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Evaluating Performance of Stone Mastic Asphalt Including Waste Steel Fibers

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Abstract

Generally, Stone Mastic Asphalt (SMA) mixtures are applied in heavy pavements because of their resistance to rutting and durability. The SMA performance is governed by material properties, mixture design limits and the interaction between aggregate and asphalt mastic. Volumetric mix-design methods do not always accurately reflect the behavior of SMA mixtures under actual traffic loading. Therefore, performance-based approaches such as Balanced Mix Design (BMD) are increasingly being used to evaluate asphalt mixtures. In this study, the performance of SMA mixtures reinforced with waste steel fibers (WSF) was examined using performance indicators such as cracking resistance, rutting resistance, and durability. The BMD framework was applied as a guiding evaluation methodology to assess the overall mixture response. Four WSF contents as 1.25%, 2.50%, 3.75%, and 5.0% by binder weight, were studied. Laboratory work included measuring for cracking and rutting indices using the Cracking Tolerance Index (CT-Index) and Rutting Tolerance Index (RT-Index), volumetric and durability properties (Tensile Strength Ratio (TSR) and Cantabro Abrasion Loss (CAL)). The results indicated the binder content (6.2%) provided balanced resistance for all indices of the SMA mixture. Moreover, incorporating WSF at 2.5% improved the performance with increases 17.8% in CT-Index, 48.2% in RT-Index, and 18.6% in TSR with reductions in unaged and aged CAL of 75.6% and 44.0%, respectively. The results highlight that WSF effectiveness depends strongly on fiber dosage, enhancing SMA performance, durability, and pavement sustainability.

Keywords: Balanced mix design; cracking tolerance index; durability; rutting tolerance index; stone mastic asphalt; waste steel fibers.

1. Introduction

For heavy pavement applications, Stone Mastic Asphalt (SMA) mixtures are well known for their superior resistance to rutting and long-term durability. Despite these advantages, one of the key factors limiting SMA performance is its susceptibility to moisture damage. Moisture at the binder–aggregate interface reduces mixture cohesion and weakens adhesive bonding, promoting stripping and debonding mechanisms. Consequently, SMA pavements may gradually lose structural integrity, with early signs of degradation such as raveling and cracking [1, 2]. From a mixture design perspective, SMA is characterized by a gap-graded aggregate structure that promotes stone-on-stone contact, typically combined with a relatively high binder content (6–8%) and stabilizing fibers (0.3–1.0%) to prevent drain-down during production and placement [3, 4]. Although this structural configuration enhances rutting resistance, it also increases susceptibility to moisture-related damage if not properly stabilized. Consequently, significant research efforts have focused on the use of modifiers to improve both mechanical performance and durability, with fiber reinforcement emerging as one of the most effective approaches. Previous studies indicate that the incorporation of steel fibers significantly enhances the mechanical performance and durability of SMA. These improvements are generally reflected in increased mixture stability, enhanced rutting and cracking resistance, and reduced abrasion loss. From a mechanistic perspective, these benefits are primarily attributed to stress redistribution and crack-bridging mechanisms within the asphalt matrix, which enhance load transfer and delay crack propagation [5]. Experimental findings consistently show that steel fibers improve key performance indicators, including Marshall stability, indirect tensile strength, and tensile strength ratio (TSR), particularly at moderate fiber dosages [6, 7]. For example, Abd and Latief (2024) reported that a steel fiber content of 0.25% increased Marshall stability by approximately 16% and improved TSR by about 10% compared to the control mixture. Similarly, reductions in abrasion loss and improvements in moisture resistance have been observed with increasing fiber content. However, the effectiveness of steel fiber reinforcement is highly dependent on fiber content and dispersion. While moderate fiber dosages generally lead to performance improvements, excessive fiber content may result in agglomeration, reduced mixture homogeneity, and performance deterioration [5,8]. This indicates the existence of an optimum fiber content that balances reinforcement benefits with potential adverse effects, emphasizing the importance of performance-based mixture design approaches.

This study hypothesizes that the incorporation of waste steel fibers (WSF) into SMA enhances cracking resistance, rutting resistance, and durability under realistic loading and environmental conditions. Despite the growing body of research on fiber-reinforced asphalt mixtures, limited studies have systematically investigated the integration of waste steel fibers within a performance-based Balanced Mix Design (BMD) framework. Moreover, the application of BMD incorporating steel fibers remains largely unexplored, particularly under local environmental and traffic conditions. Unlike conventional mix design approaches that rely on volumetric parameters, this study adopts a performance-based BMD framework integrating cracking tolerance index (CT-index) and rutting resistance index (RT-index) as key indicators to evaluate mixture behaviour under realistic conditions. Furthermore, this research contributes to the first attempts to apply this approach in Iraq, aiming to provide a practical and sustainable framework for optimizing SMA mixtures.

2. Materials

In this research, the unmodified and modified SMA mixtures were formed by using aggregates, filler, bitumen, and WSF. These sections provide an extensive outline of the characteristics of these materials.

2.1 Virgin Aggregate

Virgin aggregate is considered the main part of the SMA mixture, which was obtained from a nearby quarry and separated into coarse and fine fractions in accordance with the required gradation specifications, AASHTO M325 [9], as shown in Table 1, which presents the selected Job Mix Formula percentages. The use of a gap-graded aggregate structure has been adopted because it is an attribute of Stone Mastic Asphalt (SMA) mixtures that promotes contact between stones and offers better resistance to rutting. Table 2 describes the physical properties of coarse and fine aggregates. In addition, two forms of filler were used: Conventional Mineral Filler (CMF) and Ordinary Portland Cement (OPC). OPC, obtained from a factory in Karbala, was added to the mixture at a percentage of 2.5% of its weight, while CMF, a fine material that passes through a No. 200 sieve, was added at a percentage of 7%. Table 3 describes the physical properties of filler material.

Table 1: Gradation of Virgin Aggregate for Gap-graded AASHTO M325 [9].

Sieve or Particle Size(mm)	% Passing Material	Selected JMF (%)
19.0	100	100
12.5	90-100	95
9.5	50-80	65
4.75	20-35	27.5
2.36	16-24	20
75 μ m	8-11	9.5

Table 2: Physical properties of Virgin Aggregate for Gap-graded AASHTO M325 [9].

Coarse Aggregate			
Property	Value	Standard of Tests	Limits
Bulk specific gravity (gm/cm ³)	2.595	ASTM C127 [10]	-
Water absorption of aggregate (%)	2.1	ASTM C128 [11]	5 Max
Percent loss by Los Angeles Abrasion, %	28	ASTM C131[12]	30% Max
Crushed Content, percent - One Face	100	ASTM D 5821[13]	100 Min
Crushed Content, percent - Two Face	95	ASTM D 5821	90 Min
Fine-grained aggregate			
Bulk specific gravity of aggregate(gm/cm ³)	2.611	ASTM C127	-
Water absorption of aggregate (%)	1.874	ASTM C128	-
Liquid Limit, percent	Non-plastic	AASHTO T89[14]	25 Max
Plasticity Index, percent	Non-plastic	AASHTO T 90[15]	Non-plastic

Table 3: Morphology Properties of the Utilized Fillers.

Physical Properties of Fillers		
Properties	Filler Type	
	CMF	OPC
Specific Surface Area (m²/kg)	225	410
Density (gm./cm³)	2.610	2.987
Chemical Properties (XRF)		
SiO₂	81.15	24.91
Al₂O₃	3.78	2.324
Fe₂O₃	1.92	1.125
CaO	6.37	64.148
MgO	2.90	1.326
K₂O	0.73	0.760
Na₂O	0.19	1.714

2.2 Bitumen

The grade 60/70 binder utilized in this study was obtained from the Karbala refinery. Table 4 displays the physical properties of the bitumen that was chosen. In SMA, hard or bitumen-modified asphalt is recommended; however, such soft bitumen is uncommon. After adding a fiber, it was proposed that the final brittleness be prevented.

Table 4: The physical properties of bitumen.

Property	Test Values	ASTM Designation	Limits
Penetration, 1/10 mm, 100 gm., 25 °C, 5sec	64	ASTM D5 [16]	60-70
Specific Gravity (gm/ cm3) , 25 °C	1.03	ASTM D70 [17]	-
Ductility, 5 cm/min (cm), 25 °C	145	ASTM D113 [18]	>100
Flash Point, (°C)	285	ASTM D92 [19]	>232
Softening Point (°C)	47.5	ASTM D36 [20]	-
Rotational viscosity	3. 135(590) 4. 150 (285) 5. 165 (162.5)	ASTMD 4402/D4402M [21]	≤ 3000 centistokes

2.3 Waste Steel Fiber (WSF)

In this research, WSF was utilized as a modifier for the SMA mixture, which was incorporated into the SMA mixture using the dry process to ensure uniform distribution. It was obtained and prepared from local factories, extracted from waste tires, serving as a sustainable and cost-effective additive for SMA mixtures. Previous studies have indicated that an optimum steel fiber content of approximately 5% by binder weight can significantly enhance the performance of asphalt mixtures [22, 23]. Accordingly, in this study, 5% WSF was selected as the upper limit to capture the maximum reinforcing effect. In

addition, lower fiber contents (1.25%, 2.5%, and 3.75%) were included to represent a gradual increase in fiber dosage, enabling a systematic evaluation of mixture behaviour from low to high reinforcement levels. This range allows identification of the optimum fiber content as well as assessment of potential adverse effects at higher dosages, such as fiber agglomeration, poor coating, and reduced workability. The used WSFs are shown in Figure 1, and their features are listed in Table 5.



Figure 1: WSF extracted from discarded tires and prepared for use in SMA mixtures.

Table 5: Properties of the used WSF.

Property	Unit	Value
Length*	mm	20-30
Diameter*	mm	0.34
Aspect Ratio*	-	15
Unit weight	g/cm ³	7.2
Tensile strength	MPa	2600
Tensile modulus	GPa	200

**These properties are identified using the 85th value from the tested fiber samples*

3. Design Methods

This study employed the BMD method to design SMA mixtures in accordance with AASHTO PP 105 [24], as described below. The BMD method utilized in this work corresponds to Approach B, where the combination selection depends on fulfilling various performance-based acceptability criteria. Cracking resistance, rutting performance, and durability indices were jointly evaluated to determine the optimal binder and WSF dosage. Figure 2 displays a flowchart that summarizes the experimental investigation.

1. Initially, the aggregates and bitumen were selected to design the SMA mixture in accordance with the previously defined properties and target gradation.
2. Specimens were prepared at various bitumen percentages using a Marshall compactor or a vibration compactor, as illustrated in Figure 3. The Marshall compactor is used to prepare

specimens with a diameter of 101.6 mm for various indices such as TSR and Cantabro loss. In comparison, a vibration compactor is used to prepare specimens with a diameter of 150 mm for some indices such as CT-index, RT-index and ITS. Through several preliminary trials, the compaction time required to achieve a desired air void content of $7\% \pm 0.5\%$ was determined. After three trials, the air void specification was met, resulting in a target compaction time of approximately 2.6 minutes.

3. The bulk density, air voids, and voids in mineral aggregate (VMA), and void fill bitumen (VFB) as volumetric characteristics were evaluated to check the desired air void content of $7\% \pm 0.5\%$, as well as the drain-down test to assess mixture stability.
4. Performance indices characteristics were accomplished on the compacted specimens, where the CT-Index was utilized to assess cracking resistance, the RT-Index to measure rutting resistance, and both the TSR and CALT to determine durability for the SMA mixture.
5. The bitumen content that achieves balanced resistance to both cracking and rutting was recognized as the optimum asphalt content. Therefore, asphalt mixtures containing 5.0%, 5.5%, 6.0%, 6.5%, and 7.0% bitumen were prepared. A total of 75 compacted specimens were fabricated, with 15 specimens for each asphalt content, to evaluate the CT-Index, RT-Index, and durability indices. Furthermore, 15 loose mixture samples were prepared to examine the drain-down behavior. Table 6 summarizes the volumetric and performance requirements that the developed SMA mixture was designed to meet, in accordance with AASHTO M325 specifications. It should be noted that these specification limits are based on standard mixture design conditions (approximately 4% air voids). However, performance tests (RT-index and CT-index) were conducted at a target air void content of $7.0 \pm 0.5\%$, following the Balanced Mix Design (BMD) approach.
6. Also, the next step comprised determining the optimum Content of WSF. The evaluation included a series of performance tests, including the CT-Index, RT-Index, and durability tests, such as CALT and the TSR.

Table 7 summarizes the composition and testing program of the SMA mixtures, including WSF dosage, binder content, number of specimens, and laboratory tests conducted. The selected WSF contents (0%, 1.25%, 2.5%, 3.75%, and 5%) were chosen to represent a progressive range from low to high fiber dosages, allowing systematic evaluation of performance trends and identification of the optimum fiber content. This range was selected based on previous studies and to capture both the reinforcing effect at moderate dosages and the potential adverse effects at higher concentrations, such as fiber agglomeration and reduced coating efficiency. For each SMA–WSF mixture, 15 specimens were prepared. Performance-related specimens were compacted using a vibratory compactor to achieve a target air void content of $7.0 \pm 0.5\%$, while durability-related specimens were compacted using the Marshall compactor.

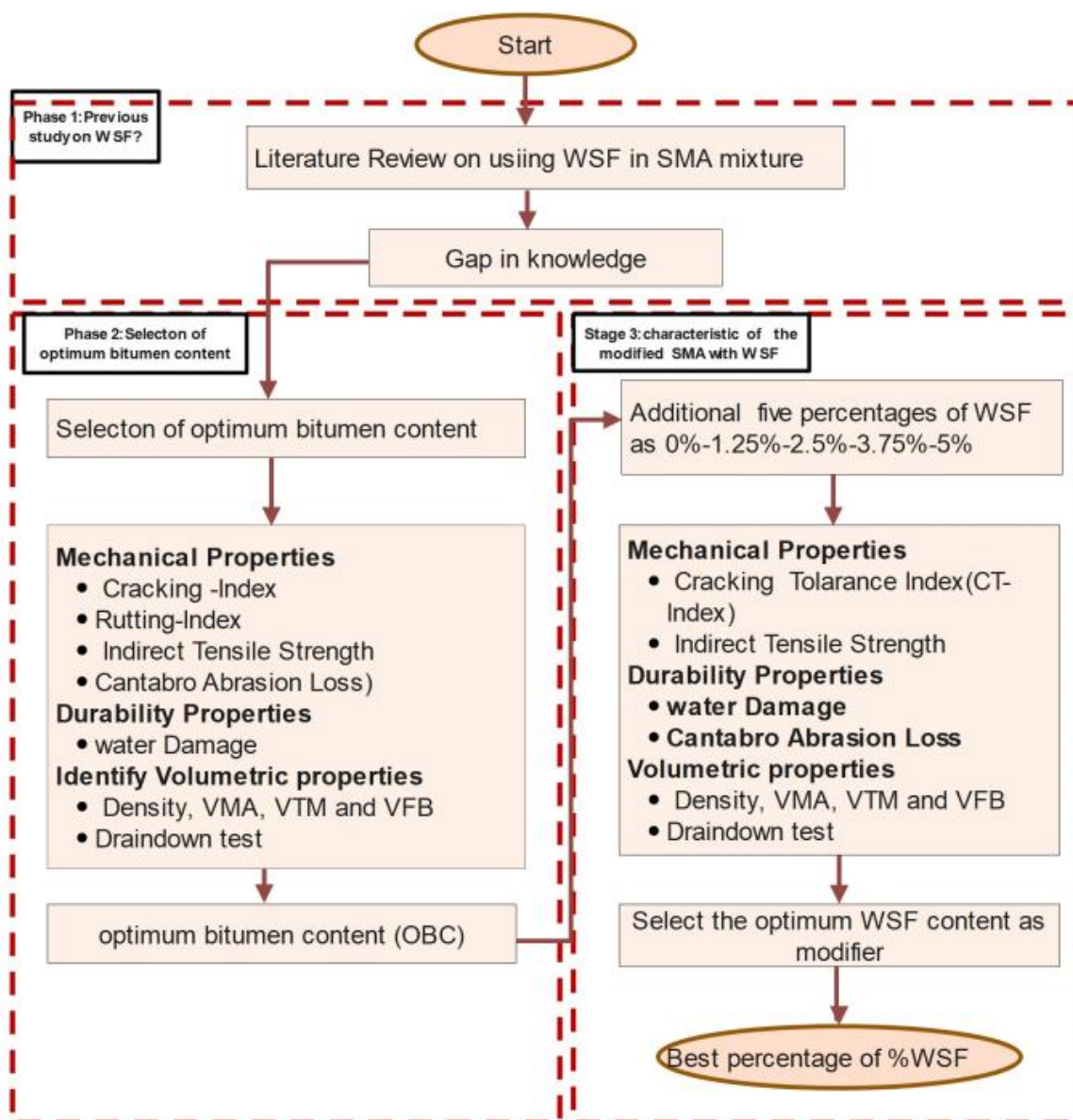


Figure 2: Flowchart of the Research Methodology

Table 6: SMA mixture specification AASHTO M325 [9].

Properties	Requirement
Air Void, %	4
VMA, %	17 min
VCA_{Mix}	Less than VCA_{DRC}
TSR	0.8min
Drain down at Production Temperature, %	0.3 max
Asphalt Binder Content, %	6 min

Note: The specification limits are based on AASHTO M325 requirements (approximately 4% air voids). However, performance tests (RT-index and CT-index) were conducted at $7.0 \pm 0.5\%$ air voids according to the Balanced Mix Design (BMD) approach.

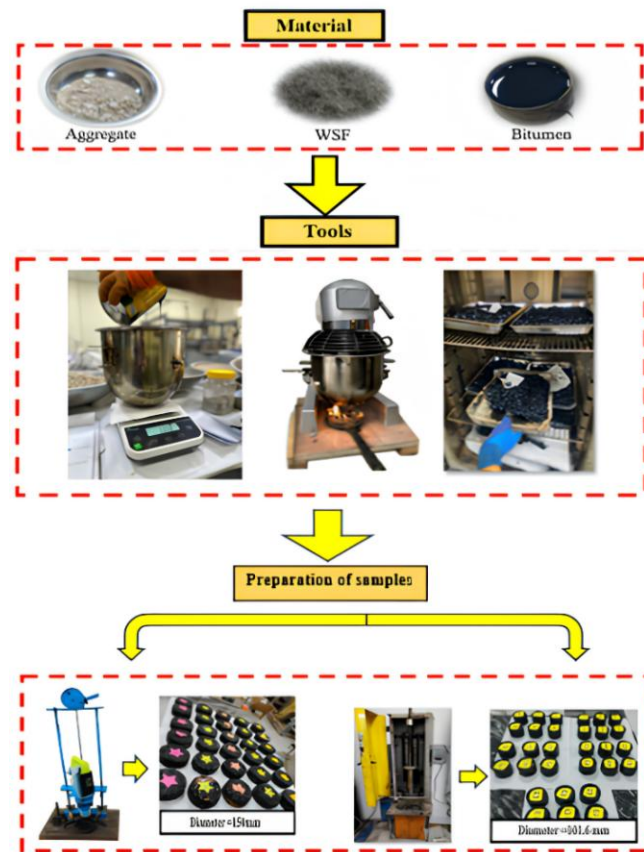


Figure 3: Sample preparation and testing process of SMA mixtures

Table 7: Composition and testing program of SMA mixtures with different waste steel fiber contents.

Mixture ID	WSF Content (%) (by binder weight)	Binder Content (%)	Total Number of Specimens Prepared	Laboratory Tests Conducted
SMA	0%	5.0, 5.5, 6.0, 6.5, 7.0	3 for each test	Volumetric properties, ITS, CT-Index, RT-Index, TSR, and Cantabro test
SMA1	1.25%	6.2	15	Volumetric properties, ITS, CT-Index, RT-Index, TSR, and Cantabro test
SMA2	2.5%	6.2	15	
SMA3	3.75%	6.2	15	
SMA4	5%	6.2	15	

Note: Fiber contents were selected to represent low, moderate, and high dosage levels to enable systematic performance evaluation.

4. Laboratory Testing

The performance of the unmodified and modified SMA mixes was assessed using a variety of laboratory tests, including ITS, RT-Index, and CT-Index. Additionally, durability indices, such as water sensitivity tests and the CALT, were also assessed. The following sections provide a detailed description of each testing procedure.

4.1 Mechanical Properties

A. The CT-Index

This Index evaluates the resistance of the SMA mixtures to cracking defects, especially at intermediate temperatures. The indirect tensile strength (ITS) test typically determines it by looking at the load-displacement response. The cracking act of the SMA mixture was assessed in this work using the CT-index, as described in ASTM D8225 [25]. The indirect tensile cracking test (IDEAL-CT) is a more advanced method for evaluating a mix's resistance to cracking, which was introduced in this study. The advantage of using this approach is that microcracks are started after the peak-bearing load is initiated, and the continual progress and spread behind this Limit causes the mixed carrying load to fall proportionately.

B. The RT- Index, or Rutting Tolerance Index

This Index was achieved in accordance with ASTM D8360 [26], which offers a comprehensive outline of the steps involved in preparing, testing, and evaluating an asphalt mixture to assess its resistance to rutting at elevated temperatures. They are the main focus because the RT-Index and other characteristics obtained from the load-displacement curve evaluate the mixture's resistance to rutting.

C. Indirect Tensile Strength (ITS) Indices

The ITS indices assess the cohesion and tensile properties of the asphalt mixture, which impact its resistance to disintegration and cracking. To evaluate the tensile strength, cylindrical samples are loaded diametrically at a steady ratio until they begin to fail. The maximum load is then used. The internal strength and tensile stress distribution of the combination can be easily and quickly evaluated with this test. The test method was achieved in line with ASTM D6931 [27].

4.2 Durability Tests

Two indicators, the Tensile Strength Ratio (TSR) and the Cantabro loss test, were utilized to assess the durability indices of SMA mixtures.

D. Tensile Strength Ratio (TSR)

TSR is a measure of the ITS in two states: the dry state (dry specimens) and the moisture state (saturated specimens), which is achieved according to ASTM D4867/D4867M [28]. A minimum TSR value is 80% recommended to ensure acceptable resistance to moisture sensitivity.

E. Cantabro Abrasion Loss Test (CALT)

In this study, CALT was utilized to evaluate one of the durability indices of SMA mixtures. In accordance with ASTM D7064/D7064M [29]. This test was conducted using the Los Angeles abrasion machine, where the specimens were rotated for 300 cycles at 30 rpm without the steel balls in place. The loose mixture is compacted and prepared for testing to represent unaged (short ageing). For the aged condition, the remaining three samples should be conditioned initially for 5 days (120 hours) in a forced draft oven at 85°C, as suggested by ASTM D7064/D7064 M (ASTM, 2013b). After that, samples shall be extracted and left to cool in the air for a while, then put in a 25 °C oven for four hours. This test is known as a durability properties test, although it may also be utilized to assess the durability properties of asphalt mixes. The asphalt samples are weighed before the test, then they are cleaned and weighed again after the test. Cantabro loss is the proportion of mass loss as a result of abrasion, which is calculated as the mass difference as a proportion before and after the test.

5. Results

This section presents the experimental results of SMA mixtures, focusing on optimum bitumen content and the effects of WSF incorporation on volumetric, mechanical, and durability properties.

5.1 Results of Selected Optimum Bitumen Content for SMA

The Optimum Binder Content (OBC) is essential for developing asphalt mixtures that exhibit long-term durability and satisfactory performance. In Stone Mastic Asphalt (SMA), which relies on a rich mortar matrix and stabilizing fibres, accurate determination of the OBC is particularly important to achieve a balanced response with respect to resistance to cracking, rutting and durability. Conventional design methods may not fully capture these performance requirements. Therefore, in this study, the BMD approach was adopted to determine the most effective OBC using two indices: the CT-Index and the RT-Index. The BMD method adopted in this study corresponds to Approach B, in which mixture selection is based on satisfying multiple performance-based acceptance thresholds. Cracking resistance, rutting performance, and durability indicators were jointly considered to determine the optimum binder content.

5.1.1 Mechanical Properties Indexes of SMA

F. RT& CT indices

The relationship between bitumen content and the CT-Index and RT-Index for the SMA mixtures is shown in Figure 4. As bitumen content increases from 5% to 7%, the CT-Index improves significantly, indicating enhanced flexibility and crack resistance due to a thicker binder film. Conversely, the RT-Index decreases, reflecting reduced rutting resistance caused by binder softening and weakened aggregate interlock. Therefore, the CT-Index has been chosen as the governing indication of the BMD method of finding the OBC. The OBC was estimated to be between 6 % and 7 % based on the CT-Index performance curve. A binder content of 6.2% was chosen as the ideal value, taking into account the minimum binder requirement for SMA blends ($\geq 6\%$). The rutting threshold is out of the range of the CT-Index within an acceptable value. In other words, the intersection achieved an acceptable CT- Index,

mainly due to the use of asphalt binder. From a mechanistic perspective, this behaviour can be attributed to the increase in asphalt film thickness, which enhances stress distribution and delays crack initiation, thereby improving the CT-index. In contrast, the reduction in RT-index at higher binder contents is associated with decreased mixture stiffness and weakened aggregate interlock, which increases susceptibility to permanent deformation.

5.1.2 Durability Tests

G. Water sensitivity (TSR)

Figure 5 illustrates the variation of the TSR, a key indicator of moisture susceptibility and long-term durability, as the bitumen content ranges from 5% to 7%. The results show a consistent increase in TSR as the bitumen content rises, reaching a peak around 6.5%, followed by a slight decrease at 7%. The upward trend up to the optimum level can be due to the improved coating of aggregate particles with a thicker asphalt binder film, which enhances waterproofing, minimizes water seepage, and maintains interparticle adhesion. This improved binder coverage reduces the loss of mechanical strength when the mixture is exposed to moisture, resulting in higher TSR values. Beyond the optimum bitumen content, excess binder may lead to reduced aggregate interlock and increased void filling, weakening the mechanical integrity and moisture resistance of the mix. This trend is in line with findings from previous studies, which stated that increasing the bitumen binder develops the moisture sensitivity resistance of asphalt mixtures up to an optimal level, after which both moisture and fatigue resistance begin to deteriorate [30]. From a mechanistic perspective, the improvement in TSR with increasing binder content is attributed to enhanced mastic continuity and stronger adhesive bonding at the binder–aggregate interface, which reduces moisture-induced stripping and maintains load transfer under wet conditions. At higher binder contents, however, excessive binder may disrupt the aggregate skeleton and reduce internal friction, leading to weaker structural integrity and increased susceptibility to moisture damage despite improved coating.

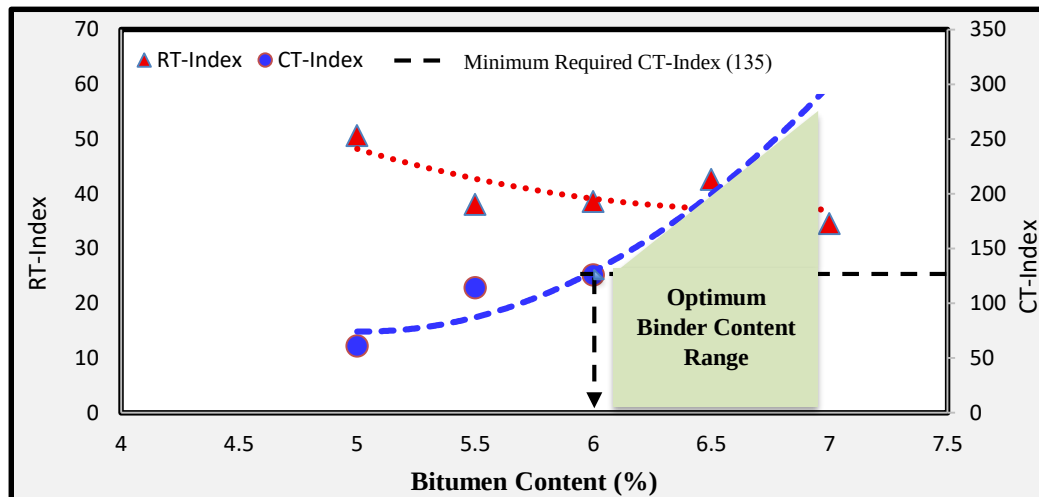


Figure 4: Determination of optimum binder content (OBC) using RT-index and CT-index based on the Balanced Mix Design (BMD) approach for unmodified SMA mixtures.

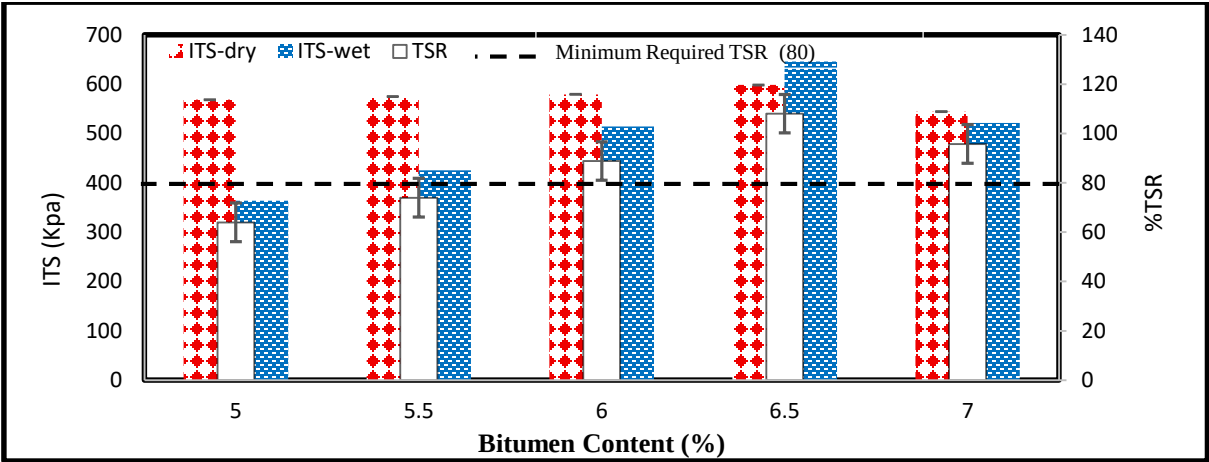


Figure 5: TSR versus % bitumen Content for unmodified SMA mixture.

H. Cantabro Abrasion Loss Test (CALT)

Increasing asphalt binder content from about 5% to 7% decreases Cantabro abrasion loss (from >5% to <1%) as shown in Figure 6, representing greater resistance to aggregate disintegration. This improvement is due to the thicker binder film at higher contents, which enhances cohesive and adhesive resistance forces, strengthens aggregate interlock, and reduces ravelling. The increased binder improves viscoelastic behaviour, aiding stress distribution and energy dissipation. Then, an optimal binder content is critical to discover an equilibrium between durability, abrasion resistance, and structural performance.

From a mechanistic perspective, the reduction in Cantabro abrasion loss with increasing binder content is attributed to improved cohesion within the mastic and stronger adhesive bonding between binder and aggregates, which enhances resistance to particle detachment under impact loading. The thicker binder film also increases energy absorption capacity, reducing micro-crack formation and aggregate loss. However, excessive binder content may lead to reduced aggregate interlock and structural stability, which can negatively affect abrasion resistance under certain conditions. This trend is in line with the findings of prior studies, which have demonstrated that an increased binder content is correlated with lower Cantabro mass loss, particularly in drier conditions [31].

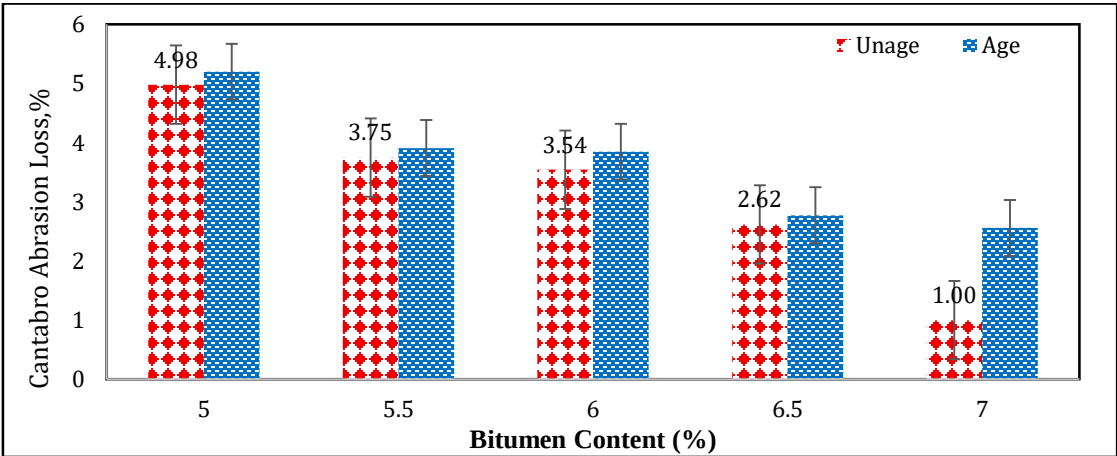


Figure 6 : Cantabro Abrasion Loss versus % bitumen Content for unmodified SMA mixture.

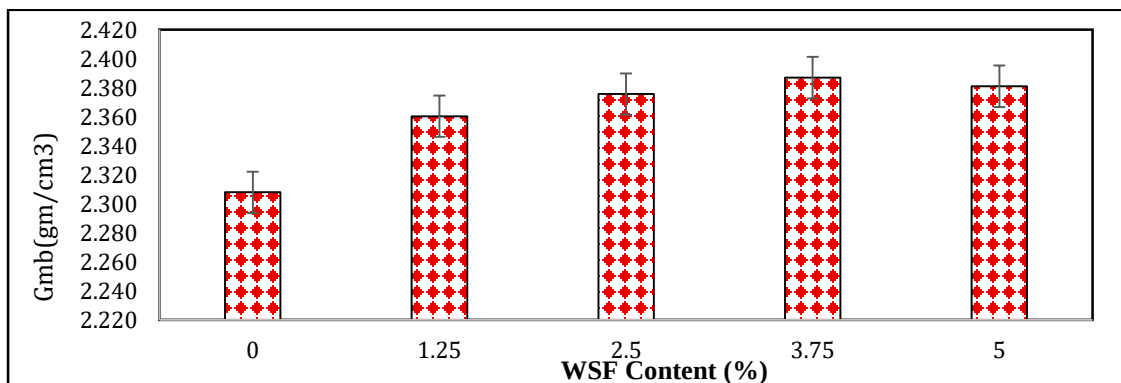
5.2 Results for Modified SMA with WSF

Characteristics of modified SMA with various amounts of WSF, such as the volumetric, mechanical, and durability characteristics are evaluated in this section.

5.2.1 Volumetric Properties

The bulk density exhibits a slight increase with increasing WSF, peaking at approximately 3.75% WSF before showing minor fluctuations, as shown in Figure 7. This behavior suggests that the optimal fiber content enhances packing and compaction efficiency, probably occurring as a result of steel fibers' bridging effect, resulting in the aggregate skeleton's resistance to deformation during compaction.

From a mechanistic perspective, the initial increase in bulk density with increasing WSF content can be attributed to improved particle rearrangement and enhanced packing efficiency due to the bridging effect of fibers, which helps stabilize the aggregate skeleton during compaction. The fibers act as reinforcing elements that limit excessive particle movement and promote a denser structure. However, at higher fiber contents, fiber agglomeration and increased internal resistance may hinder proper compaction and reduce packing uniformity, leading to slight fluctuations in bulk density.

**Figure 7: Bulk Density with steel fiber content (%WSF) in SMA mixtures.**

Also, Figure 8 shows that the air voids decrease with increasing WSF until around 3.75%, after which it stabilizes or slightly increase. The initial reduction indicates that fibers contribute to filling void spaces within the mixture, resulting in a denser aggregate matrix and potentially improving durability by limiting air infiltration. These observations are consistent with findings reported by [32], who noted that steel fibers improve aggregate interlock and decrease the percentage of void Content.

Additionally, Figure 8 indicates that the VMA initially decreases slightly with the addition of WSF, up to approximately 2.5–3.75%. This trend indicates that at low fiber dosages, the fibers may enhance aggregate packing by partially filling existing voids within the mineral skeleton. Comparable findings were reported by [33], who observed that small amounts of fibers improved aggregate interlock and reduced void Content through a filler-like effect. Conversely, as the fiber content increases to higher

levels (around 5%), VMA begins to rise, which is attributed to the formation of additional void spaces due to the fibers acting as discrete inclusions that disrupt the aggregate structure. Also, Figure 8 demonstrates a continuous decrease in the Voids Filled with Bitumen (VFB) as WSF content increases. This trend suggests that higher fiber dosages disrupt the uniform distribution of the asphalt binder, reducing binder film continuity and diminishing the effective coating of aggregates. Similar observations were noted by [33], who reported that fiber incorporation can absorb a portion of the binder, limiting its ability to encapsulate aggregates fully and consequently lowering the effective VFB. Collectively, these findings indicate that while moderate fiber contents can enhance the densification of the aggregate skeleton, excessive fiber additions may negatively affect binder distribution and compromise the overall volumetric balance of the mixture.

From a mechanistic perspective, these volumetric changes are governed by the dual role of fibers within the mixture. At low contents, fibers act as micro-reinforcing elements that enhance mastic stability and improve aggregate packing through a filler-like effect, leading to reduced air voids and stabilized VMA. However, as fiber content increases, the fibers begin to behave as discrete inclusions that disrupt aggregate contact points and hinder effective compaction. This results in increased internal resistance, reduced packing efficiency, and a decline in binder effectiveness, ultimately lowering VFB. Therefore, the observed behavior reflects a transition from a densification-dominated regime to a structure-disruption regime with increasing fiber content.

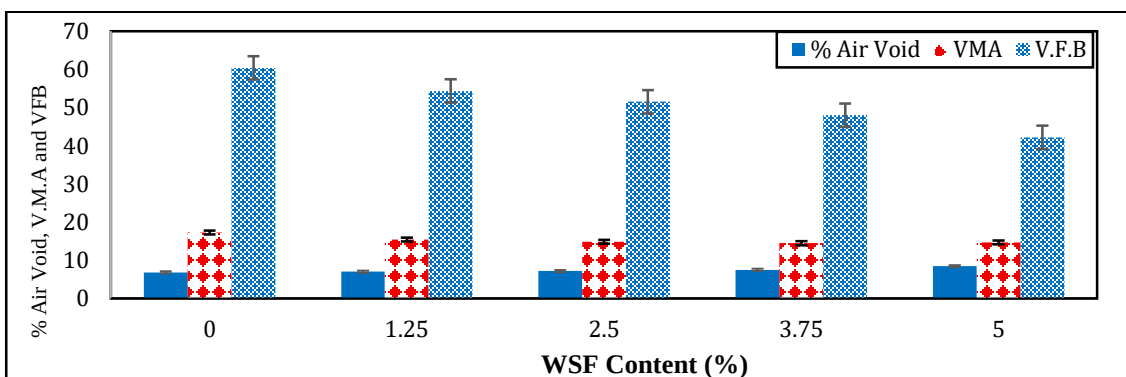


Figure 8: Variation of air voids (AV), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) with steel fiber content (%WSF) in SMA mixtures.

5.2.2 Mechanical Properties Indexes of SMA

• RT& CT indices

Figure 9 illustrates the variation of RT-index and CT-index with WSF content in SMA mixtures. The RT-index increased significantly as the WSF content increased from 0% to approximately 2.5%, indicating enhanced rutting resistance due to the reinforcing effect of steel fibers, which improves internal load distribution and mixture stiffness [33]. However, beyond this optimum content, the RT-index decreased gradually, suggesting that excessive fiber addition adversely affects mixture cohesion and workability. This behaviour indicates a clear crossover point beyond the optimum fiber content, where

further addition of WSF becomes detrimental to mixture performance. At low to moderate dosages, steel fibers enhance mechanical behaviour through improved stress distribution and fiber-bridging mechanisms. In contrast, at higher fiber contents ($\geq 3.75\%$), performance deterioration was observed. This can be attributed to fiber agglomeration, inadequate asphalt coating, and the formation of non-uniform weak zones within the mixture [34]. In addition, excessive fiber content reduces workability and compaction efficiency, resulting in increased air voids and reduced overall mixture integrity. Consequently, beyond the optimum fiber content, the negative effects outweigh the reinforcing benefits. In contrast, the CT-index exhibited a continuous increasing trend with increasing WSF content, indicating improved cracking resistance. This improvement is associated with the fiber-bridging mechanism and enhanced energy absorption capacity provided by steel fibers, which delay crack initiation and propagation. Overall, the results demonstrate a trade-off relationship between rutting and cracking performance. While moderate WSF contents (approximately 1.25–2.5%) provide a balanced improvement in both RT-index and CT-index, higher fiber contents lead to a crossover point where rutting resistance deteriorates despite continued improvement in cracking resistance, consistent with previous findings [34].

From a fracture mechanics perspective, the improvement in CT-index can be attributed to the development of an extended fracture process zone (FPZ) facilitated by the presence of steel fibers. These fibers act as crack-bridging elements that transfer tensile stresses across crack faces, thereby reducing stress intensity at the crack tip and delaying crack propagation. At moderate fiber contents, this mechanism enhances post-peak behavior and increases energy dissipation capacity. However, at higher fiber dosages, fiber clustering disrupts stress transfer efficiency and leads to localized stress concentrations, which limits the effectiveness of the bridging mechanism despite the continued increase in CT-index.

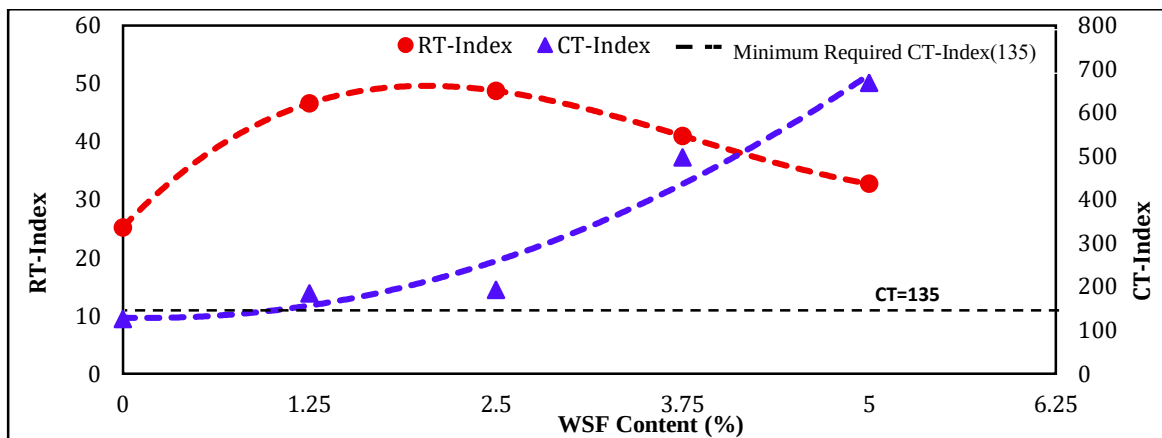


Figure 9: Variation of RT-index and CT-index with WSF content in SMA mixtures.

• Indirect Tensile Strength (ITS)

As seen in Figure 10, the load versus displacement graphs reveal that the addition of waste steel fibers improves the sample's stiffness and ductility by raising both the peak load it can support and the

displacement at peak load. When the mixture successfully blends strength and flexibility, the most balanced performance happens about 2.5% WSF. Low binder–aggregate bonding homogeneity or fiber aggregation are probably the reasons why higher fiber contents (>2.5%) show lower returns or minor performance declines. ITS values increase notably with fiber content, by 8.2%, 20%, -0.5%, and -10.5% for 1.25%, 2.5%, 3.75%, and 5% WSF, respectively, as shown in Figure 11. This trend indicates that fibers reinforce the mixture’s internal structure, enhancing tensile stress distribution under traffic loading. The improved reinforcement reduces cracking susceptibility and contributes to better structural performance of flexible pavement. These results align with previous studies showing that an optimal fiber content improves tensile strength and ductility, enhancing the mixture’s capacity to resist traffic-induced stresses and ensuring long-term pavement performance [7].

From a mechanistic standpoint, the observed improvement in tensile behaviour is attributed to the crack-bridging action of steel fibers, which enhances stress transfer across microcracks and delays crack coalescence. This leads to an increase in peak load as well as improved post-peak ductility. The extended tail in the load–displacement curve reflects higher energy absorption capacity and a more stable fracture process. However, at higher fiber contents, fiber agglomeration reduces the efficiency of stress transfer and creates localized stress concentrations, limiting further improvements in tensile strength and ductility.

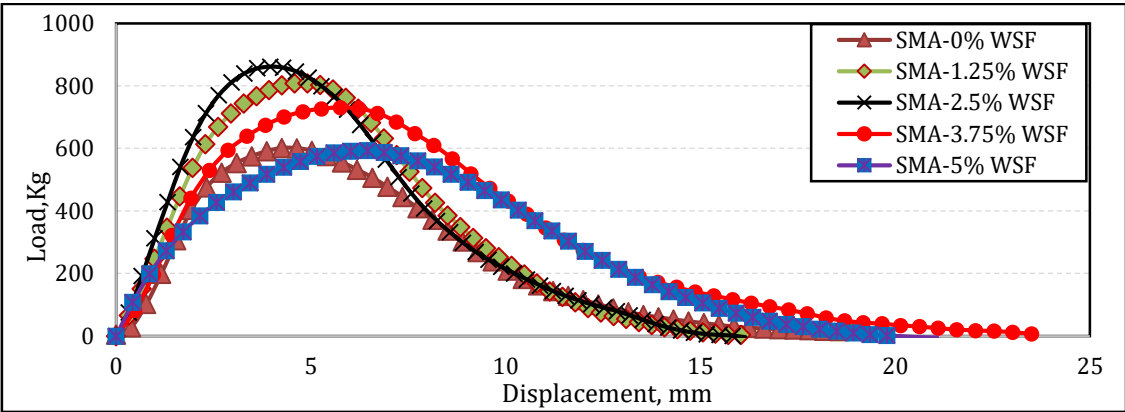


Figure 10: Load versus displacement for unmodified and modified SMA with WSF.

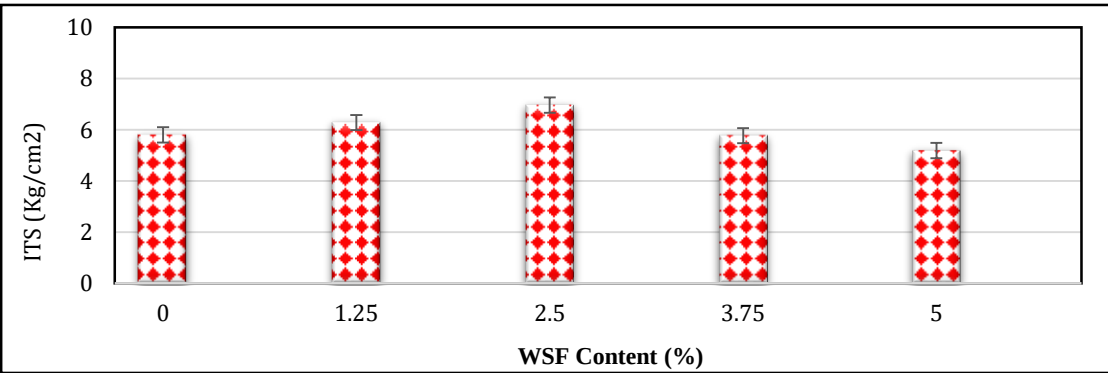


Figure 11 Variation of ITS with WSF content in SMA mixtures.

5.2.3 Durability Properties

• TSR indices

The results in Figure 12 show that for percentages of 1.25%, 2.5%, 3.75%, and 5% of WSF, respectively, the TSR increases to 8.0%, 9.3%, -4.3%, and -12.3%. This indicates that a moderate amount of WSF advances the mixture's capacity to resist moisture sensitivity and bridge cracks. By distributing loads, preventing cracks from developing, and reducing water penetration, the fibers most likely act as reinforcement bridges within the asphalt matrix, preserving tensile strength under wet conditions. However, increasing the WSF content beyond the optimum (3.75% and 5%) leads to a decrease in the TSR. This drop can be attributed to poor fiber dispersion, agglomeration, or insufficient binder coating, which creates weak zones in the matrix, increases internal voids, and hinders effective stress transfer. From a mechanistic perspective, the improvement in TSR at moderate WSF contents is attributed to enhanced crack-bridging and stress redistribution within the asphalt matrix, which limits crack opening and reduces pathways for moisture infiltration. The fibers help maintain the integrity of the mastic–aggregate interface under wet conditions, thereby reducing stripping and preserving tensile strength. However, at higher fiber contents, poor dispersion and fiber agglomeration create localized weak zones and increase internal void connectivity, facilitating moisture ingress and weakening the adhesive bond. This results in reduced TSR despite the presence of reinforcing fibers.

Generally, the results identify an optimal WSF content of approximately 2.5%, achieving the best balance between mechanical and durability characteristics. Though moderate fiber content enhances structural integrity and moisture resistance, excessive fiber content has adverse effects due to matrix heterogeneity. The findings are in line with previous studies, [33], which stated that fiber-modified asphalt mixtures display enhanced resistance to moisture damage, as the fibers help restrict crack propagation and promote uniform stress distribution. Also, researchers [35] confirmed that moderate additions of steel fibers enhance the TSR. According to researchers [36], moderate fiber dosages enhance durability and mechanical performance, while higher fiber levels compromise the asphalt matrix's homogeneity and lower the mixture's overall performance.

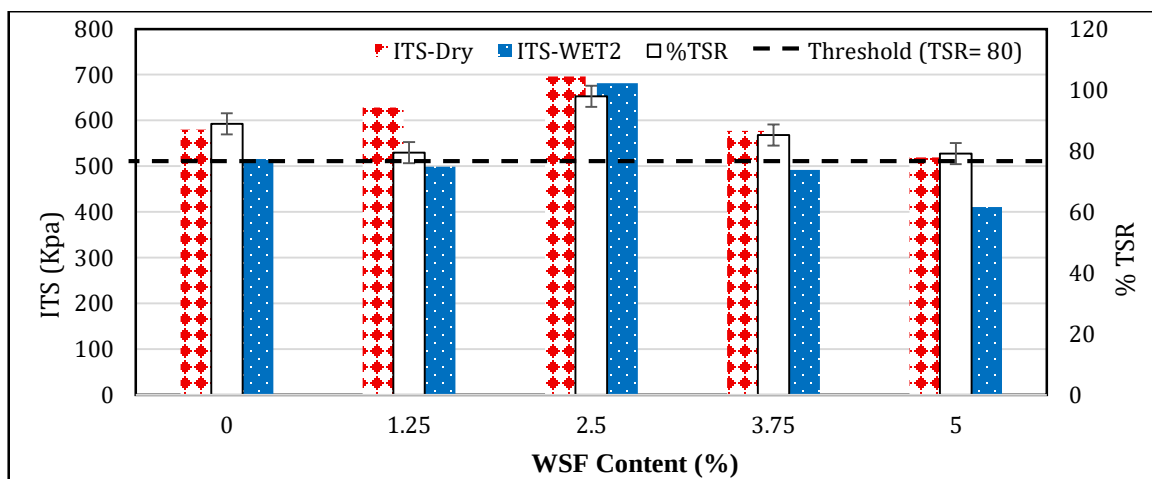


Figure 12: Variation of ITS and TSR with WSF content in SMA mixtures.

• Cantabro Abrasion Loss Test (CALT)

The impact of WSF percentage on the Cantabro abrasion loss of SMA mixtures in both aged and unaged conditions is shown in Figure 13. Under unaged conditions, the results show that the addition of WSF improves the aggregate interlocking and inner cohesion of the asphalt matrix through the growth of a reinforcing network, as indicated by the decrease in Cantabro abrasion loss with increasing WSF concentration. However, after age, combinations with more than 2.5% WSF exhibit a significant increase in abrasion loss, above the allowed standard Limit of 20%. The structural integrity of the mastic is weakened, and aggregate disintegration is promoted by fiber aggregation, binder oxidation, and local stress concentration, all of which contribute to this unfavorable behavior. From a mechanistic perspective, the reduction in Cantabro abrasion loss under unaged conditions is attributed to the formation of an effective fiber–mastic reinforcing network, which enhances cohesion and improves resistance to particle detachment under impact loading. However, after aging, the stiffening of the asphalt binder reduces its ability to deform and dissipate stresses, leading to increased brittleness of the mastic. In this condition, the presence of poorly dispersed or agglomerated fibers creates stress concentration zones, which accelerate microcrack initiation and propagation under impact loading. This results in a significant increase in abrasion loss despite the reinforcing effect of fibers. Therefore, an optimal WSF of approximately 2.5% was identified, beyond which the adverse effects of low dispersion and excessive binder stiffness outweigh the reinforcement benefits.

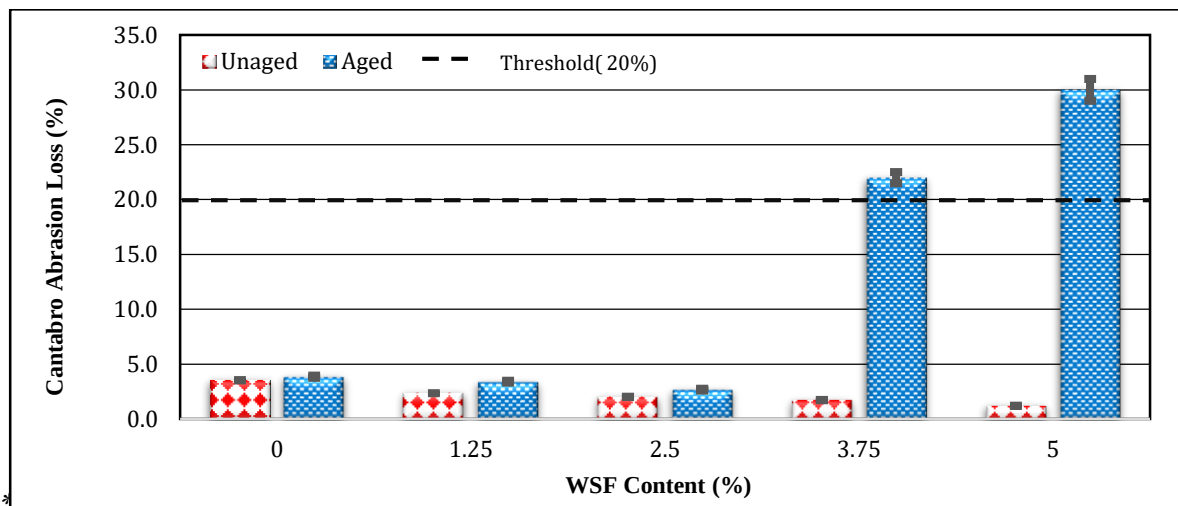


Figure 13: Variation of Cantabro abrasion loss with WSF content in SMA mixtures.

5.3 Statistical Analysis of Results

To further confirm the trends observed, a statistical analysis was performed using an independent sample t-test to compare the control mixture (0% WSF) with the optimal mixture containing 2.5% WSF. As indicated in Table 8, adding 2.5% WSF resulted in statistically significant enhancements in cracking resistance (CT index), rutting resistance (RT index), and tensile strength (ITS), with p-values below 0.05. This indicates that the improvements noted are statistically sound and not due to random variation, but

rather the reinforcing effect of steel fibers. Conversely, the TSR results did not exhibit a statistically significant difference ($p > 0.05$), implying that WSF's role is mainly mechanical rather than related to moisture resistance. Overall, the statistical results endorse the choice of 2.5% WSF as the optimal fiber content, offering a balanced enhancement in performance within the Balanced Mix Design (BMD) framework. This statistical validation further bolsters the reliability and robustness of the proposed mixed-design approach.

Table 8: Statistical significance analysis using t-test (control vs 2.5% WSF).

Performance Indicator	Control (Mean $\pm$ SD)	2.5% WSF (Mean $\pm$ SD)	p-value	Significance
CT-index	126.0 $\pm$ 3.6	192.4 $\pm$ 6.4	0.0003	Significant ($p < 0.05$)
RT-index	25.23 $\pm$ 0.45	48.77 $\pm$ 1.30	0.0001	Significant ($p < 0.05$)
ITS	5.80 $\pm$ 0.15	6.94 $\pm$ 0.18	0.0002	Significant ($p < 0.05$)
TSR	88.8 $\pm$ 1.3	97.9 $\pm$ 1.9	0.062	Not significant ($p > 0.05$)

Note: Statistical significance was evaluated using an independent samples t-test at a 95% confidence level ($\alpha = 0.05$).

6. Conclusions

From the laboratory program that was conducted and the data that were analyzed, the following conclusions will be drawn in the following order:

- The incorporation of waste steel fibers (WSF) significantly enhanced the mechanical performance of the SMA mixtures. The CT index increased by approximately 52%, whereas the RT index improved by nearly 93% at the optimum fiber content (2.5%) compared to the control mixture.
- The tensile strength (ITS) showed an increase of approximately 20%, indicating improved load-bearing capacity and stress distribution within the mixture.
- The optimum WSF content was identified as 2.5% (by binder weight), which provided the most balanced performance in terms of cracking resistance, rutting resistance, and abrasion durability, within the BMD framework.
- Although the TSR values showed some variation, no statistically significant improvement was observed, confirming that WSF primarily enhances the mechanical properties rather than moisture resistance.
- At higher fiber contents ($>2.5\%$), performance deterioration was observed owing to fiber agglomeration, reduced mixture homogeneity, and inefficient stress transfer mechanisms.

- The novelty of this study lies in the integration of waste steel fibers within the Balanced Mix Design (BMD) framework to identify an optimum fiber content based on performance indices (CT-index, RT-index, ITS, and TSR), supported by statistical validation (t-test). This approach provides a more reliable and performance-based methodology for the sustainable SMA mixture design.

AI Declaration

None

Disclosures

The authors declare no conflict of interest.

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Abbreviations

The following abbreviations are used in this manuscript:

SMA	Stone Mastic Asphalt
BMD	Balanced Mix Design
WSF	Waste Steel Fibers
CT-index	Cracking Tolerance Index
RT-index	Rutting Tolerance Index
ITS	Indirect Tensile Strength
TSR	Tensile Strength Ratio
CALT	Cantabro Abrasion Loss Test
OBC	Optimum Binder Content
VMA	Voids in Mineral Aggregate

VFB	Voids Filled with Bitumen
AV	Air Voids
OPC	Ordinary Portland Cement
CMF	Conventional Mineral Filler
FPZ	Fracture Process Zone

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تقييم أداء الأسفلت الحجري الماستيكي المُعزَّز بألياف الفولاذ المُعاد تدويرها

الخلاصة: تُستخدم خلطات الأسفلت الحجري الماستيكي (SMA) في رصف الطرق ذات الاحمال المروريه العاليه نظراً لمقاومتها الفائقة للتشوه الدائم ومتانتها؛ إلا أن أداءها يعتمد بشكل واضح على حدود تصميم الخلطة وخصائص المواد. قد لا تُغطي طرق تصميم الخلطات التقليدية، التي تعتمد على معايير حجمية السلوك الماستيكي المعقد لخلطات SMA بشكل كامل في ظل ظروف التحميل الواقعية. لذلك، تم اعتماد منهجيات متقدمة، مثل مفهوم تصميم الخلطة المتوازنة (BMD)، لتقييم خلطات الأسفلت. تبحث هذه الدراسة أداء خلطات SMA المُدمجة بألياف فولاذية مُعاد تدويرها (WSF) باستخدام مؤشرات أداء متعلقة بالتشقق والتشوه الدائم والمتانة. يُستخدم إطار عمل BMD كنهج تقييمي إرشادي لتقييم استجابة الأداء الكلية للخلطات. تم اختبار أربع جرعات من WSF بنسب 1.25% و 2.50% و 3.75% و 5% من وزن الببتومين. في المختبر، تُقيم الخصائص الميكانيكية من خلال اختبارات مثل مؤشر تحمل التشققات (CT-Index) ومؤشر تحمل التحدد (RT-Index)، بالإضافة إلى مؤشرات الحجم والمتانة، بما في ذلك نسبة قوة الشد (TSR) وفقدان التآكل وفقاً لمعيار كانتابريا (CAL). أشارت النتائج إلى أن نسبة المادة الرابطة المثلى في الخلطات الإسفلتية المعدلة (SMA) هي 6.2% لتحقيق توازن بين مقاومة التحدد والتشقق ومتطلبات المتانة. وقد أدى إضافة ألياف فولاذية مُعاد تدويرها بجرعة مثلى (2.5%) إلى تحسين أداء الخلطات الإسفلتية المعدلة، حيث زادت نسبة تحمل التشققات بنسبة 17.8%، ونسبة تحمل التحدد بنسبة 48.2%، ونسبة قوة الشد بنسبة 18.6%، بينما انخفضت نسبة فقدان التآكل وفقاً لمعيار كانتابريا بنسبة 75.6% في الخلطات غير المعالجة والمعالجة بنسبة 44.0% على التوالي. تُبرز هذه النتائج أهمية التحكم في جرعة الألياف لتحسين المتانة والأداء، مما سيكون له أثر إيجابي على استدامة رصف الخلطات الإسفلتية المعدلة.

الكلمات المفتاحية: تصميم الخلطة المتوازنة؛ مؤشر مقاومة التشقق؛ المتانة؛ مؤشر مقاومة التحدد؛ الإسفلت الماستيكي الحجري؛ ألياف فولاذية مُعاد تدويرها.