



Journal of Materials and Engineering Structures

Research Paper

Enhancing Asphalt Mixture Properties through Waste Plastic and Steel Fiber Additives: A Comprehensive Study

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ARTICLE INFO

Article history:

Received : 22 May 2024

Revised : 27 February 2025

Accepted : 3 March 2025

Keywords:

Stone Matrix Asphalt

Waste Polypropylene

Steel fibre

MarshallStability

ABSTRACT

Asphalt concrete is extensively used in road construction due to its superior mechanical properties and long-term durability. This study investigates the effect of steel fiber reinforcement on the performance characteristics of Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) mixtures. The Marshall mix design method was employed to develop SMA mixtures, and the Marshall Stability Test was conducted to determine the optimal steel fiber dosage. Steel fibers were incorporated to improve resistance to rutting and cracking, with the optimal dosage identified as 0.3% of the total mix weight. Furthermore, this study examines the behavior of steel fibers in SMA applications and optimizes the plastic content in AC mixtures. The results indicate that incorporating 2.5% waste plastic enhances AC's workability and handling characteristics compared to conventional mixtures. Additionally, a 3% waste plastic content demonstrated improved drain-down resistance and tensile strength properties, highlighting its potential for performance enhancement in asphalt pavements.

1 Introduction

The increasing demand for sustainable and long-lasting road infrastructure has driven significant advancements in asphalt concrete technology. Stone Matrix Asphalt (SMA) and conventional Asphalt Concrete (AC) are widely used for pavement construction, but their performance limitations—such as moisture susceptibility, rutting, and drain-down—necessitate modification with stabilizing additives [1]. In response, researchers have explored the incorporation of fibers and polymers to enhance the mechanical and durability properties of asphalt mixtures [2]. However, an optimal and sustainable approach to modifying SMA and AC using a combination of waste-derived materials remains an ongoing investigation.

This study evaluates the combined effects of steel fibers and waste polypropylene (PP) plastic as modifiers in SMA and AC mixtures, respectively, focusing on enhancing mechanical properties, durability, and sustainability[3,4]. While SMA is

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inherently resistant to rutting and fatigue cracking due to its gap-graded aggregate structure and high binder content, it suffers from moisture-induced damage and drain-down. The addition of steel fibers has shown promise in mitigating these issues by improving tensile strength, reducing permanent deformation, and enhancing interlocking between aggregates. Previous studies have employed Response Surface Methodology (RSM) to optimize fiber dosage, with an optimum steel fiber content of 0.3% by weight, significantly improving performance. However, limited research has examined the synergistic effect of fiber reinforcement and SMA's aggregate structure in resisting settlement and fatigue cracking, which this study aims to address [5].

Similarly, waste plastic modification of AC has emerged as an environmentally friendly solution to enhance asphalt properties while addressing plastic waste disposal concerns. Studies have demonstrated that incorporating high-density polyethylene (HDPE) and polyethylene terephthalate (PET) improves Marshall Stability and deformation resistance. However, the specific impact of waste polypropylene (PP) plastic on the stiffness, fatigue resistance, and temperature susceptibility of asphalt mixtures remains underexplored. This research systematically evaluates the effectiveness of waste PP plastic as a bitumen modifier in AC, investigating its influence on stability, drain-down resistance, and cracking potential [6].

Novelty of the Research

While previous studies have independently examined fiber-reinforced SMA and waste plastic-modified AC, this study comprehensively evaluates both modifications under different loading and environmental conditions. The novel contributions of this research include A comparative analysis of SMA and AC modifications, establishing a correlation between fiber-reinforced SMA and plastic-modified AC in terms of stability, deformation resistance, and durability. A detailed examination of the mechanisms governing steel fiber and PP plastic modifications, addressing how these additives influence binder interaction, aggregate interlocking, and load-bearing capacity. Previous studies have primarily overlooked an investigation into the settlement resistance and fatigue cracking performance of modified mixtures.

Objectives: (1) To compare the performance characteristics of SMA modified with steel fibers and AC modified with steel fibers, focusing on moisture resistance and permanent deformation. (2) To evaluate the effectiveness of waste PP plastic as a modifier in conventional AC mixtures and compare its performance to unmodified AC.

By addressing these objectives, this study contributes valuable insights into optimizing SMA and AC mixtures for enhanced pavement performance, emphasizing sustainability and utilizing waste materials in modern road construction. The modification of asphalt mixtures using steel fibers and waste polypropylene (PP) plastic fundamentally alters their mechanical behavior and durability characteristics. Steel fiber reinforcement in SMA improves aggregate interlocking, enhances load distribution, and reduces binder drain-down, increasing Marshall Stability and tensile strength. Steel fibers' high tensile strength and modulus of elasticity create a reinforcing network that prevents premature rutting and fatigue cracking. Conversely, waste PP plastic in AC modifies the bitumen's viscoelastic properties, improving stiffness, resistance to deformation, and moisture susceptibility. The interaction between PP plastic and bitumen enhances the adhesive bonding with aggregates, reducing the likelihood of stripping and increasing pavement longevity. This study evaluates these modifications, establishing a direct correlation between material composition and performance enhancement.

2 Literature Review

Pursuing sustainable road construction has increased interest in modifying asphalt mixtures with waste materials, particularly waste plastics and fibers. As the Introduction highlights, SMA and AC mixtures exhibit distinct performance characteristics that can be further enhanced through strategic modification using steel fibers and waste polypropylene (PP) plastic. This section reviews relevant research on the effectiveness of plastic and fiber additives in asphalt mixtures, providing a foundation for the present study's comparative analysis.

Waste Plastic Modification in Asphalt Mixtures

Waste plastics have been extensively studied as potential modifiers for enhancing asphalt pavement durability while addressing environmental concerns related to plastic waste disposal. Several studies have demonstrated that incorporating shredded waste plastics (SWP) into SMA mixtures improves performance, particularly regarding rut resistance and binder stability. One study found that SMA mixtures with 8% SWP (by weight of bitumen) exhibited comparable properties to polymer-modified bitumen (PMB), suggesting that waste plastics can serve as effective stabilizing agents without requiring expensive polymer additives [7]. Similarly, researchers have explored the modification of open-graded asphalt (OGA) mixtures using sisal fiber and waste plastics to reduce binder drain-down and enhance structural integrity. The findings

indicated that these modifications improved moisture damage resistance and reduced road construction's environmental impact [8]. Furthermore, polyethylene terephthalate (PET) waste has been identified as a promising asphalt additive, with studies reporting 6–8% PET incorporation as an optimal range for increasing stiffness and rutting resistance [9].

Another approach to sustainable asphalt modification involves partially replacing virgin bitumen with residual plastic fibers. Research has shown that this method maintains plastic deformation resistance comparable to PMB-based mixtures while enhancing sustainability and mechanical performance [10]. Additionally, investigations into waste plastic-modified asphalt mixtures' stability and volumetric properties have revealed that the optimum bitumen content (OBC) varies depending on the plastic dosage. For instance, adding 4% waste plastic significantly improved Marshall Stability, indicating a stronger and more durable asphalt mixture [11].

However, the effectiveness of plastic modification is dosage-dependent. Studies on multilayer plastic waste in PMB mixtures found that higher plastic concentrations enhanced dispersion properties and negatively affected thermal stability [12,13]. Additionally, research on waste plastic bottle (PET)-modified SMA concluded that 6% PET by bitumen weight was an ideal dosage, leading to enhanced performance and cost-effective utilization of plastic waste [14,15].

Steel Fiber Reinforcement in Asphalt Mixtures

The application of steel fibers in SMA has gained attention due to their ability to enhance mechanical performance, particularly in reducing rutting, increasing tensile strength, and minimizing permanent deformation. Steel fibers interlock with aggregates, providing better resistance against moisture susceptibility and fatigue cracking, which are common concerns in SMA applications. Studies employing Response Surface Methodology (RSM) have optimized steel fiber content at 0.3% by total mix weight, yielding significant improvements in structural integrity and durability [16,17].

Despite these advancements, limited research has directly compared fiber-reinforced SMA and waste plastic-modified AC under varied loading conditions. Additionally, while previous studies have focused on rutting resistance and volumetric stability, aspects such as settlement resistance and fatigue cracking remain underexplored, creating a gap that this study aims to address.

Research Gap and Need for Comparative Evaluation

While individual studies have examined plastic waste incorporation in AC and fiber reinforcement in SMA, limited research directly compares their effects on asphalt mixture performance. Furthermore, the combined influence of steel fibers in SMA and waste PP plastic in AC on mechanical properties, durability, and resistance to cracking has not been systematically evaluated. This study aims to bridge this research gap by conducting a comprehensive performance assessment focusing on stability, moisture resistance, settlement resistance, and fatigue performance in modified asphalt mixtures.

This research contributes to developing optimized, cost-effective, and environmentally friendly pavement solutions by linking laboratory evaluations with sustainability considerations.

3 Materials and Methods

3.1 Materials

The selection of materials plays a critical role in determining the performance of modified Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) mixtures. Based on the findings from previous research, these materials have demonstrated significant potential for enhancing strength, durability, and sustainability in asphalt mixtures. This section details the materials used in this study, including aggregates, fillers, steel fibers, asphalt binders, and waste PP plastic.

3.1.1 Aggregates

Aggregates constitute the structural skeleton of asphalt mixtures and significantly influence their stability, strength, and resistance to deformation. This study follows the Indian Roads Congress (IRC) aggregate grading system, which combines coarse aggregate, fine aggregate, and mineral filler to achieve optimal load distribution and interlocking [18]. The nominal maximum aggregate size (NMAS) of 12.5 mm was used, adhering to IRC specifications. The SMA wearing course thickness was maintained between 40 to 50 mm. Table 1 presents the physical properties of the aggregates used, obtained from COEP's Transportation Engineering Lab.

3.1.2 Fillers

Fillers enhance the cohesion, stability, and resistance to moisture damage in asphalt mixtures. Materials such as fly ash, lime, hydrated lime, stone dust, and cement are commonly used as fillers. However, this study selected stone dust as the filler material due to its proven effectiveness in improving asphalt mix stability. According to IRC: SP:79 [19], the mineral filler should be finely divided matter, and fly ash should not be used as a filler due to its tendency to alter binder adhesion properties.

3.1.3 Steel Fiber

Steel fibers act as reinforcing elements in SMA, preventing excessive deformation and improving mechanical stability. Their inclusion enhances the bonding between bitumen and aggregates, forming a stronger, more rigid network that resists crack initiation and propagation [20]. Additionally, steel fibers reduce binder drain-down, a common issue in SMA, by increasing the surface area available for bitumen absorption. The high modulus of elasticity (11 GPa) and tensile strength (0.95 GPa) of steel fibers contribute to increased Marshall Stability and Indirect Tensile Strength (ITS), making fiber-reinforced SMA more resistant to rutting and fatigue failure. This study utilized superfine steel fibers specifications. Dosage: Varied from 0.3% to 1.2% (with increments of 0.3%) by total aggregate weight, Thickness: 0.025 mm, Density: 7.5 g/cm³.

3.1.4 Asphalt Binder

The asphalt binder is a crucial component in asphalt mixtures, ensuring aggregate cohesion, flexibility, and resistance to aging. This study selected viscosity-grade (VG-30) bitumen for its suitability for high-traffic pavements and resistance to temperature-induced softening. The physical properties of VG-30 bitumen were tested following IS and ASTM standards [21–28], with results summarized in Table 1.

3.1.5 Waste Polypropylene (PP) Plastic

Waste PP plastic modifies the rheological properties of bitumen, increasing its stiffness and reducing its temperature susceptibility. Incorporating PP plastic into AC results in a bitumen-polymer interaction that enhances adhesion between the binder and aggregates, reducing the risk of stripping and moisture-induced damage. PP plastic also improves the cohesive strength of the mix, contributing to higher Marshall Stability and tensile resistance. However, excessive plastic content can lead to stiffness-induced brittleness, negatively affecting the mixture's fatigue resistance. The optimal plastic dosage ensures a balance between stiffness, durability, and resistance to deformation. The waste PP plastic used in this study was sourced from scrap dealers in Pune, primarily collected from discarded industrial food packaging [15]. Since this waste plastic was non-recyclable through conventional means, it underwent milling at 40–45 kg/h, resulting in fragments of 8–9.5 mm in length and 1.5–2.5 mm in width. The material was supplied by Vishal Bio-Tech Pvt Ltd, Pune, a company specializing in plastic waste processing.

Table 1- Mechanical Properties of Aggregate and Binder

Samples	Test	Standards	Vital values IRC: SP: 79	Experiential values (%)
Coarse Aggregate	Impact value	IS2386	Max24%	9.54%
	Abrasion value	IS2386	Max25%	19.23%
	Water absorption	IS2386	Max2%	1.12%
	Elongation and Flakiness index combined	IS2386	Max30%	29.7%
Bitumen	Penetration (1/10 th of mm)	IS1203	50-70	62
	Softening point ring and ball apparatus (°C)	ASTM D5	40-55°C	48.7°C
		ASTM D36		
	Ductility test (cm)	IS1208	>75 cm	80

3.2 Methods

The methodology follows standardized aggregate gradation, sample preparation, and performance testing procedures to ensure an optimized SMA and AC mix design. This section details the gradation of aggregates, an essential parameter for ensuring pavement stability, durability, and load-bearing capacity.

3.2.1 Aggregate Gradation

Achieving an optimal aggregate gradation is critical in asphalt mix design, as it directly influences the pavement's rutting resistance, durability, and overall structural integrity. A well-graded aggregate skeleton ensures proper interlocking between particles, enhancing SMA and AC mixtures' load distribution and performance. In this study, aggregate gradation was designed following the Ministry of Road Transport and Highways (MoRTH) guidelines (2013) [29] and Indian Roads Congress (IRC) 29 specifications [30]. American Association of State Highway and Transportation Officials (AASHTO) MP 8-05 and AASHTO PP41-02 standards [31, 32]. The nominal maximum aggregate size (NMAS) of 12.5 mm was selected to maintain consistency with pavement design requirements. The gradation curve used in this study is presented in Figure 1, demonstrating adherence to the recommended particle size distribution for achieving optimal mechanical interlocking and binder retention [33–36].

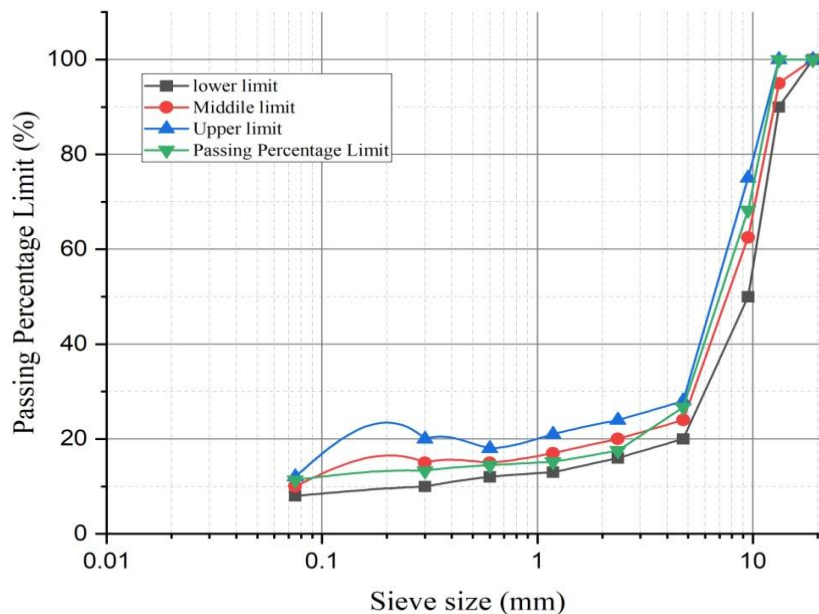


Fig.1- Aggregate Gradation with NMAS=12.5mm for the present study

4 Experimental procedures

The experimental methodology was designed to evaluate the performance characteristics of Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) mixtures modified with steel fibers and waste polypropylene (PP) plastic, respectively. The procedures followed standardized testing protocols to ensure reproducibility, accuracy, and relevance to real-world pavement applications.

4.1 Mix Design and Sample Preparation

The mix design was developed based on the guidelines outlined by Brown and Cooley [37] in the *National Asphalt Technology Report* and IRC: SP: 79-2008. The compaction method for SMA followed the recommendations of Brown and Mallick [38], which suggested rotational compression to simulate field compaction conditions. Their findings indicated that the air void distribution obtained through rotational compaction closely aligned with that achieved using the Marshall

Stability Test (MST) with 50 compaction blows per face. Waste polypropylene (PP) plastic was incorporated as a bitumen modifier for AC mixtures. The bitumen and granular waste PP plastic were preheated to approximately 180°C before undergoing thorough mixing to ensure uniform dispersion. The modified binder was then blended with aggregates, and specimens were prepared for Marshall Stability and Indirect Tensile Strength (ITS) testing, with results summarized in Tables 2 and 3.

Mix Design Approach

The Marshall Mix Design method was employed for SMA mixtures, with the experimental program divided into two key phases. First, determination of Optimum Binder Content (OBC): SMA specimens were prepared to determine the OBC following IRC: SP: 79-2008 recommendations. Second Modification with Steel Fibers: Using the determined OBC, SMA mixtures were further modified with steel fibers, and their mechanical performance was assessed. For specimen preparation, cylindrical samples (101.6 mm diameter, 63 ± 2.5 mm height) were compacted using a Marshall hammer, applying 50 blows per face.

Mixing and Compaction Process

- Aggregates (coarse and fine) were preheated to 150°C before mixing.
- Heated bitumen was added to the aggregate blend, followed by thorough manual mixing to ensure uniform coating.
- The loose mixture was then compacted at 150°C using the Marshall compactor.

Material Proportions

- Bitumen Content: Varied from 5.5% to 7% (by total aggregate weight) in 0.5% increments for the control mix (using stone dust as a filler).
- Steel Fiber Content: Incorporated at 0.3%, 0.6%, 0.9%, and 1.2% of the total aggregate weight. These dosages were selected to analyze their impact on stability, flow, voids, and durability.

Sample Replication and Testing

Three replicate specimens weighing approximately 1,200 g were prepared for each mix design variation to ensure statistical reliability. Once the OBC was established, additional specimens were fabricated for Indirect Tensile Strength (ITS) testing, assessing their resistance to cracking and tensile failure.

4.2 Testing Methods

A series of laboratory tests were conducted to evaluate the performance characteristics of the modified Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) mixtures. These tests assess key properties such as drain-down resistance, stability, moisture susceptibility, and tensile strength, ensuring compliance with standardized methodologies.

4.3 Drain-Down Test

The Schellenberg drain-down test (ASTM D6390)[39] measures the susceptibility of asphalt mixtures to binder separation under the influence of gravity and high temperatures. This test provides insight into the stability and cohesion of the asphalt mixture and its long-term performance. The drain-down percentage is critical, as excessive binder loss can weaken pavement structures. This study conducted the drain-down test on mixtures containing fillers, fibers, and binders. Results showed that mixtures without fillers and fibers exhibited higher drain-down, whereas adding stone dust and steel fibers significantly reduced binder loss. This reduction is attributed to the increased surface area of the filler and fibers, which enhances binder retention. The recorded drain-down values remained below the 0.3% limit of IRC: SP-79 (2008), confirming adequate mix stability. Figure 2 illustrates the testing setup and binder retention characteristics.



Fig.2 - Drain down testing setup and binder retention.

4.3.1 Marshall Stability Test

The Marshall Stability Test (ASTM D6926, ASTM D6927) [40, 41] is widely used for evaluating the strength and flow properties of asphalt mixtures. This method helps determine the optimum binder and fiber content required to achieve maximum load-bearing capacity while maintaining structural integrity.

Marshall specimens were prepared for this study using the specified aggregate gradation (Figure 1). Each 101.6 mm diameter, 63 ± 2.5 mm height specimen was compacted with 50 blows per face using a Marshall hammer. The stability of the mix was defined as the maximum load it can sustain before failure, while flow referred to the deformation at the point of failure. These values were used to evaluate the resistance of modified SMA and AC mixtures to deformation and permanent rutting.

4.3.2 Boiling Water Test

The Boiling Water Test (ASTM D36) [42] assesses the moisture susceptibility of asphalt mixtures by measuring the stripping degree—the adhesion loss between the asphalt binder and aggregate due to water exposure. In this test, a 250 g oven-dried sample, passing through a 20 mm sieve but retained on a 12.5 mm sieve, was heated to 170°C before being combined with 17 g of bitumen to 150°C . The mixture was allowed to cool to $70\text{--}100^{\circ}\text{C}$, after which boiling water was added, and the sample was observed for 10 minutes. The percentage of stripped binder was recorded as the stripping value.

The results indicated that AC mixtures modified with waste PP plastic exhibited lower stripping values than unmodified AC mixtures, suggesting improved moisture resistance. According to MoRTH standards, the stripping value should not exceed 5%. In this study, Unmodified AC mixtures recorded a stripping value of 3.5%. PP-modified AC mixtures had stripping values ranging from 0% to 4.5%, depending on the plastic content (1.5%–3.5%). These results confirm that waste PP plastic enhances moisture resistance, reducing susceptibility to water-induced damage.

4.3.3 Indirect Tensile Strength Test

The Indirect Tensile Strength (ITS) Test (ASTM D6931) [43,44] measures the tensile resistance of asphalt mixtures, which is critical for assessing fatigue cracking and structural durability. The test involves applying a compressive load along a diametric plane, inducing tensile stress perpendicular to the applied load, leading to specimen failure. For this study, specimens (100 mm diameter, 63 ± 2.5 mm height) were prepared using the Marshall mix design. A loading rate of 51 mm/min was applied until failure. The peak load was recorded, and the ITS was calculated using a standard geometric correction factor to calculate the indirect or split tensile strength using the following equation: 1. ITS results provide insight into the tensile performance of the modified mixtures, with higher ITS values indicating better resistance to cracking and improved durability.

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

Where;

t = Specimen height immediately before test, mm

P =Maximum load, N

D=Specimen diameter, mm

St =IDTstrength, KPa

5 Results and Discussions

The performance evaluation of SMA and AC mixtures was conducted by varying the bitumen content from 5.0% to 7.5% (in 0.5% increments). The optimum binder content (OBC) was determined for each mix based on stability, volumetric properties, and mechanical performance. Figures 3–10 illustrate the key trends and comparative analysis, while Tables 2 and 3 present the corresponding numerical findings.

5.1 Marshall Stability and Flow Analysis

The Marshall Stability Test (MST) is a key performance indicator for asphalt mixtures, measuring their load-bearing capacity and resistance to deformation. The results for SMA and AC mixtures are presented in Tables 2 and 3, detailing stability values, flow rates, and volumetric properties such as air voids (Va), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB). The MST results for SMA mixtures modified with steel fiber. The control SMA mix (without fiber or filler) exhibited a stability value of 12.8 kN at 7.2% binder content. The increase in Marshall Stability observed in steel fiber-modified SMA mixtures (24.22% improvement) can be attributed to the reinforcing effect of steel fibers, which create a more interconnected aggregate structure that resists external loading. The enhanced load transfer and interlocking properties of fibers improve the overall structural integrity of SMA. Increasing fiber content beyond 0.3% (0.6%, 0.9%, and 1.2%) resulted in a gradual decrease in MST, suggesting that excessive fiber addition leads to fiber clustering and reduced compaction efficiency. Flow values for fiber-modified SMA ranged between 2.80 mm and 3.90 mm, remaining within the permissible limits (2–4 mm, MoRTH 2013). Similarly, AC modified with 2.5% waste PP plastic demonstrated a 26.11% increase in MST, confirming that bitumen-plastic interactions improve adhesion and stiffness. However, when the plastic content exceeded 3%, MST values declined due to excessive stiffening and reduced flexibility, increasing brittleness. Beyond 2.5% plastic content, stability decreased, suggesting that excessive plastic modification may reduce aggregate cohesion and increase stiffness susceptibility. Flow values ranged between 2.4 mm and 4.0 mm, confirming that plastic-modified AC maintains deformation resistance without excessive rigidity.

Figure 3 shows the Marshall Stability results for AC modified with waste polypropylene (PP) plastic. The highest MST value was recorded at a bitumen content of 6.3% with 2.5% waste PP plastic (by weight of bitumen). The results indicate that adding waste PP plastic enhances the structural integrity of the asphalt mix, improving its load-bearing capacity and resistance to plastic deformation.

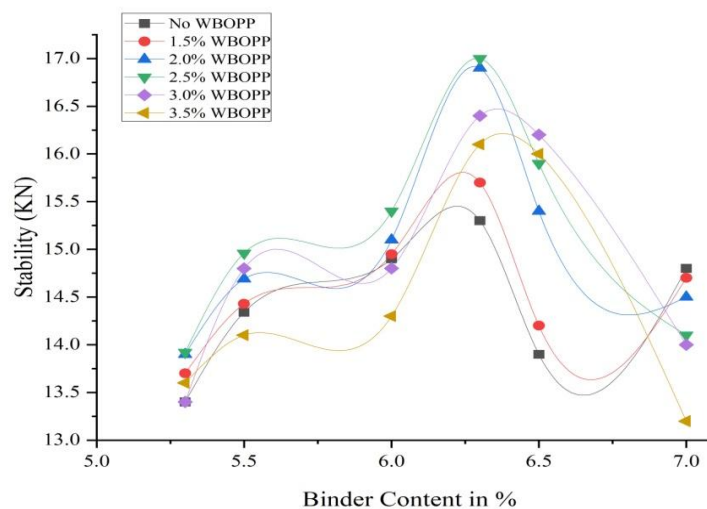


Fig.3 - MS for AC by PP modification

Figure 4 demonstrates the influence of steel fiber and filler content on MST in SMA mixtures. The highest MST was observed at 6.3% bitumen content with 0.3% steel fiber (by total mix weight). The reinforcement effect of steel fibers improves the interlocking between aggregates, leading to higher load resistance and reduced susceptibility to deformation.

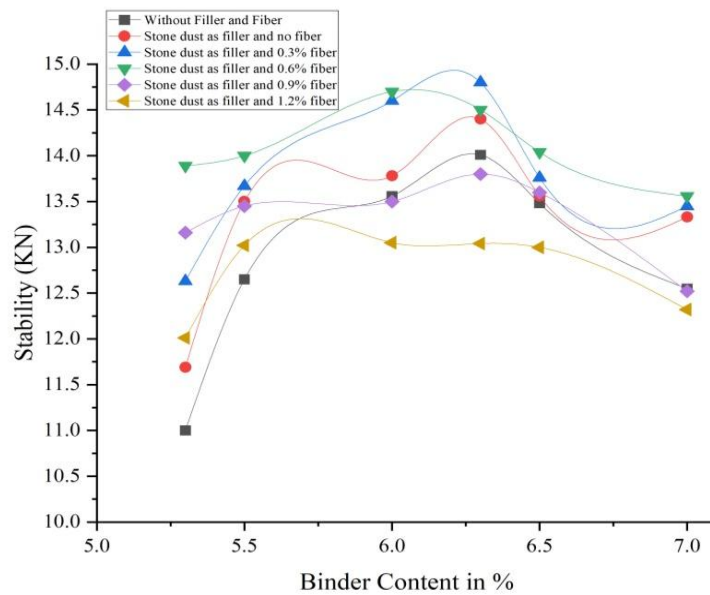


Fig. 4 - MS for AC altered by Fiber

Figures 5 and 6 illustrate the flow values for fiber-modified AC and waste PP plastic-modified AC. The flow values remained within the permissible range (2–4 mm) as per MoRTH (2013). Steel fiber modification reduced flow values, indicating a stiffer mix due to increased fiber-matrix interaction and improved cohesion. Conversely, PP plastic-modified AC exhibited a more controlled flow variation, suggesting that waste plastic contributes to improved workability without excessive stiffness. According to IRC SP:79, SMA mixtures must have a minimum VMA of 17%.

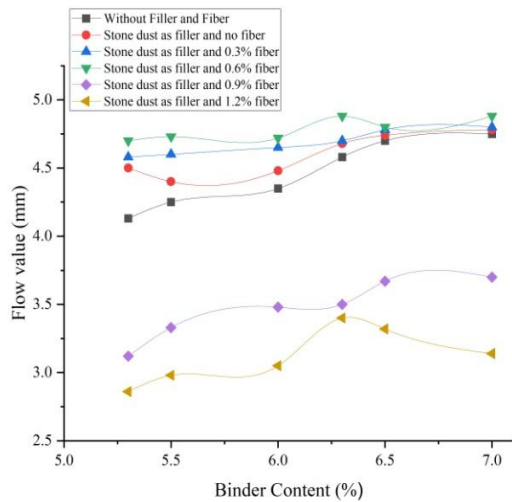


Fig. 5 - Flow values for AC by PP modification

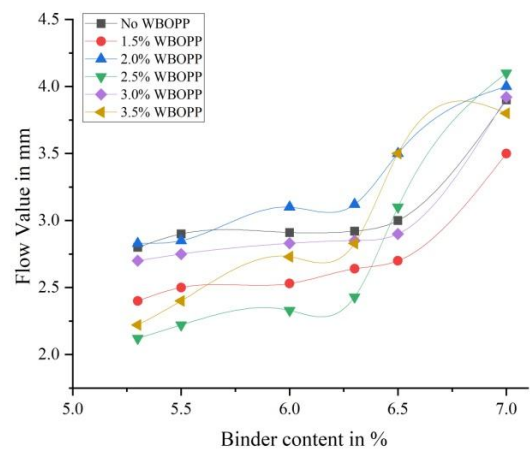


Fig. 6 - Flow values for AC altered by Fiber

Figures 7 and 8 show that all fiber- and plastic-modified mixes meet this requirement. Higher VMA values were observed in steel fiber-modified SMA, confirming improved aggregate packing and binder retention. The results align with Brown et al.'s (1997a, b) findings, demonstrating that fibers act as stabilizers, preventing excessive binder drain-down and ensuring mix durability.

Higher VFB values observed in modified mixtures (Tables 2 and 3), confirming improved bitumen adhesion and reduced permeability. Air Voids (Va): The air void content remained within permissible limits (3–5%), ensuring adequate compaction and long-term durability. Steel fiber-modified SMA showed lower air voids than plastic-modified AC, indicating better aggregate interlocking and binder stabilization.

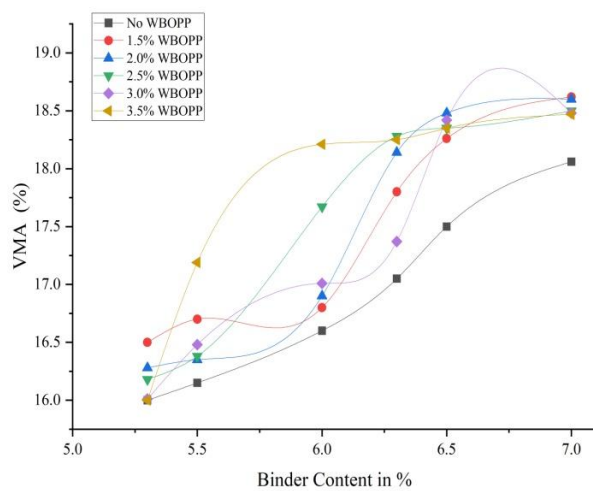
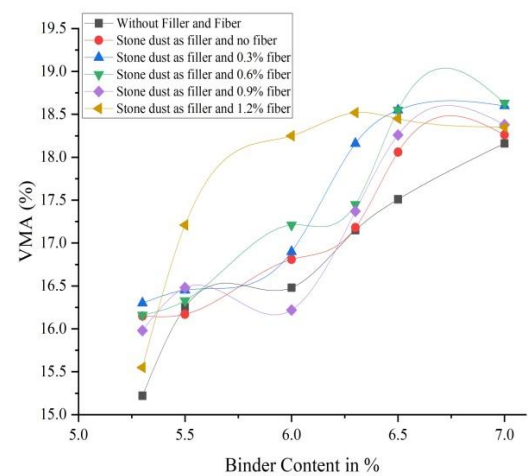
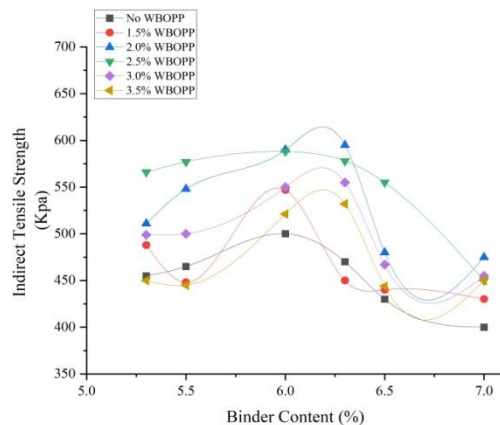
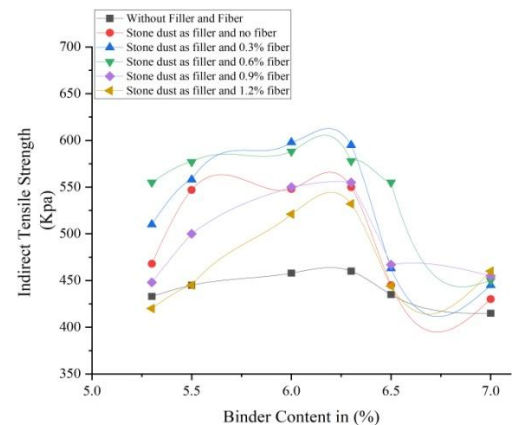
Table 2 - Test results of SMA and AC Mix

Bituminous mix test sample	Engineering and statical parameter	Without Filler and Fiber	Stone dust as filler and no fiber	Stone dust as filler and 0.3% fiber	Stone dust as filler and 0.6% fiber	Stone dust as filler and 0.9% fiber	Stone dust as filler and 1.2% fiber
ForSMA 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
	Mean	12.750	13.025	15.775	15.475	14.750	14.275
	Standard deviation	0.112	0.228	0.228	0.259	0.335	0.249
	Standard error	0.056	0.114	0.114	0.129	0.168	0.124
	Drain down at OBC (%)	1.39	0.45	0.22	0.18	0.12	0.11
	Mean	1.35	0.43	0.22	0.17	0.12	0.10
	SD	0.050	0.016	0.008	0.006	0.007	0.011
	SE	0.025	0.008	0.004	0.003	0.004	0.006
	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
	SD	0.037	0.043	0.024	0.125	0.066	0.078
	SE	0.022	0.025	0.014	0.072	0.038	0.045
	VMA (%)	18.98	18.8	18.62	18.25	17.8	17.49
	Mean	18.727	18.783	18.622	18.201	17.685	17.323
	SD	0.197	0.024	0.045	0.056	0.091	0.122
	SE	0.114	0.014	0.026	0.032	0.052	0.071
	VFB (%)	74.36	75.61	76.91	76.99	76.97	78.27
	Mean	74.287	75.503	76.410	76.962	76.955	78.170
	SD	0.066	0.218	0.481	0.047	0.044	0.193
	SE	0.038	0.126	0.278	0.027	0.025	0.111
	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
For 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
	Mean	13.087	13.520	14.420	14.430	15.190	14.233
	SD	0.098	0.351	0.348	0.177	0.290	0.170
	SE	0.057	0.203	0.201	0.102	0.168	0.098
	Flow values	4.00	3.40	3.60	3.10	3.67	2.60
	Mean	3.947	3.410	3.617	3.184	3.630	2.617
	SD	0.050	0.070	0.209	0.103	0.057	0.024
	SE	0.029	0.040	0.120	0.060	0.033	0.014
	VMA (%)	18.02	18.84	19.6	18.78	18.98	19.23
	Mean	17.780	18.720	19.640	18.700	18.773	19.250
	SD	0.312	0.275	0.263	0.267	0.307	0.022
	SE	0.180	0.159	0.152	0.154	0.177	0.012
	VFB (%)	67.68	70.21	72.1	74.14	73.17	75.12
	Mean	67.413	70.257	71.767	74.180	72.579	75.183
	SD	0.296	0.589	0.403	0.166	0.478	0.285
	SE	0.171	0.340	0.233	0.096	0.276	0.165
	Air voids (%)	5.46	5.87	5.65	4.91	5.15	3.81
	ITS (kPa)	420	474	498	497	504	514

Note SD- Standard Deviation, SE- Standard error, VFB- Voids filled with bitumen.

Table 3 Test results of AC Mix modification of PP Plastic

Engineering and statical parameter	No WPP	1.5% WPP	2.0% WPP	2.5% WPP	3.0% WPP	3.5% WPP
Binder content (%)	5.3	5.5	6.0	6.3	6.5	7.0
Stability (kN)	13.4	14.34	15.1	16.9	16	14
Flow values	2.8	2.5	3.1	2.43	2.9	2.4
VMA (%)	18.06	18.62	18.84	17.67	16.48	18.21
Air voids filled by bitumen (%)	67.76	72.26	75.75	71.98	74.21	71.19
Air voids (%)	5.64	5.24	4.48	4.85	4.45	5.17
ITS (kPa)	455	547	598	578	621	523

**Fig. 7 - VMA in AC modified with WPP.****Fig. 8 - VMA for AC altered by Fiber****Fig. 9 - ITS for AC modified with WPP****Fig. 10 - ITS for AC modified with fiber**

5.2 Indirect Tensile Strength Analysis

The Indirect Tensile Strength (ITS) test (ASTM D6931) evaluates the asphalt mixtures' tensile resistance and cracking susceptibility. It is a crucial parameter for assessing thermal cracking resistance, fatigue life, and structural integrity. A higher ITS value indicates an asphalt mixture's ability to resist tensile stresses induced by temperature fluctuations and traffic loads. The ITS values for SMA mixtures modified with steel fiber were evaluated at 25°C, with results presented in Figure 10 and Table 2. Steel fiber-modified SMA exhibited higher ITS values than unmodified SMA, confirming the reinforcement effect

of fibers in improving tensile strength and crack resistance. The highest ITS value was recorded at 0.3% fiber content, beyond which ITS values declined due to fiber clustering and reduced bitumen-fiber interaction. The ITS results for AC mixtures modified with waste PP plastic are shown in Figure 9 and Table 3. The improvement in ITS values for steel fiber-modified SMA (18.57% increase) confirms that fiber reinforcement enhances tensile resistance and crack-bridging effects. Steel fibers distribute tensile stresses more effectively, delaying crack propagation and improving fatigue resistance. The ITS values of PP plastic-modified AC mixtures increased by 8%, indicating improved bitumen cohesion and resistance to tensile failure. However, ITS values declined at plastic contents exceeding 3% due to excessive stiffening, reduced ductility, and increasing susceptibility to premature cracking. These findings highlight the importance of optimizing fiber and plastic content to balance strength, durability, and flexibility.

Both modifications demonstrated optimal ITS improvements at specific dosage levels (0.3% steel fiber and 2.5% PP plastic), beyond which performance declined. The findings confirm that modifying asphalt mixtures with steel fiber and waste PP plastic can significantly enhance tensile properties, making them suitable for applications requiring improved cracking and fatigue failure resistance.

5.3 Evaluation of Fiber-Modified SMA and AC

Figure 11 presents the MST results for SMA and AC mixtures modified with 0.3% steel fiber and stone dust as filler. The results indicate that fiber-modified SMA exhibited a higher MST value than fiber-modified AC, confirming its superior load-bearing capacity and structural stability. The improved stability in fiber-reinforced SMA is attributed to enhanced aggregate interlocking, fiber reinforcement, and better load distribution.

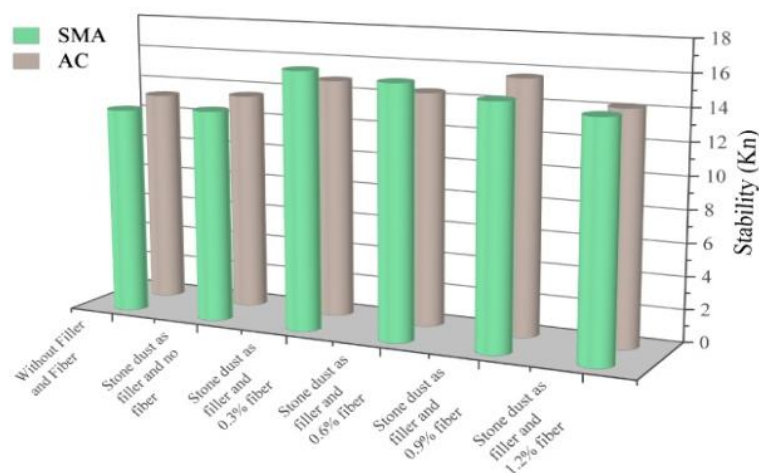


Fig. 11 - Evaluation of MS among AC and SMA

Figure 12 compares the flow values of SMA and AC mixtures, representing the deformation under applied loads. The results show that SMA mixtures exhibited lower flow values (ranging between 2–4 mm, as per MoRTH standards), indicating higher resistance to permanent deformation. In contrast, AC mixtures demonstrated relatively higher flow values, suggesting a more flexible but less deformation-resistant structure. The reinforcing effect of fibers in SMA reduces excessive flow, ensuring a stiffer and more durable pavement mix.

Figure 13 illustrates the ITS comparison between SMA and AC mixtures modified with fiber reinforcement. The higher ITS values recorded in SMA confirm its superior resistance to cracking and tensile failure. AC mixtures exhibited lower ITS values, indicating that fiber reinforcement improves cracking resistance, but it is less effective in AC than SMA. The structural rigidity and higher binder content of SMA, combined with fiber reinforcement, contribute to enhanced tensile strength and long-term pavement durability.

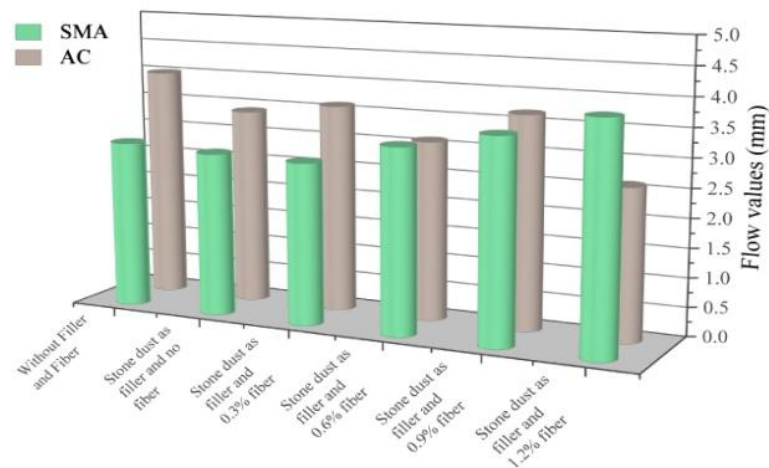


Fig. 12 - Evaluation of Flow values among AC and SMA

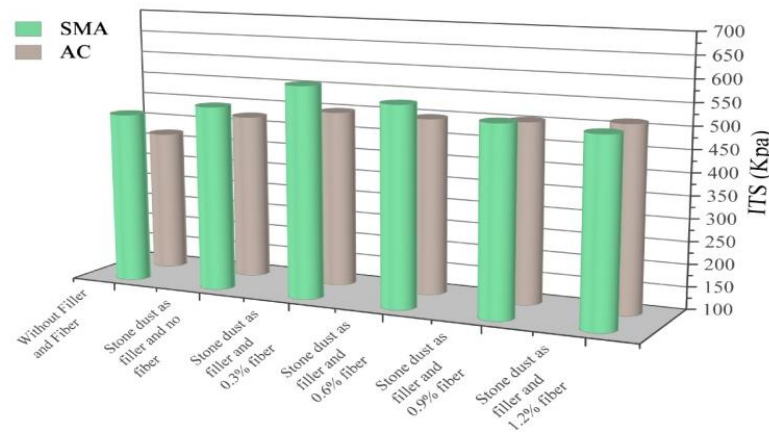


Fig. 13 - Evaluation of ITS among AC and SMA

6 Conclusions

This study evaluated the performance of Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) mixtures modified with steel fiber and waste polypropylene (PP) plastic, focusing on stability, tensile strength, deformation resistance, and durability.

The optimal binder content (OBC) was determined to be 6.3% for both SMA and AC mixtures, based on the Marshall Stability Test (MST) and volumetric properties.

Steel fiber modification (0.3% by weight) significantly improved SMA performance, enhancing Marshall Stability by 24.22% and Indirect Tensile Strength (ITS) by 18.57%, confirming its effectiveness in increasing resistance to permanent deformation and cracking.

AC mixtures modified with 2.5% waste PP plastic exhibited a 26.11% increase in MST and an 8% increase in ITS, indicating improved stiffness and durability. However, excessive plastic content (>3%) reduced ITS, suggesting an optimal dosage threshold.

Flow values for all modified mixtures met MoRTH and IRC: SP: 79 standards, ensuring adequate workability and structural integrity.

Modifying waste PP plastic improved the mechanical properties of AC, contributing to better resistance against plastic deformation and increased service life.

Modified mixtures exceeded MoRTH's stability requirements ($MSN > 9 \text{ kN}$), allowing for potential reductions in bitumen content, cost savings, and enhanced sustainability.

Incorporating waste plastics and steel fibers in asphalt mixtures promotes eco-friendly pavement solutions, reducing plastic waste disposal issues while enhancing pavement longevity and performance.

This research highlights the technical feasibility and practical benefits of modifying asphalt mixtures with steel fibers and waste PP plastic. Future studies should explore long-term field performance, rutting resistance, fatigue behavior, and optimal fiber-polymer combinations to maximize the benefits of sustainable pavement materials.

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