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Cracking Resistance and Fracture Behavior of Modified Asphalt Mixtures

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Abstract: Cracking is a physical failure-finite in size—that occurs due to repeated loading by traffic, both traffic and environmental factors. In this study, the fracture and cracking resistance of glass fiber reinforced (SBS) polymer modified mixtures is analyzed. Four formulations were designed: Conventional Asphalt with and without GF (CA, CA-GF) and SBS modified asphalt with and without GF (SBS, SBS-GF). The performances under loading were evaluated on the basis of Marshall properties, ITS and SCB tests. Marshall stability of the modified SBS was 26% higher than that for those with GF, and the others were also improved by adding GF to CA mixture up to 22% and SBS mixture by 12.5%. The increase in ITS of SBS-modified asphalt reached to 93.4 % due to the addition of GF and up to about 23.5% using CA mixture and up to about 10% for SBS blend. The combination of SBS+GF showed the higher cracking tolerance (CT index = 239.755), this means that, both modified by SBS and reinforced by GF increased in CT Index with 71.7% and 18.8%, and when combined between CA/SBS's mixtures also represented an increase in CT index equal to 37%. indicating that ductility and fracture resistance were improved. The SCB test has also displayed improvement in Gf with (164.4%) when SBS modified asphalt, and densification by (22.5%) for CA and (30.1%) for SBS have been approximately achieved due to the fibrer glass additions. F Unsurprisingly, these findings indicate that incorporating SBS and GF together could effectively enhance asphalt pavement during service as well as its crack resistance, particularly at high stress and variable temperatures.

Keywords: Modified asphalt (SBS), Glass fibers (GF), CT index, Semi-circular bending test (SCB), and fracture energy.

Introduction

Asphalt concrete is constituted with brittle parts (aggregates) and a viscous material (asphalt cement). The viscous nature of the matrix renders asphalt concrete a viscoelastic material. Consequently, the stress-strain behavior is loading and temperature dependent. A qualitative description of the time-relation response of asphalt concrete can be achieved based on rheological models (Perng, 1989). The loading application on the structure surface causes tensile strains at the lowest point of asphalt layer. The tensile strength of the asphalt concrete mixture always exceeds the stress due to traffic loading, hence the material can remain "crack-free" for a number of repetitions. Fatigue cracks start at the base of the in mentioned layer in sensitive locations as a result of repeated loading. Cracks proceed and penetrate to the surface. Nevertheless, prevalent pavement design methodologies, like the (AASHTO) technique, do not use such factors. This is partially attributable to the imprecision of such criteria and the insufficient comprehension of the mechanisms of fracture under diverse settings. A logical failure criterion must account for fracture initiation, propagation, and total fatigue failure (Mobasher et al., 1997). Cracks often form in overlays during using time because of localized weak points, like as pre-existing cracks. This is mostly attributed to traffic congestion and temperature fluctuations (Nguyen et al., 2020).

Modern highway traffic places heavy requirements on pavement qualities. Functionalized materials offer a feasible option to overcome some of the deficiencies and constrainments due to temperature sensitivity, contributing to overall improvement in the performance and durability of asphalt pavement exposed under such high service temperatures conditions, where significant traffic loads are always involved. The SBS is used in asphalt modification products to enhance stability and temperature cracking resistance of the pavement. However, SBS is liables resistance to light and moisture; hence the behaviour of asphalt decays step by step during storage, transportatio n and construction., and usage (Zhang et al., 2017; Hao et al., 2020; Liu et al., 2020). Nonetheless, polymer modification may significantly influence some essential rheological characteristics of bitumen, and there has been a paucity of studies on the thermo-rheology of SBS-modified bitumen using advanced testing methodologies and analyses.

Günay (2022) found that traditional testing demonstrates that SBS copolymer modification enhances the stiffness of the binder, as seen in the rotational viscosity test. Jasim and Ismael (2021) concluded that the amalgamation of SBS polymers with asphalt enhances asphalt qualities, also producing development in rheological properties (softening point and viscosity). Also, Romeo et al. (2010) concludred polymer alteration at modirate temperatures did not significantly affect the resilience modulus; nevertheless, during creep tests, the creep rate was reduced, indicating decreased micro-damage buildup. SBS polymer-modified mixes have a superior energy percent compared to their unmodified counterparts, leading to enhanced top-down cracking performance.(Hill & Buttlar, 2016) Used semi-circular bending test and Hamburg-DC(T) to study the crack path in the Region Of Interest (ROI) as shown in Figure 1, and evaluate the mixture modification by adding SBS to the conventional asphalt.

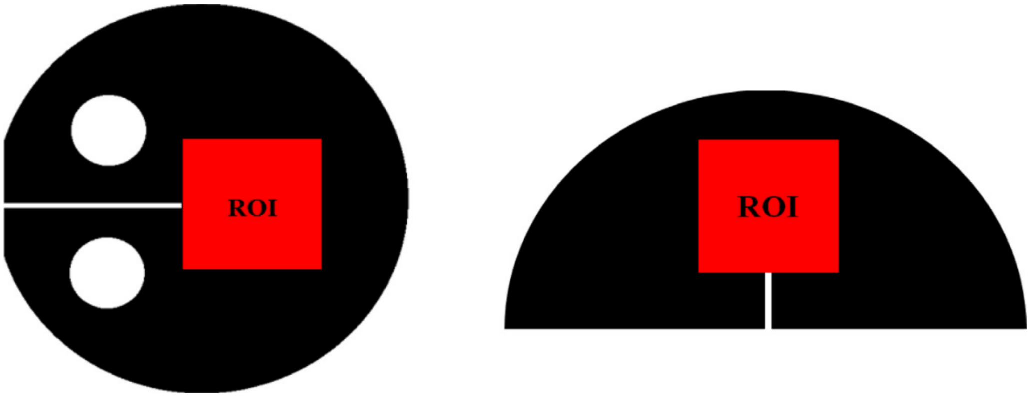


Figure 1. Area of study for: (a) DC(T); and (b) SCB (Hill & Buttlar, 2016).

On the other hand, Glass fiber is a synthetic material characterized by great tensile strength, with a Young's modulus of around 70 GPa. The use of glass fiber in asphalt mixes enhances stability, durability, and ductility owing to its superior mechanical qualities (Abtahi et al., 2010). Furthermore, it enhances the flow value and standing againest fracture propagation within the combination. At low temperatures, glass fibers exhibit resistance to pavement cracking due to their capacity to inhibit fracture formation (Najd et al., 2005). (Eisa et al., 2021a) Incorporate glass fibers into the asphalt mixture at varying percentages of 0.25%, 0.50%, 0.75%, and 1.0% of the total weight of the asphalt mix. The findings indicate that the optimal glass fiber content is 0.25% by weight of the total mix, resulting in a 10% increase in stability value, a 13% reduction in adjusted flow value, and a 19.7% decrease in rutting value compared to the control asphalt mixture. After that, Khaled et al. (2024) study the role of glass fiber length on the characteristics and behavior of the combination. Seven distinct amounts (0, 0.25, 0.5, 0.75, 1, 1.25, and 1.5) of glass fiber relative to the total weight of aggregates over 3 different dimensions (10, 20, and 30 mm). The results demonstrate that a glass fiber length of 20 mm in mixtures enhances moisture resistance and minimizes the risk of irreversible deformation with increasing traffic loads and elevated temperatures. Additionally, asphalt mixtures incorporating 0.5% glass fiber exhibited superior quality compared to other formulations.

Al-Mosawy and Al-Obaedi (2023) Investigated the (ITS) of the pavement layers for a segment of the highway treated with SBS addition, demonstrating that the use of SBS additive substantially enhanced the ITS. The ITS findings have improved by about 25% with a standard deviation of 6% in comparison to the scenario without additions. While, Eisa et al. (2021b) examine the influance of GF on the standard mixture and used Tensile Strength Ratio (TSR) for assessment, revealing an approximate 5% increase in TSR value relative to the Control Mix. The HMA mixes modified by GF exhibited significant resistance to moisture damage events.

Al-Qadi et al. (2015) processed more than 200 ideal-CT load-displacement data formed from different mixtures and detected important points presented in these data. With the exception of a few data lines, inflection area in lines were located. Moreover, (Zhou et al., 2017) evaluate the characteristics of IDEAL-CT and its sensitivities to various elements, including RAP and RAS sensitivity, the binder type sensitivity, aging conditions sensitivity, and air voids sensitivity, while assessing the CT index test in relation to other standard tests.

Enhancing and improving asphalt concrete performance and service life is therefore a strong requirement to cope with more and more modern traffic conditions. SBS applied in wide range to modify asphalt and enhance the high-temperature resistance, anti-rutting ability, and tensile property by using additives; however, low-temperature performance and aging remain its problems. While, the addition of glass fibers provides considerable promise for an effective means to developed against the cracks, stability, and durability of asphalt mixtures subjected to thermal stress and heavy traffic.To understand the rheological response of modified mixtures, along with the establishment of accurate failure criteria, is necessary in improving pavement design and prolonging its service life. More studies are needed to overcome existing limitations and optimize the modification process.

This research addresses the lack of integrated analysis on SBS and glass fiber combinations, introduces multi-method fracture testing, validates results statistically, and identifies optimal content advancing crack resistant asphalt design to mitigate the reflection cracks phenomena and extend the pavement service life.

Methodology and Materials

In Figure 2 below, the methodology of this work is listed.

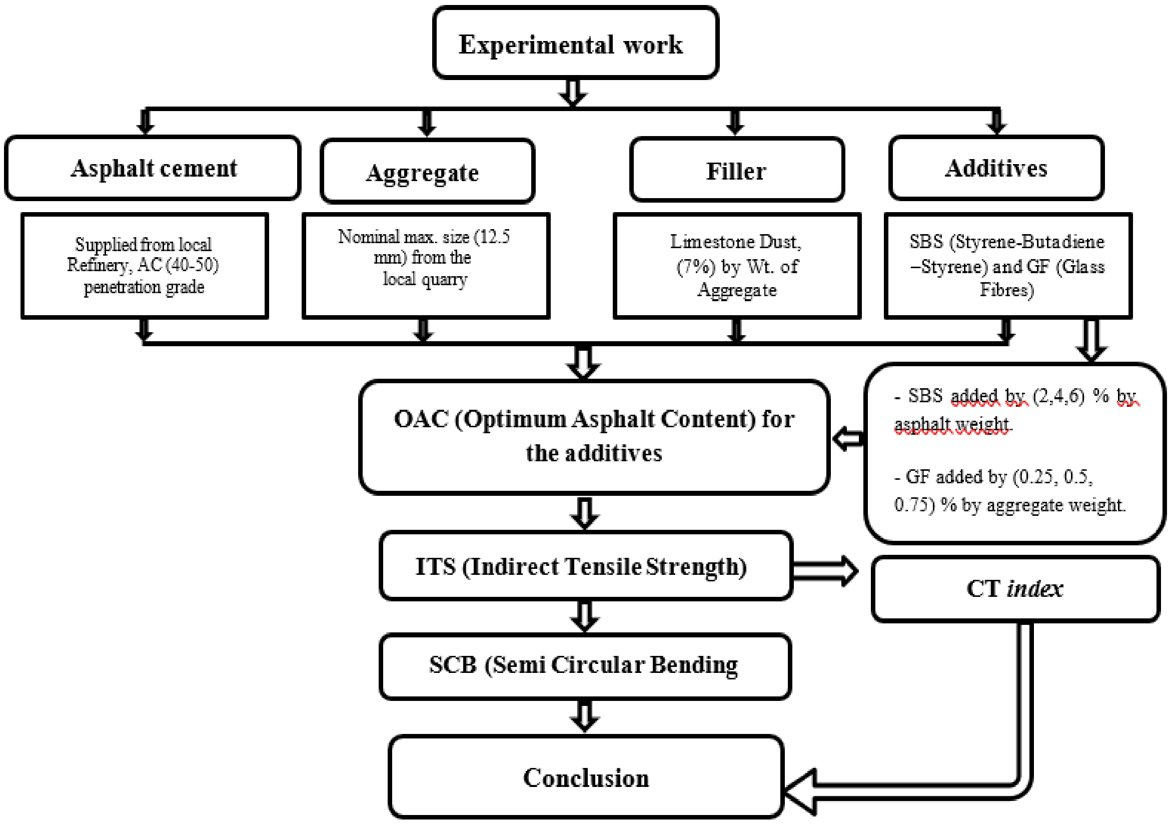


Figure 2. Work flow chart.

The laboratory work program included examining the materials used in this research. First, was running the first type of asphalt binder under the title penetration grade 40/50. This strategy was used to identify the best asphalt content percentage, for this purpose Marshall properties were evaluated using Marshall specimens. All the tests have been prepared according to the Iraqi standards. The second material used in the experiment is the asphalt mixture which is prepared to meet the requirement of wearing course. The synthetical binder was SBS while, the used aggregates had an upper size of 12.5 mm. The SBS was added with three percentages with 2,4,6 SBS with respect to asphalt by weight respectively. Glass fiber was added and used also with three percentages by

0.25,0.5,0.75 percent of the asphalt respectively. The SBS was blended with asphalt in a high speed mixer at 180°C for 60 minutes. The SBS mixture was then used to coat the aggregates which were pre-coated at 160°C with material. Glass fibers were added to the aggregate and heated to 160°C and dry-mixed prior to the addition of the binder. Mixing was continued for 5 minutes to achieve well dispensed mixtures. After mixing, the compaction was done in the Marshall hammer of 75 blows on each side for the Marshall samples; then they were cured at room temperature 25°C for 24 hours prior to testing. Then merge the Mesa in a water bath at a temperature-control bath, at a temperature controlled in water bath at temperature 32°C to make samples with in a water bath and held at 33C to 40 hours for directly stability test.

Two kinds of tests were made to examine the role of the modified asphalt mixture on the resistance of propagation cracks: ITS (Indirect Tensile Strength), CT Index test (Cracking Tolerance) and SCB test (Semi-Circular Bending Test). Cylindrical specimens of marshall test were cast for performing ITS and CT Index tests. The SCB specimens were semi-circular (diameter = 150 mm, thickness = 50 mm) with a notch of 15 mm deep. The Environmental conditions. ITS and CT Index tests The specimens were conditioned at a temperature of 25°C for a time period of 4 hours, whereas, SCB tests The specimens subjected to conditioning at a temperature of 15°C for an elapsed duration of 4 hours.

Asphalt Cement

The Al-Dura Petroleum Factory supplied the asphalt raw material with a (40-50) penetration value. It is possible to see in (Table 1) the physical properties of the binder. According to the (SCRB R/9, 2003), the results of the testing are by the requirements that were established (SCRB, 2003).

Table 1. Asphalt (40-50) properties.

Test	Result	SCRB Specification Limits (SCRB, 2003)	ASTM Designation No.
PEN. (25ºC, 100 gm, and 5sec)	45.5 (0.1mm)	40 - 50	D-5
S.P (Ring and Ball)	51 (º C)	-------	D-36
Ductility, (25 º C and 5cm/minute)	154 (cm)	≥ 100	D-113
S.G. @ 25 º C	1.039	-------	D-70
F.P., (Cleveland open Cup)	295 (º C)	>232	D-92

Coarse and Fine Aggregate

The Al-Nibaie sandstone quarry is the location of the construction (fine and coarse) aggregate used in producing hot-mix asphalt for this research. The coarsely crushed material is retained with sieve No. 4. The fine aggregate (silt type) ranged in particle size between No.4 and No. 200 with Atterberg limits indicative of coarse silt as defined by the laboratory test results. Physical properties of the aggregates are shown in Table 2.

Table 2. Aggregates characteristics.

Property	ASTM	Results
Coarse		
Bulk Specific Gravity	C-127	2.579
Apparent Specific Gravity	C-127	2.601
Percent Water Absorption	C-127	0.54
Percent Wear	C-131	15.8
Fine		
Bulk Specific Gravity	C-128	2.61
Apparent Specific Gravity	C-128	2.632
Percent Water Absorption	C-128	0.952

Mineral Filler

In this research, Limestone dust that passing sieve No 200 (0.075 mm) used in mixture. It's supplied from the lime factory in Karbala governorate. (Table 3) shows the properties of the mineral filler used.

Table 3. Mineral filler characteristics.

Property	Result
% Passing No. 200	95
Specific gravity	2.71

Additive SBS (Styrene-Butadiene Styrene)

SBS is a thermo-plastic polymer that enhances the behaviour of producd material. SBS becomes pliable at elevated temperatures, facilitating its incorporation and blending with asphalt binder. SBS was acquired from the Kraton Company in France and used with asphalt cement to generate an asphalt mixture with favorable qualities. The SBS was combined with asphalt using a high speed shear mixer. (Table 4) presents the physical and chemical parameters of SBS, whereas (Figure 3) illustrates the SBS that used in work.

Table 4. Properties of SBS

Property	SBS (styrene-butadiene styrene)
Physical state	solid
Density (Kg/m³)	1247
Melting point (C°)	197
Apparent	yellow

Figure 3. SBS polymer used in the study.

Glass Fibers

Glass fiber is an inorganic short fiber. Glass fiber efficiently alters water stability and low-temperature resilience. The product supplied by JUSHI Group company in China, and the product type (562A). The properties of glass fibers are shown in (Table 5). (Figure 4) shows the glass fibers used in this work.

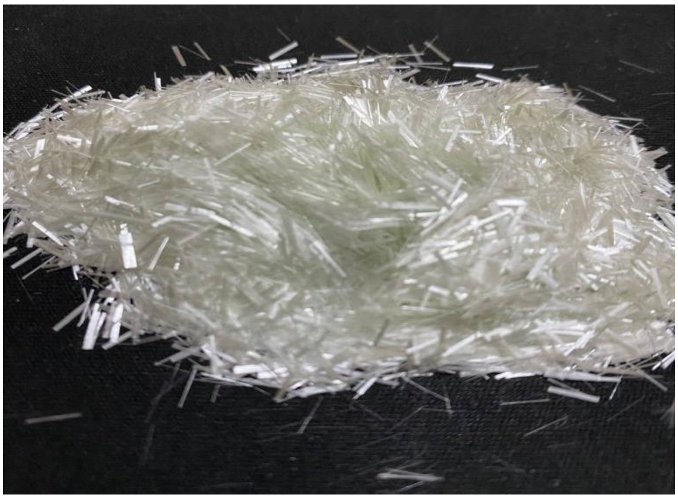


Figure 4. Glass fibers used in the study.

Table 5. Glass fibers characteristics.

Property	Value
Density (gm/ cm3)	2.5
Melting point (Co)	> 400
Poisson's Ratio	0.29
Tensile Strength (Gpa)	3.4
Modulus of Elasticity (Gpa)	72
Length (mm)	7
Diameter (mm)	0.21
Aspect Ratio	33.3

Selection of Aggregates Gradation

For this study, the gradation of aggregate was chosen by the standards that were suggested by the (SCRB, 2003), The nominal maximum size of aggregate for wearing course is 12.5 millimeters. (Figure 5) illustrates the gradation that was chosen according to the criteria.

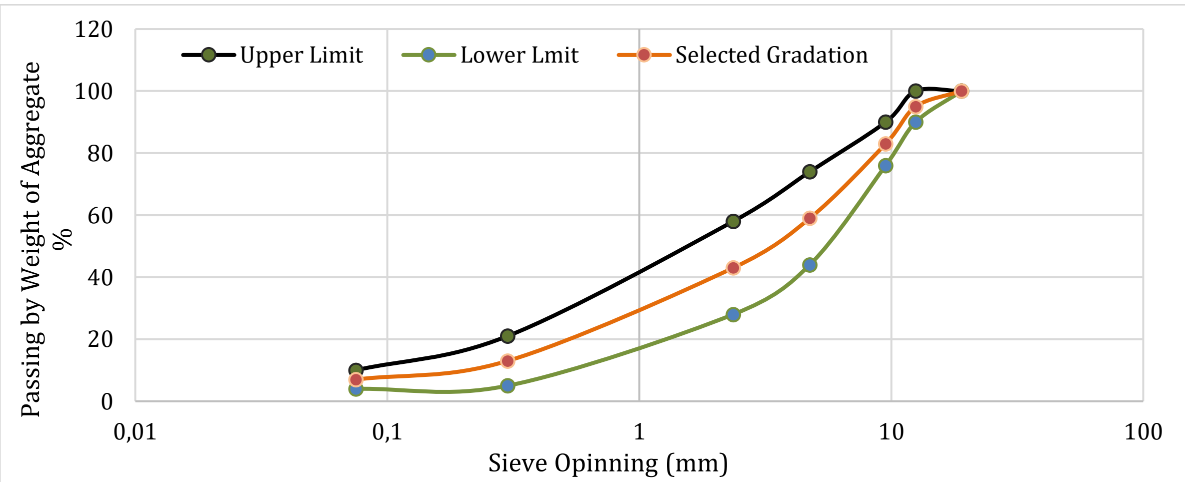


Figure 5. Gradation meet the (SCRB, 2003).

Tests

Indirect Tensile Strength Test (ITS)

The ITS test is generally like to be using the asphalt mixture, a correlation relationship exists between the tensile strength of mixture and its fatigue cracking resistance. The ITS test measures tensile (or indirect tensile) properties of asphalt mixtures as they are related to pavement cracking and attempts to predict the tensile strength for HMA as well as the initiation of cracks. ITS values are commonly employed to evaluate relative performance of asphalt mixes and for rutting or cracking resistance. A high tensile strain at failure suggests that a specimen can withstand higher strain before breaking and exhibit an improved crack resistance. A full test was done using the ASTM D6931-12 to determine the cracking resistance of the specimen.. It is possible to get the ITS by applying Equation 1.

$$\text{ITS} = \frac{2\,P}{D\,T\,\pi} \qquad \text{...... (1)}$$

Where:
P=value of peak load (N), T= thickness (mm), and D= diameter (mm).

The load rate of 50 mm/min, and the load cell accuracy is (0.01 N) with a temperature of 25 C^0. LVDT to measure vertical deformation. As shown in (Figure 6).

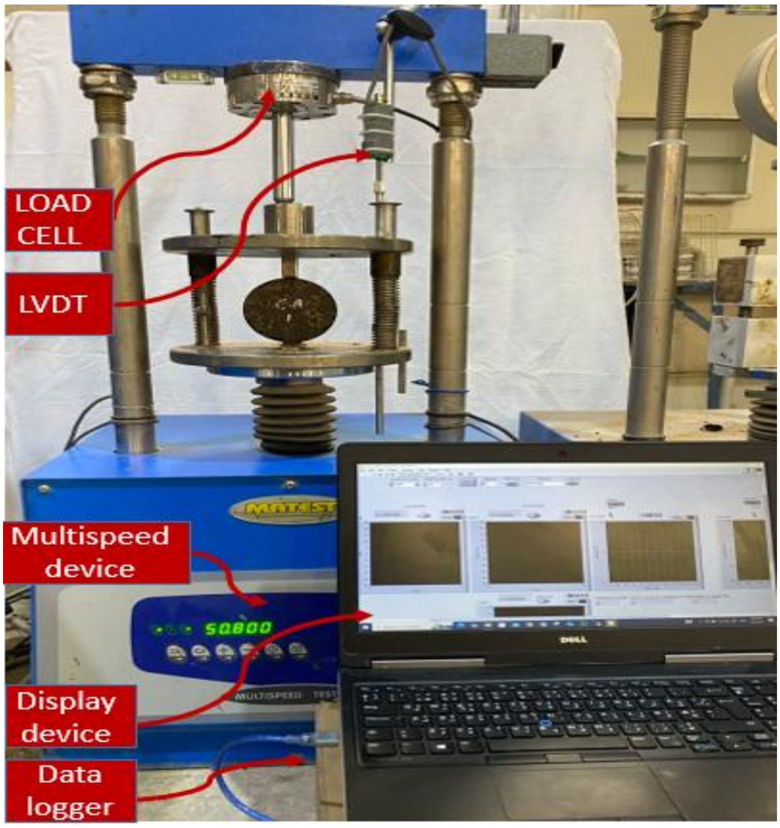


Figure 6. (ITS) test.

IDEAL-Crack Tolerance Test (IDEAL-CT index)

The IDEAL-CT is a test that is very similar to the conventional ITS. It is conducted at ideal temperature using cylindrical specimens at a loading 50 mm/ min. Tests may be performed on cylindrical specimens of any size, with diameters ranging from 100 to 150 mm and thicknesses ranging from 38 to 75 mm, among other sizes. According to the IDEAL-CT, a behaviour-related cracking may be derived from the load deformatıon curve that has been measured.

The results are calculated according to the following procedure:

- Work of fracture (Wf) = (Gf) × D × t .... (2)
- $(\text{Gf}) = \frac{wf}{D\times t}$ .... (3)
- $\text{CT}_{\text{index}} = \frac{t}{62} \times \frac{Gf}{|m75|} \times \frac{l\,75}{D} \times 10^6$ .... (4)

Where:
t= thickness (mm), G= fracture energy (Joules/m2), $|m75|$=absolute value of post-peak slope m75 (N/m), l75= displacement at 75% of peak load after the peak (mm), and D= diameter (mm).

Semi-Circular Bending Test (SCB)

The fracture behavior was assessed by an SCB test. The specimen has a half-disc shape with 15 mm notch depth. The specimens were previously mentioned. The specimens were pre-conditioned at 15 °C for 4 h before the SCB test. The maximum load achieved and the deformation of the specimens were recorded. This test method assesses the fracture energy (Gf) of the mixtures. Loading is applied at 5 mm/min and the accuracy of load cell is drying oven (0.01 N). The LVDT is used to calculate the vertical deformation. As shown in (Figure 7).
The SCB test results are calculated according to the following procedure:

- $G_f = \frac{Wf}{Alig}$ …….. (5)
- $A_{lig} = (r - a) \times t$ ……. (6)
- $Wf = \int Pdu$ ……. (7)

Where:
Gf = fracture energy (J/m2), Wf = fracture work (J), Alig = ligament area (m2), r = sample radius (m), a = notch length (m) , and t = sample thickness (m).

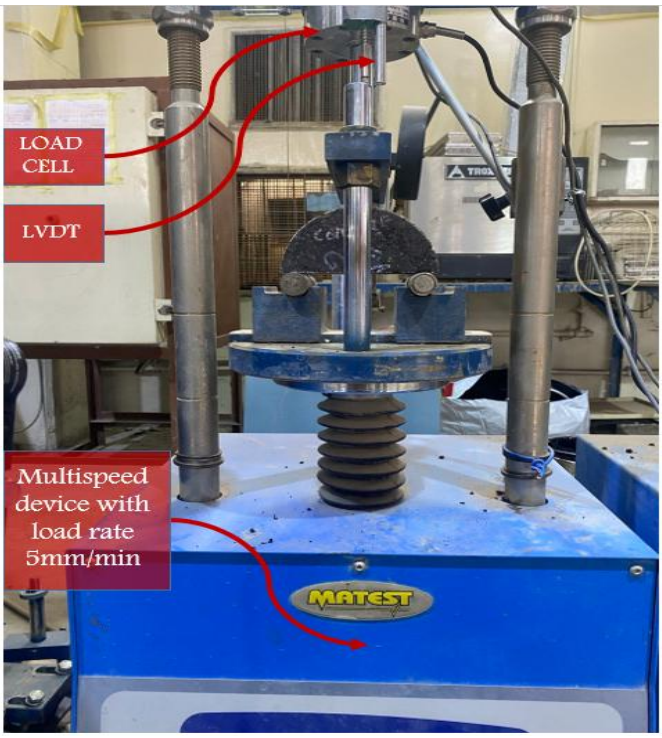


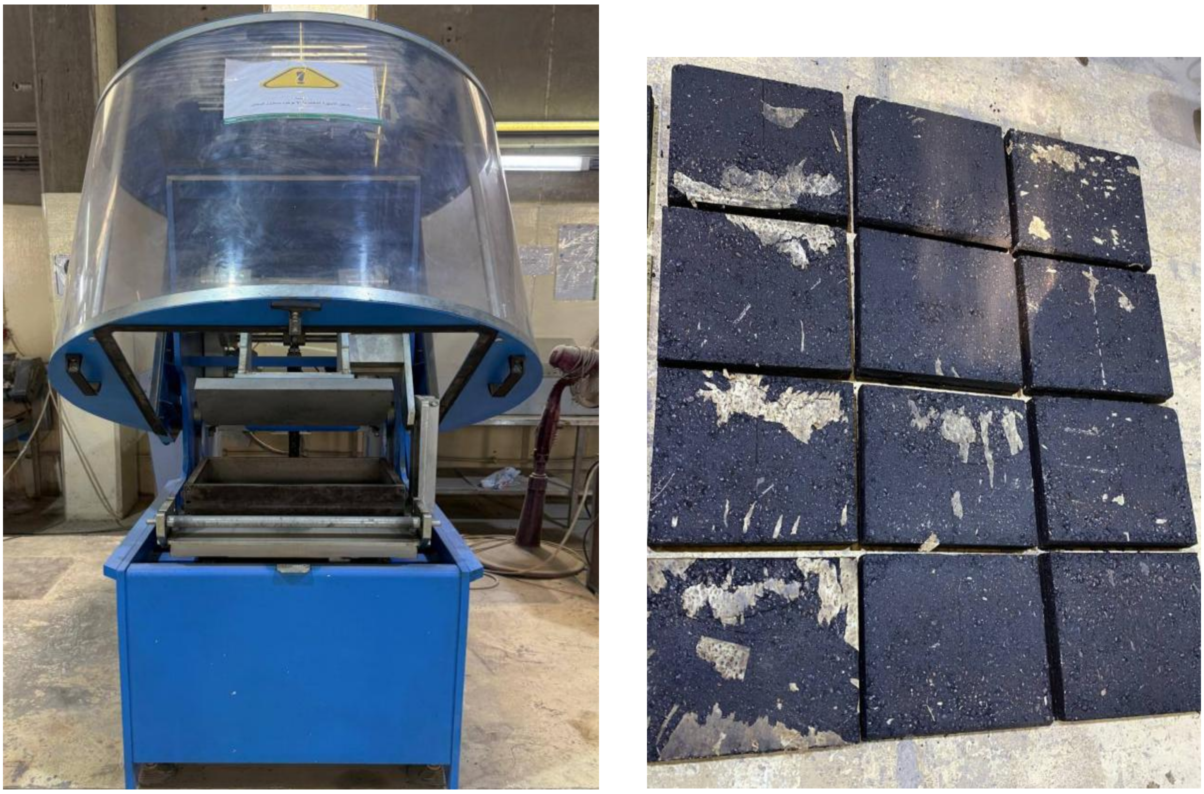
Figure 7. Semi-circular bending test.

Samples Preparation

Four types of asphalt mixture were prepared (conventional and modified asphalt with SBS) with glass fibers reinforcement with two types as shown in (Table 6). The optimum SBS that blends with conventional asphalt was (4%) by weight of asphalt based on Marshall properties. While, the optimum glass fibers that were added to conventional and modified mixtures with (0.5%) by weight of mix. The chosen SBS and GF contents were based on performance evaluation across a range of trial percentages. Four slabs were created by using the Roller Compactor Machine for four mixtures with slab dimensions (300*400) mm with 50 mm thick, as shown in Figure 8.

Table 6. Mixture description used in the study

Mixture Code	Description
CA	Conventional asphalt mix (control)
CA+GF	Conventional asphalt + 0.5% glass fibers (by total mix weight)
SBS	Asphalt modified with 4% SBS (by asphalt weight)
SBS+GF	Asphalt with 4% SBS + 0.5% glass fibers



(a) (b)

Figure 8. (a) Roller compactor machine. (b) Slabs of asphalt mixtures.

These slabs were providing the samples of (ITS) and (SCB) with cores that were extracted, two types of core cylinders used (6 inches) to (SCB) samples and (4 inches) to (ITS) samples.

Results and Discussion

Marshall Properties

Five HMA mixtures with materials properties showed previously, Asphalt contents of 4%, 4.5%, 5.0%, 5.5%, and 6.0% were prepared, three samples for each percentage. The Marshall design was employed for the wearing layer mix to study the characteristics of the mix. in accordance with AASHTO specifications. The four HMA mixtures were evaluated using the Marshall apparatus to determine stability and flow values. The (O.A.C) was determined to be 4.91%, which provided maximum stability, suitable paramters. Various contents of glass fiber (GF) at 0.25%, 0.50%, and 0.75% by weight of the total mix were prepared, and the Marshall mix design method was employed to ascertain the (O.GF.C). The optimum value of 0.5% by weight of the total mix was selected, yielding the best Marshall properties. On the other hand, three contents of SBS (2,4, and 6) % by weight of asphalt added to Conventional Asphalt, and found that the value of (4%) produced the best Marshall properties.

The results show that the stability developed by (26) % when SBS is blended with conventional asphalt. while, the asphalt reinforced with glass fibers shows an increasing trend, where it increased by (22) % and (12.5) % when glass fibers were added to the mixture of conventional asphalt and modified asphalt, respectively. (Table 7) shows the Marshall properties for many mixtures.

Table 7. Marshall properties for various asphalt mixtures.

Marshall Properties	Mix Type conventional (CA)	Conventional With GF - (CA+GF)	Modified With SBS - (SBS)	ModifiedWith SBS and GF - (SBS+GF)	(SCRB, 2003) Specifications (wearing layer)
Stability (kN)	11.03	13.8	13.9	15.6	8 Min.
Bulk Density (gm/cm3)	2.309	2.315	2.322	2.328	-
Air Voids (%)	3.76	3.63	3.57	3.46	3-5
Flow (mm)	3.4	2.9	2.6	2.3	2-4

Indirect Tensile Strength Test

The tensile characteristics of asphalt mixtures are assessed in accordance with the AASHTO test method, which including applying a force to a Marshall mould with its diametric plane at a specified rate, resulting in steady stress distribution. The (ITS) method is utilized to calculate the tensile data of asphalt mixtures, which aids in assessing pavement performance. The results of ITS in Mpa can be represented in (Table 8) and (Figure 9). The results show that modifying asphalt with SBS developed the ITS value, the ITS value developed by (93.4%) % compared with conventional asphalt. On the other hand, the results show that GF improves the ITS value, where the ITS value improved by (23.5) % for conventional asphalt and improved by (10) % for modified asphalt with SBS. The glass fibers influence on the conventional asphalt more effective than modified asphalt with SBS.

The ITS results indicate that SBS enhances tensile strength by improving elasticity and stress distribution. Glass fibers contribute additional strength through crack-bridging. Their impact is more pronounced in conventional asphalt than SBS-modified mixes, suggesting a saturation effect. These improvements enhance pavement resistance to tensile stresses, reducing cracking under load.

Table 8. ITS test results.

Mixture Type	ITS (MPa)	Improvement vs. CA
CA	0.533	–
CA+GF	0.658	+23.5%
SBS	1.030	+93.4%
SBS+GF	1.125	+111.0%

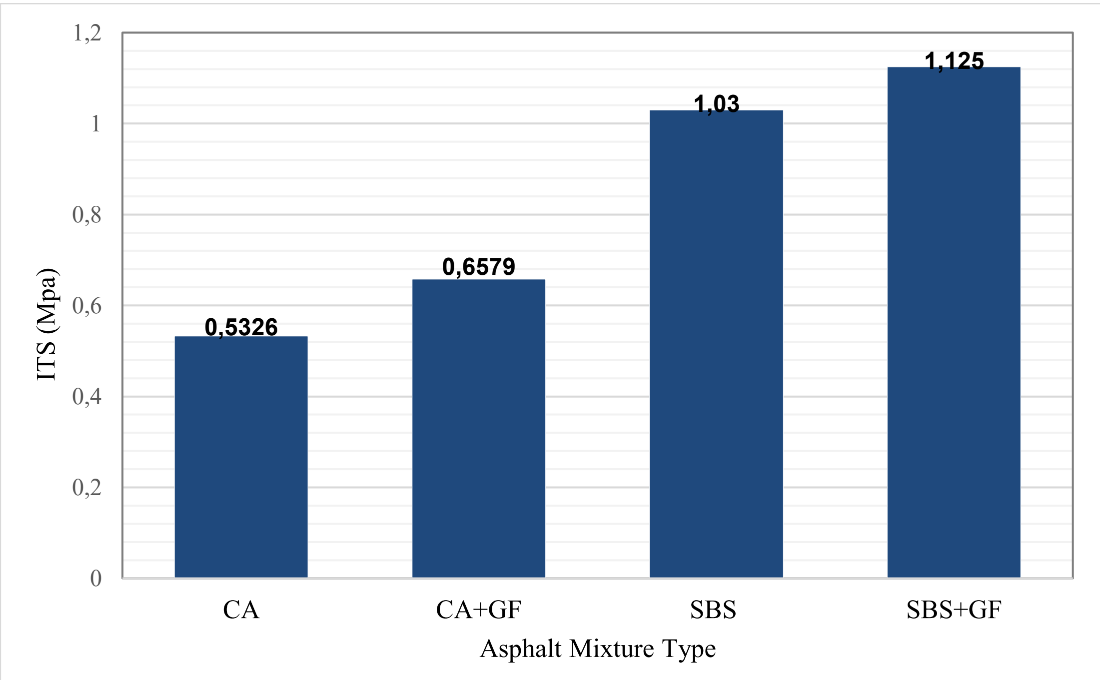


Figure 9. Indirect tensile strength test results.

IDEAL-CT Index

The IDEAL-CT is to derive a behaviour -related cracking from observe load-deformation curves. (Figure 10) shows the displacement due to the applied load for the (ITS) test. The curves were analyzed with MATLAB to study the parameters of CT index equation. The outcomes of the IDEAL-CT were given in (Table 9). The (CT Index) takes the energy absorption and fracture response of specimens during indirect tensile test operations into account. This trend indicates that SBS-modified binders provide great improvement in resisting cracking. 13,23 Especially in the presence of SBS, glass fibers (GF) further improve properties and indicate a synergistic effect. These results show that themodified mixtures – especially the SBS+GF produce higher fracture resistance, and ductility than typical conventional mixture. As an indication of better energy absorption, the mixture SBS+GF had the highest W_x and G_x due to more stress required before complete failure. Consistent with the CT Index variation trend, we find that they also increase gradually from CA to SBS+GF. An increased elasticity due to SBS, energy dissipation and the crack-bridging capacity of glass fiber can be some reasons for this enhancement. This confirms the previous results pointing out that the addition of a reinforcing polymer and fiber additives enhances both fracture energy and toughness.

CA has lowest l75 and a relatively steep |m75|, indicating brittle failure. For modified mixtures, SBS+GF has the smallest |m75| and highest l75 showing its superior ductility with a more controlled failure. The related CT index values are increased by (71.7) % for the asphalt with SBS modified, (19) % and (37) % for the GF in CA and SBS/GF mixtures respectively. This is in agreement with the intuitive consideration where fibers hinder crack propatation so that the onset of peak can be delayed and the post-peak displacement increment become larger.

The IDEAL-CT results reveal that SBS and GF modifications significantly enhance cracking tolerance by altering the fracture response of asphalt mixtures. Mechanistically, SBS increases elasticity and promotes stress redistribution, while GF contributes to anti-cracking and post-crack resistance. The SBS+GF mix, with the highest CT Index, lowest |m75|, and highest l75, demonstrates superior ductility and delayed failure. These characteristics indicate a shifting to ductile behavior, critical for resisting reflective and fatigue cracking. Such improvements employ that hybrid-modified mixtures are favorite for high traffic and climate-sensitive pavements, giving more service life and minmize maintenance periodes in real-world applications.

Table 9. CT index calculations.

Asphalt mixture type	Work of fracture (Wf) Joules	Failure energy (Gf) Joules/m2	$\lvert m75\rvert$ (N/m)	l 75 (mm)	CT index	Improvement vs. CA
CA	19.00000	3470.15748×10^6	1223.17×10^3	4.53	101.9	–
CA+GF	21.47394	4227.1555×10^6	1241.21×10^3	4.48	121.106	+18.8%
SBS	42.58338	8382.555118×10^6	1901.49×10^3	5.00	174.960	+71.7%
SBS+GF	48.71309	9589.1909×10^6	1720.67×10^3	5.42	239.755	+135.3%

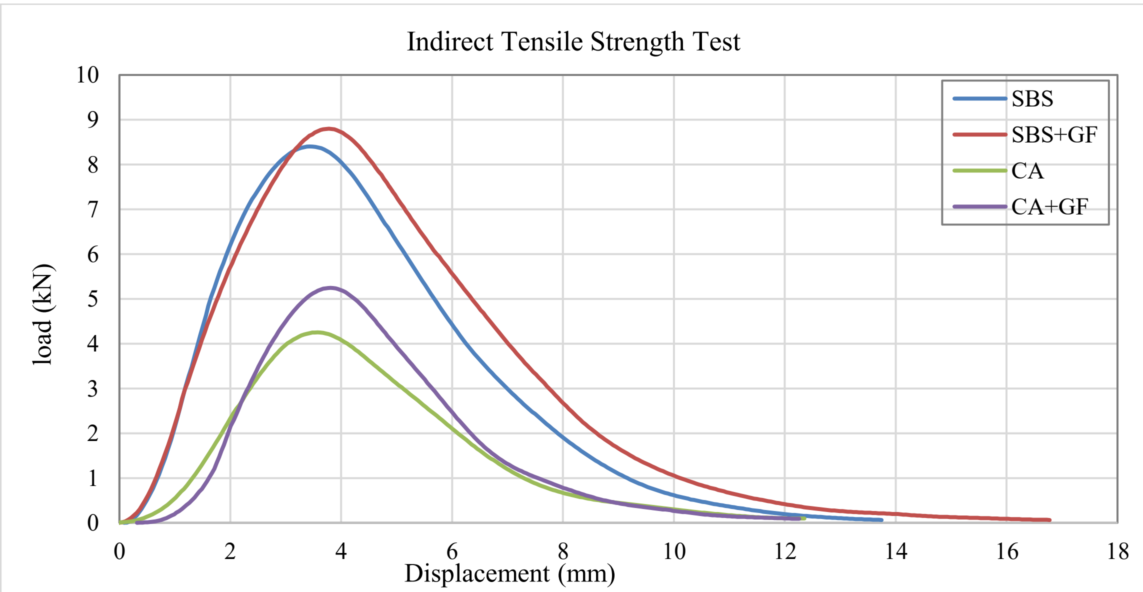


Figure 10. Indirect tensile strength test (Load-displacement curves).

Semi-Circular Bending Test

The simplicity of the specimen has made the SCB a favorite test for assessing fracture properties of both samples made in a laboratory-compacted type and field cores; The semicircular shape allows testing more specimens (exactly twice as many), from one to two halves, obtained from either core or samples prepared by compaction. It has been shown that with proper changes in the angle of the notch or the distance between fixed roller, SCB test can be powerful for studying mixed-mode fracture trend of mixtures. The advantages of the SCB as an HMA cracking test are optimized when the complete loading history of a specimen is taken into account with processing of the full load-displacement response.

Figure 11 shows the SCB data due to load and displacement. Table 10 presents the fracture performance of four asphalt mixture types studied using the (SCB) test at 15°C. All test curves were analyzed and the parameters by using MATLAB codes. Work of Fracture (Wf) in Joules, Failure Energy (Gf) in J/m², and Maximum Load in kN form the key performance indicators. Evaluation of asphalt mix resistance to cracking and its energy dissipation properties depends on these criteria. With SBS+GF displaying the highest values, SBS-modified mixtures (SBS and SBS+GF) outperform conventional asphalt (CA) in both Wf and Gf.

Table 10. SCB curves results.

Asphalt mixture type	Work of fracture (Wf) Joules	Failure energy (Gf) Joules/m2	Maximum load (KN)	Improvement vs. CA
CA	6.31	2103.333	4.1999	–
CA+GF	7.73	2576.667	5.2316	+22.5%
SBS	16.68	5560.000	10.2124	+164.4%
SBS+GF	21.71	7236.67	11.7124	+244.0%

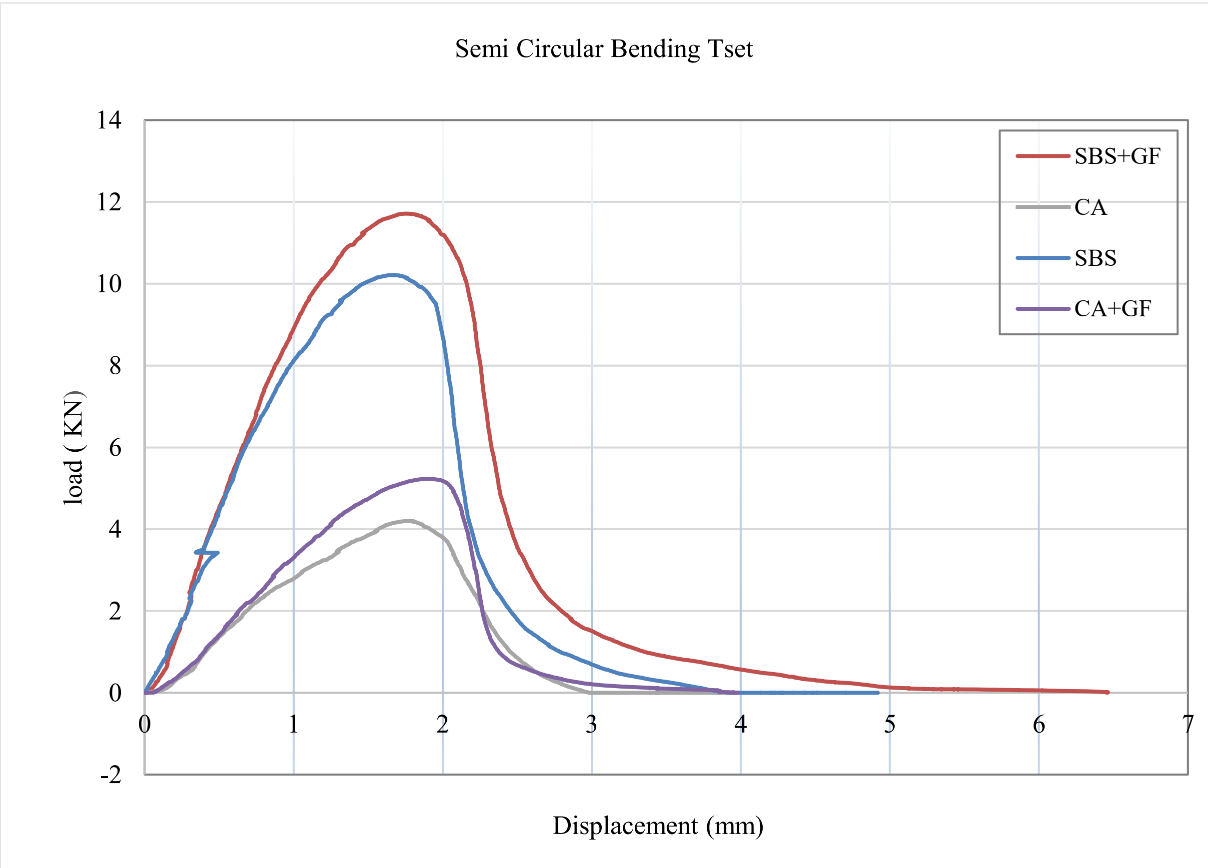


Figure 11. SCB test (load-displacement curves).

Gf rose 244% when SBS+GF was compared to CA. This increases the capacity to absorb fracture energy, so enhancing the resistance of cracks. Glass fibers (GF) improved fracture energy of CA and SBS matrices alike. For CA+GF, Gf increased by 22.5% compared to CA. For SBS+GF, Gf increased by 30.1% compared to SBS. Fibers likely contribute by minimizing microcracks and delaying crack propagation. Also, modification binder with SBS show enhancement in Gf with (164.4%) when compared with CA.

Wf, representing the total energy storaged in speciment until reach fracture, aligns closely with Gf trends, since Wf is a function of the total area under the load-deformation curve. The highest Wf shown by SBS+ GF confirms the synergistic effect of polymer and fiber modification on toughness and fracture resistance. The peak strength of every mixture is reflected in the maximum load. Again proving better load-bearing capacity, Also, the loads that required to failure increased with modification and GF reinforcement which indicate that the asphalt mixture's enhanced capacity to withstand higher tensile stresses before crack initiation. SBS+GF exhibits the highest maximum load (11.7124 kN), nearly tripling that of conventional asphalt (4.1999 kN). This substantial increase indicates stronger internal cohesion and better resistance to crack formation. It confirms the effectiveness of polymer and fiber reinforcement in improving structural integrity.

The enhanced performance observed in SBS- and GF-modified mixtures can be attributed to distinct but complementary mechanisms. SBS improves elasticity and viscoelastic recovery, reducing stress concentrations at crack tips. Glass fibers contribute by bridging microcracks, delaying crack coalescence and propagation. The synergistic effect in SBS+GF mixtures increases energy absorption (Wf, Gf) and post-peak ductility, indicating a transfing mode from brittle behaviour to ductile behaviour fracture.

Conclusion

This work aimed to investigate the fracture behavior and crack propagation resistance of mixtures, the combined effect of polymer modification using (SBS) and reinforcement with glass fibers (GF). The behavior was assessed by means of several laboratory experiments comprising both (SCB) and (ITS) tests. This study exposed how these additives improve the mechanical and fracture properties of mixtures.

The experimental findings reveal that SBS and GF have different but complementary purposes, so enhancing the performance of pavement. SBS greatly raised the asphalt mix tensile strength and fracture energy with its thermoplastic behavior and elastic recovery. On the other hand, glass fibers slowed down the spread of cracks, most likely employing stress redistribution inside the matrix and crack-bridging systems. When used together, the synergistic interaction between SBS and GF was especially amazing since it generated a mixture (SBS+GF) with the best resistance to cracking among all studied configurations.

The results guide one to the following generalizations:

- By increasing tensile strength and energy absorption capacity, SBS polymer (4% by asphalt weight) confirmed fit for high-stress environments. Adding glass fibers (0.5% by total mix weight), especially in the CA mixture, enhanced fracture resistance and slowed down crack propagation.
- The SBS+GF mix showed the best performance across all measures, maximum load, fracture energy (Gf), work of fracture (Wf), and CT Index, indicating that hybrid modification is more effective than using a single additive.
- The CT Index values validate the enhanced flexibility and durability of modified mixtures, especially in resisting fatigue cracking.

At last, hybrid modification with SBS and GF presents a practical and reasonable approach to raise the lifetime and performance of asphalt pavements. These modifications especially apply to roads with temperature fluctuations and heavy traffic loads. Future research should be mostly focused on the long-term durability of these mixtures under aging and environmental exposure, as well as field validation.

Recommendations

It's recommended to use the hybrid modification of SBS and Glass fibers to enhance the resistance to the crack initiation and propagation, also develop the mechanical performance, and long-term durability under diverse loading and temperature conditions.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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