produced using the Marshall Stability Test (MST) with 75 hammer blows on each side. This study introduced waste plastic (PP) and natural fibers as bitumen modifiers for Asphalt Concrete (AC) mixes. Both bitumen and granular PP plastic were heated to around 180°C and mixed thoroughly to ensure uniform dispersion. This modified binder was then blended with aggregates, and specimens were cast for Marshall Stability and Indirect Tensile Strength (ITS) tests, with outcomes shown in Table 2.

3.1 Mix Design Methodology

The Marshall Mix Design technique was utilized for SMA preparation, dividing the study into two principal stages. In the first stage—determination of the Optimum Bitumen Content (OBC)—SMA samples were produced in accordance with IRC: SP: 79-2008 to identify the most effective bitumen percentage. In the second stage, Sisal fibers were incorporated into the SMA using the established OBC, and their mechanical characteristics were examined. Cylindrical samples with dimensions of 101.6 mm in diameter and 63 ± 2.5 mm in height were formed using a Marshall compactor, delivering 75 hammer blows per face.

3.1.1 Mixing and Compaction Procedure

- Coarse and fine aggregates were heated to 150°C before blending.

- Preheated bitumen was added to the hot aggregate mix, followed by hand mixing to ensure complete coating.
- The blended mixture was compacted at 150°C using the Marshall compaction technique.

3.1.2 Material Proportions

Bitumen Content: Ranged between 5.5% and 7% by the total aggregate weight, in 0.5% intervals for the reference mix containing stone dust filler. Sisal Fiber Content: Added in proportions of 0.2%, 0.4%, 0.6%, and 0.8% by the aggregate weight to assess their effects on stability, flow, void content, and overall durability.

3.1.3 Specimen Replication and Testing Protocol

To ensure experimental accuracy and statistical confidence, three replicate samples—each weighing around 1,200 grams—were created for every mix variation. Following the determination of OBC, further specimens were prepared to conduct Indirect Tensile Strength (ITS) tests, evaluating the mixtures' resistance to cracking and tensile stress failure.

Table 2. Test results of SMA and AC Mix

Bituminous mix test sample	Engineering and statistical parameters	Without Filler and Fiber	Stone dust filler and no fiber	Stone dust filler and 0.2% fiber	Stone dust filler and 0.4% fiber	Stone dust filler and 0.6% fiber	Stone dust filler and 0.8% fiber
SMA mix	Binder content (%)	7.2	6.5	6.5	6.4	6.2	6
	Stability (kN)	12.8	13.1	15.9	15.5	14.8	14.3
	Drain down at OBC (%)	1.39	0.45	0.22	0.18	0.12	0.11
	Flow values	2.90	2.83	2.80	3.20	3.50	3.90
	Mean	2.860	2.770	2.770	3.167	3.487	3.803
	VMA (%)	18.98	18.8	18.62	18.25	17.8	17.49
	VFB (%)	74.36	75.61	76.91	76.99	76.97	78.27
	Air voids (%)	4.87	4.5	4.3	4.2	4.1	3.8
	ITS (kPa)	486.23	516.92	576.19	548.39	522.67	514.18
Bituminous mix test sample	Engineering and statistical parameters	Without Filler and Fiber, WPP	Stone dust filler + no fiber	Stone dust filler+ 0.2% fiber+1.5% WPP	Stone dust filler + 0.4% fiber+2.0	Stone dust filler + 0.6% fiber +2.5% WPP	Stone dust filler + 0.8% fiber +3.0% WPP
AC Mix	Binder content (%)	5.3	5.5	6.0	6.3	6.5	7.0
	Stability (kN)	13.2	13.5	14.8	14.4	15.6	14.3
	Flow values	4.00	3.40	3.60	3.10	3.67	2.60
	VMA (%)	18.02	18.84	19.6	18.78	18.98	19.23
	VFB (%)	67.68	70.21	72.1	74.14	73.17	75.12
	Air voids (%)	5.46	5.87	5.65	4.91	5.15	3.81
	ITS (kPa)	420	474	498	497	504	514

Note: VFB- Voids filled with bitumen

4 Performance Evaluation Methods

4.1 Drain-Down Test

The Schellenberg drain-down test (ASTM D6390) [39] evaluates the tendency of asphalt mixtures to experience bitumen separation when exposed to gravity and elevated temperatures. This assessment offers valuable information regarding the mixture's cohesion, stability, and potential durability over time. The drain-down percentage is a crucial indicator, as excessive bitumen loss can compromise the structural integrity of pavements. This investigation examined the drain-down behavior for mixtures incorporating fillers, fibers, and different bitumen types. The findings revealed that samples without fillers and fibers displayed a greater drain-down, whereas the inclusion of stone dust and Sisal fibers notably minimized bitumen loss. This improvement is credited to the enlarged surface area of the fillers and fibers, promoting better bitumen retention. The observed drain-down percentages remained within the 0.3% threshold specified by IRC: SP-79 (2008), validating the stability of the prepared mixes. Figure 2 depicts the characteristics of bitumen retention.

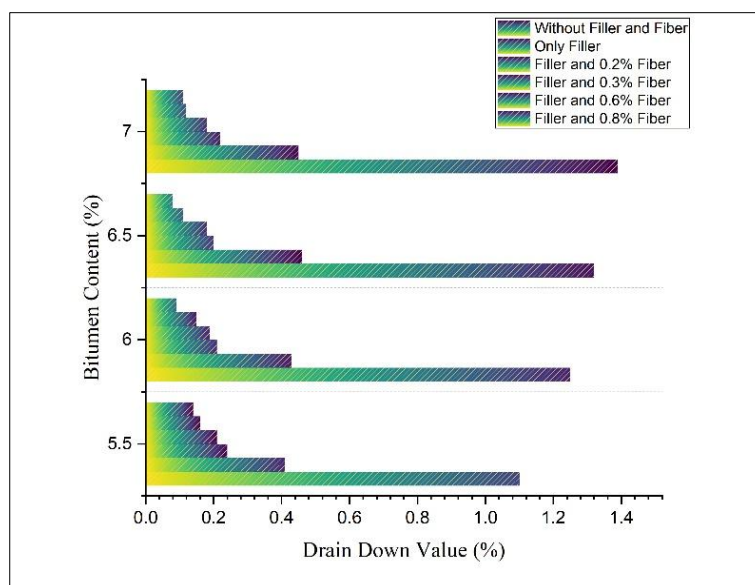


Fig 2. Binder content (%) Vs Drain Down Value Test

4.2 Marshall Stability Test

The Marshall Stability Test (ASTM D6926, ASTM D6927) [40,41] is frequently used to assess the strength and deformation properties of asphalt mixes. This process facilitates the determination of the ideal bitumen and fiber contents required to maintain structural stability and increase load-carrying capacity. For this study, Marshall specimens were created in accordance with the designated aggregate gradation (Figure 1). A Marshall hammer was used to condense each sample, which had dimensions of 101.6 mm in diameter and 63 ± 2.5 mm in height, with 75 blows on each side. The maximum force the combination could withstand before failing was used to define its stability, and the deformation at the failure site was used to define its flow. These criteria were essential when assessing the resistance of modified SMA and AC mixes to deformation and the creation of permanent ruts.

4.3 Boiling Water Test

By measuring the degree of stripping, which indicates the loss of adhesion between bitumen and aggregate when exposed to water, the Boiling Water Test (ASTM D36) [42] evaluates the moisture sensitivity of asphalt mixtures. A 250 g sample was dried in an oven, passed through a 20 mm sieve, and retained on a 12.5 mm sieve for this test. It was then heated to 170°C and mixed with 17 g of bitumen at 150°C. After mixing, boiling water was added when the sample cooled to a temperature between 70 and 100°C. The stripping value, or the proportion of bitumen lost, was recorded after ten minutes of mixed observation. The findings showed that waste plastic (PP) plastic-modified AC mixtures had lower stripping values than unmodified AC mixtures, suggesting improved resistance to moisture damage. MoRTH guidelines state that the stripping

value shouldn't exceed 5%. The stripping value of the PP-modified AC mixtures in this study ranged from 0% to 4.5%, depending on the plastic content (1.5%–3.5%), while the unmodified AC combinations had a stripping value of 3.5%. These findings indicate that discarded PP plastic reduces the potential for water-related breakdown and enhances moisture resistance.

4.4 Indirect Tensile Strength Test

The tensile resistance of asphalt mixes is measured by the Indirect Tensile Strength (ITS) Test (ASTM D6931) [43, 44, 45], which is crucial for determining their susceptibility to fatigue cracking and their structural longevity. During this test, a compressive force is applied along a diametric plane, causing tensile stress perpendicular to the force and ultimately leading to specimen failure. For this investigation, specimens with a 100 mm diameter and 63 ± 2.5 mm height were created using the Marshall mix design. A load was applied at a rate of 51 mm/min until failure. The ITS value was then computed using a conventional geometric correction factor, as per the above equation, after the peak load was recorded. Since greater ITS values signify increased durability and breaking resistance, the ITS data offer essential insights into the tensile characteristics of the changed mixes.

$$St = \frac{2000P}{\pi Dt} \quad (1)$$

Where,

t = Specimen height immediately before test, mm P = Maximum load, N

D = Specimen diameter, mm S_t = IDT strength, KPa

5 Results and Discussions

5.1 Marshall Stability Evaluation of Fiber- and Plastic-Modified Asphalt Mixtures

The Marshall Stability Test (MST) assesses asphalt composites' structural capacity and deformation resistance. Table 2 summarizes MST results for Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC), including stability, flow, air voids (Va), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB). The unmodified SMA (7.2% bitumen) showed a stability of 12.8 kN. Incorporating 0.4% Sisal fiber improved stability by 24.22%, attributed to enhanced matrix interlocking and load transfer. However, fiber dosages beyond 0.4% reduced MST due to compaction inefficiencies from fiber agglomeration. Flow values (2.80–3.90 mm) remained within MoRTH limits (2–4 mm). Similarly, AC modified with 2.5% waste plastic (PP) and 0.4% fiber recorded a 26.11% MST gain, indicating improved stiffness and adhesion due to polymer-bitumen interaction. Stability decreased beyond 2.5% plastic due to excessive rigidity and brittleness. Flow values (2.4–4.0 mm) confirmed retained deformability within permissible limits.

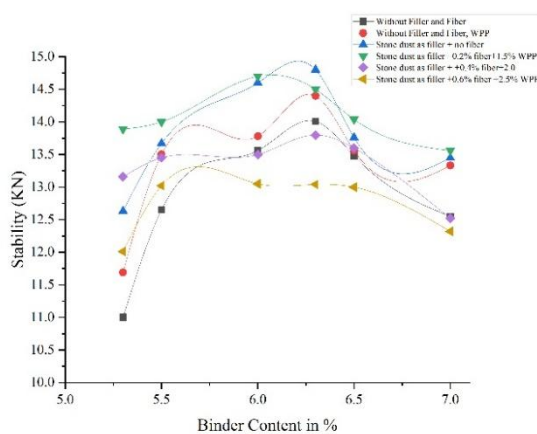


Fig. 3 - Stability for AC altered by Fiber + WPP

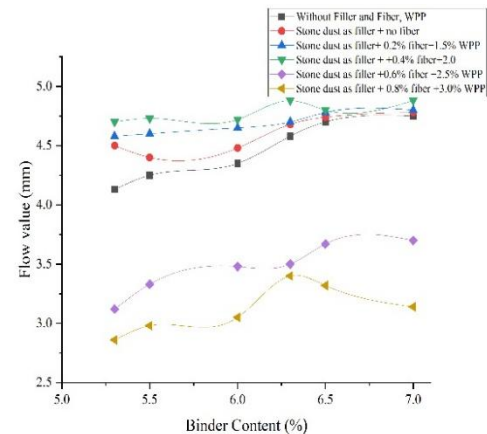


Fig. 4 - Flow values for AC altered by Fiber + WPP

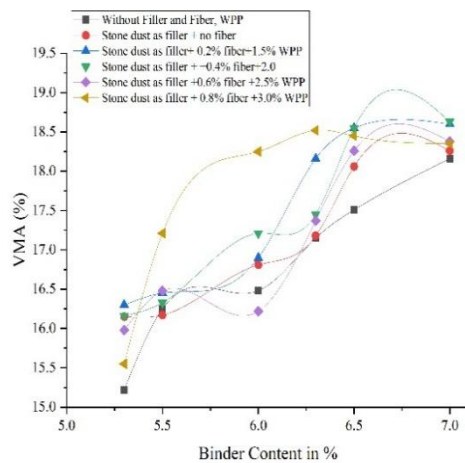


Fig. 5 - VMA for AC altered by Fiber +WPP

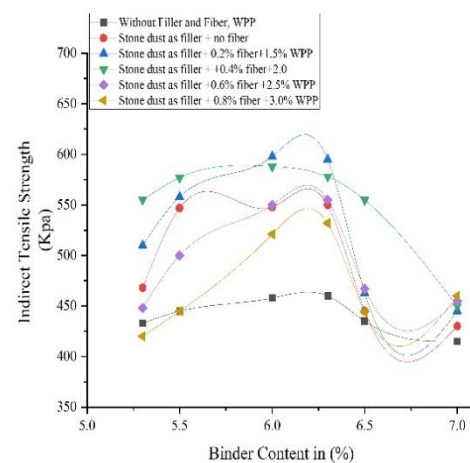


Fig. 6 - ITS for AC modified with fiber +WPP

Figures 3–6 illustrate MST and flow trends for modified mixes. The peak MST occurred at 6.3% bitumen with 0.4% Sisal fiber in SMA and 2.5% PP in AC. VMA values met IRC SP:79's 17% threshold, especially in fiber-modified SMA, indicating better aggregate packing and binder retention. Higher VFB and controlled Va (3–5%) across mixes further confirm improved compaction, cohesion, and reduced permeability. The findings support the role of fiber and plastic modifiers in enhancing mechanical stability and durability in asphalt systems.

5.2 Tensile Performance Evaluation of Fiber- and Plastic-Modified Asphalt Mixtures

The Indirect Tensile Strength (ITS) test (ASTM D6931) quantifies the resistance of asphalt composites to tensile stress and cracking, which is crucial for evaluating thermal fatigue and structural durability. ITS results for Sisal fiber-modified SMA at 25°C (Table 2) revealed superior tensile strength compared to unmodified mixes, with peak performance at 0.4% fiber content. Beyond this, ITS declined due to fiber agglomeration and diminished fiber-binder interaction. Similarly, AC mixtures modified with waste plastic (WPP) and fiber showed enhanced ITS values (Figure 6, Table 2). Sisal fiber yielded an 18.57% improvement, attributed to better tensile stress distribution and crack-bridging behaviour. WPP-modified AC showed an 8% ITS increase, affirming enhanced binder cohesion. However, plastic contents above 2.5% led to reduced ductility and early cracking due to excessive stiffening. Optimal ITS performance was observed at 0.4% fiber and 2.5% plastic dosages. These results emphasize the efficacy of fiber and plastic modifiers in improving tensile resistance and fatigue life, provided content levels are correctly optimized.

5.3 Comparative Structural Performance of Fiber-Modified SMA and AC Mixtures

Figures 7–9 illustrate the comparative performance of SMA and AC mixtures modified with 0.4% Sisal fiber and stone dust filler.

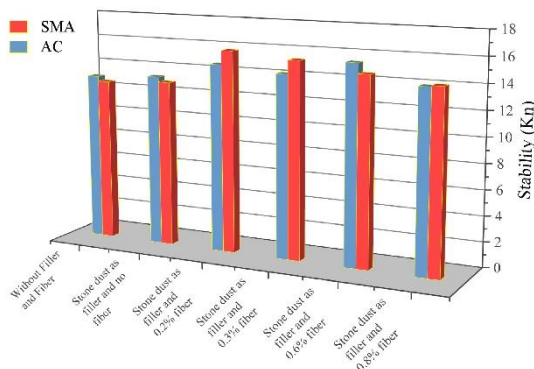


Fig. 7 - Evaluation of Stability among AC and SMA

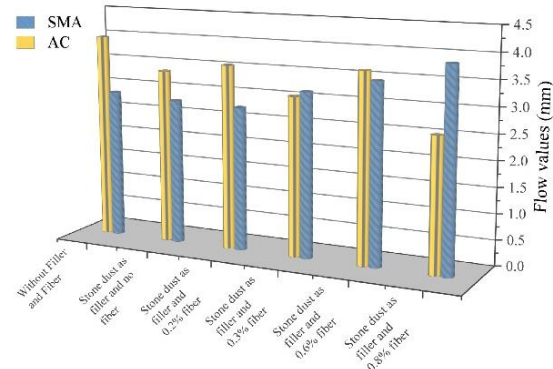


Fig. 8 - Evaluation of Flow values among AC and SMA

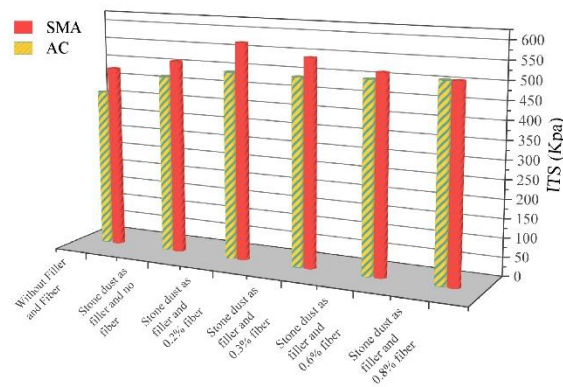


Fig. 9 - Evaluation of ITS among AC and SMA

SMA exhibited higher Marshall Stability Test (MST) values than AC, indicating superior structural integrity due to enhanced aggregate interlocking and efficient fiber reinforcement. Flow values (Figure 8) were lower in SMA (2–4 mm, per MoRTH standards), reflecting greater resistance to permanent deformation than more flexible AC mixes. Regarding tensile resistance (Figure 9), SMA also outperformed AC, with higher Indirect Tensile Strength (ITS) values, confirming its enhanced crack resistance and durability. The improved performance of fiber-reinforced SMA is attributed to its higher bitumen content, increased rigidity, and effective stress distribution, making it more resilient under loading conditions.

6 Conclusions

This investigation assessed the mechanical and structural behavior of Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) mixtures modified with Sisal fiber and recycled plastic (PP) plastic, focusing on key parameters such as load stability, tensile resistance, deformation tolerance, and durability.

- The optimum bitumen content (OBC) was identified as 6.3% for both SMA and AC, derived through Marshall Stability and volumetric evaluations.
- Incorporation of 0.4% Sisal fiber (by weight of total mix) notably enhanced SMA, with a 22.26% increase in Marshall Stability and a 20.56% rise in Indirect Tensile Strength (ITS), validating improved resistance to rutting and thermal cracking.
- AC blends modified with 2.5% waste PP plastic exhibited a 26.11% enhancement in MST and an 8% gain in ITS, reflecting superior rigidity and durability; however, dosages above 2.5% reduced tensile performance, indicating an optimal threshold.
- Flow values across all modified compositions adhered to MoRTH and IRC: SP:79 specifications, ensuring proper deformability and mix cohesion.
- The inclusion of PP plastic significantly enhanced the mechanical resilience of AC, promoting greater plastic flow resistance and extended pavement lifespan.
- All modified mixtures exceeded the MoRTH-specified minimum stability norm (MSN > 9 kN), suggesting opportunities for reduced bitumen usage, cost-efficiency, and sustainable material practices.
- The integration of Sisal fibers and post-consumer plastic waste presents an environmentally conscious approach to pavement engineering, simultaneously addressing ecological concerns and improving pavement performance.

This study affirms the viability of using natural and recycled modifiers in asphalt mixtures and recommends further exploration into long-term in-service behavior, rut resistance, fatigue characteristics, and optimized fiber–polymer synergy for enhanced sustainable pavement technologies.

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