

Article

Fiber Showdown: A Comparative Analysis of Glass vs. Polypropylene Fibers in Hot-Mix Asphalt Fracture Resistance

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Abstract: Cracks in asphalt mixtures compromise the structural integrity of roads, increase maintenance costs, and shorten pavement lifespan. These cracks allow for water infiltration, accelerating pavement deterioration and jeopardizing vehicle safety. This research aims to evaluate the impact of synthetic fibers, specifically glass fiber (GF) and polypropylene fiber (PPF), on the crack resistance of Hot-Mix Asphalt (HMA). An optimal asphalt binder content of 5% was used in all sample designs. Using the dry mixing technique, GFs and PPFs were incorporated into the HMA at dosages of 0.50%, 1.00%, and 1.50% by weight of the aggregate. The effects of these fibers on the mechanical fracture properties of the HMA were assessed using Semi-Circular Bending (SCB), Indirect Tensile Asphalt Cracking Tests (IDEAL-CTs), and Three-Point Bending (3-PB) tests. This study focused on fracture parameters such as fracture work, peak load, fracture energy, and crack indices, including the Flexibility Index (FI) and Crack Resistance Index (CRI). The results from the SCB and IDEAL-CT tests showed that increasing GF content from 0.5% to 1.5% significantly enhances the flexibility and crack resistance of HMA, with FI, CRI, and CT Index values increasing by 247.5%, 55%, and 101.35%, respectively. Conversely, increasing PPF content increases the mixture's stiffness and reduces its crack resistance. The PP-1 mixture exhibited higher FI and CT Index values, with increases of 31.1% and 10%, respectively, compared to the PP-0.5 mixture, based on SCB and IDEAL-CT test results. The SCB, IDEAL-CT, and 3-PB test results concluded that fibers significantly influence the fracture properties of bituminous mixtures, with a 1% reinforcement dosage of both PPFs and GFs being optimal for enhancing performance across various applications.

Keywords: fracture energy; glass fibers; crack resistance; semi-circular bending (SCB); polypropylene fibers; flexibility index



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1. Introduction

Cracking and rutting are among the most significant challenges that impede the performance of Hot-Mix Asphalt (HMA) in achieving its functional objectives, which include ensuring safety, enhancing ride quality, and extending the lifespan of pavement structures [1–3]. Frequent loading and temperature fluctuations are significant contributors to the development of fatigue and thermal cracks in asphalt. As stress from loading increases, fatigue cracks tend to propagate more rapidly, eventually leading to potholes and further structural deterioration of the pavement. Therefore, studying the various fracture performances of HMA is crucial in determining the optimal methods for resisting the initiation and spread of different types of cracks caused by various loading conditions on asphalt pavements [4–6].

For many years, various fracture performance tests and models have been employed to analyze the initiation and propagation of cracks in HMA. Linear elastic theory-based modeling has been particularly useful in predicting fracture behavior, especially concerning

fatigue cracks. Additionally, experimental models have been used to assess the impact of asphalt binder properties and mixture characteristics on fracture mechanics, specifically under conditions leading to thermal cracking [7,8]. Selecting the appropriate procedure for measuring the fracture performance of HMA involves various considerations, such as the feasibility and effectiveness of the test in assessing different design variables, the potential for establishing standardized testing methods, and the correlation of test results with field conditions. Consequently, the choice of a suitable method for measuring the fracture behavior of HMA is a complex process. Previous research findings have proposed different approaches for measuring the fracture performance of HMA, including Semi-Circular Bending (SCB), Indirect Tensile Asphalt Cracking Test (IDEAL-CT), and Three-Point Bending (3-PB) test [9–12].

The SCB test was originally developed to characterize and analyze the fracture performance of rocks. Over time, its application expanded to asphalt technology, where it is now widely used to evaluate the tensile strength, crack resistance, and fatigue performance of asphalt mixtures [13–17]. The SCB test is highly valued in road technology for several reasons, including its ease of sample preparation, cost-effectiveness, and quick execution. It is particularly sensitive to variables in asphalt mix design and can be performed on field core specimens with specified thicknesses. Moreover, the results of the SCB test are closely linked to the real-world behavior of asphalt cracks. The importance of understanding asphalt mixtures' performance at low temperatures has driven the development of the SCB test to study factors influencing fracture energy in such conditions. Studies have shown a strong correlation between predicted fracture energy at low temperatures and field data from various pavement sections [18–20].

The IDEAL-CT is like the traditional IDT (indirect tensile strength) test, which is still widely used in many countries to assess the fracture resistance of asphalt mixtures and tensile strength and viscoelastic features [21–23]. The IDEAL-CT is characterized by the ease of specimen preparation (no need for drilling, gluing, or cutting), simplicity (no intensive training required), and efficiency (completing the test takes no more than a minute). The test can be conducted by employing a typical indirect tensile strength testing device [24–26].

The 3-PB test is considered a promising tool for calculating the fracture energy of HMA [27]. It is an easily implementable and commonly used test to determine the fracture behavior of asphalt mixtures. It is widely employed to assess the fracture energy in specimens of HMA. It was demonstrated that regular techniques of determining mechanical strain on specimens, such as strain gauges, were not capable of consistently measuring localized or non-uniform strain [28]. Reinforced HMA with fibers is a type of mixture designed by incorporating fibers at various doses, usually as a percentage of the weight or volume of the aggregate or asphalt binder. Determining the fiber dosage in HMA requires careful attention and continuous improvement to avoid issues such as fiber clumping within the mix, in addition to operational feasibility concerns. Therefore, the preference still lies in adding low doses of fibers to HMA [29–32]. In addition to fiber dosage, other critical parameters such as fiber length, types, and mixing procedures should also be emphasized, given the growing usage of fibers in HMA. Selecting an appropriate fiber length is one of the criteria that influence the effectiveness of reinforcement. Longer fibers can lead to clumping during mixing, while very short fibers become expensive fillers that fail to achieve the desired reinforcement [33]. Wet mixing and dry mixing represent the primary classifications for incorporating fibers into HMA. In the wet mixing approach, the fibers are blended with the asphalt binder before the addition of an aggregate. This method is applied when utilizing fibers with a low melting point that is close to the mixing temperature, ensuring effective incorporation [34,35]. In the dry mixing process, the fiber dosage is blended with the aggregate before adding the bitumen binder. The dry mixing technique is preferable when utilizing fibers with high melting points [36,37]. Fibers used in pavement reinforcement technology are categorized into two primary groups based on their material origin: natural fibers and synthetic fibers. Glass fibers (GFs) and polypropylene fibers

(PP.Fs) are synthetic fibers widely employed in HMA pavement applications due to their ability to enhance asphalt mixture properties, along with the added benefits of easy availability and straightforward application. GFs are classified as inorganic fibers characterized by high melting points and tensile strength, as well as being non-flammable [38]. Different lengths of GFs serve as effective modifiers for constructing bituminous pavements. For instance, the addition of 12 mm long GFs significantly enhances the mechanical properties of the mixture, such as Marshall stability and elastic deformation, at the same bitumen content, thereby preventing rutting and bleeding at high temperatures. Incorporating various doses of 10 mm GFs has shown substantial improvement in the moisture resistance and rutting resistance of bituminous mixtures. Regarding fracture behavior, GFs with lengths of 3 and 8 mm have demonstrated a significant increase in fracture energy values and flexibility indices of the modified mixture [39–41]. The results support numerical analyses showing the impact of GFs on improving bituminous mixtures. Reinforcing reclaimed pavements with glass fiber doses increases fracture resistance under the influence of repeated freeze–thaw cycles. Multi-criteria analysis indicates that incorporating GF into porous mixtures, with lengths ranging from 4 to 10 mm and tensile strengths between 2000 and 3000 MPa, significantly enhances the tensile strength of the bituminous mixture, though this incorporation results in a slight reduction in void content and porosity [42]. Moreover, the integration of GFs fortifies the bituminous matrix by forming a network structure and facilitating the absorption of bitumen and aggregates, thereby enhancing the mixture's resistance to fatigue, rutting, and cracking [43]. PP.Fs are one of the most widely used bituminous modifiers due to their positive impact on the properties of bituminous binders and mixtures. PP.Fs have demonstrated high efficacy in enhancing the durability of bituminous mixtures, including resistance to heat, rutting, oxidation, moisture, and fatigue [44]. Additionally, PP.Fs exhibit three-dimensional reinforcement characteristics, setting them apart from other fiber types [45,46]. Performance assessments of bituminous binders modified with 5% thermally degraded PP show decreased heat sensitivity, resulting in enhanced mechanical performance [47]. Upon investigating the impact of aging conditions on Marshall bituminous samples modified with PP.Fs, findings indicate that fiber-reinforced mixtures exhibit superior flexibility, durability, and adhesive performance compared to control samples, along with improved moisture resistance and fracture indicators [48]. Moreover, investigations into the effect of PP.F length on fiber dispersion within modified mixtures reveal that shorter fibers disperse more effectively than longer ones. The results from the four-point beam test and the IDEAL-CT indicate that PP.F-reinforced mixtures possess enhanced crack resistance across various temperatures compared to non-reinforced mixtures [49]. By evaluating the impact of PP.Fs on fracture parameters, the results from 3D image analysis and the response surface method reveal that bituminous mixtures modified with up to 0.2% PP.Fs by aggregate weight enhance peak load values and indirect tensile strength, while also reducing the brittleness index and the percentage of broken aggregates [50].

This investigation examined the effects of varying rates of G.Fs and PP.Fs on the properties of Hot-Mix Asphalt (HMA) prepared with the same optimal bitumen content. This study compared the impact of G.Fs and PP.Fs on resistance to damage and crack propagation by analyzing the results from SCB, IDEAL-CT, and 3-PB tests. While previous research primarily focused on individual tests such as SCB, IDEAL-CT, or 3-PB to evaluate the fracture behavior of HMA [51–55], this study took a more comprehensive approach by analyzing the results of three different tests conducted under various loading rates and specimen geometries. This research thoroughly examined key parameters related to fracture behavior, including fracture energy, peak load, fracture work, Flexibility Index (FI), and Crack Resistance Index (CRI). Additionally, the SCB test specimens were prepared using a Marshall specimen as the base material.

2. Materials, Manufacturing Methodology, and Mechanical Testing

2.1. Materials

Aggregate: The functional behavior of HMA is closely linked to the properties of the mineral aggregate, which makes up 95% of its matrix weight, with the remaining 5% being asphalt binder [56]. Various types of aggregates can be used in asphalt mixtures, differing in size and mineral composition. The performance and mechanical behavior of asphalt mixtures are directly influenced by the properties of the aggregate, including type, grading, particle size, and geometric shape. In this research, limestone aggregate was selected for preparing the study specimens due to its superior moisture resistance compared to other aggregates, such as silica [57]. The gradation of the aggregate mixture, which included coarse limestone aggregate, fine sand aggregate, and mineral powder in specific proportions, met the specified limits according to AASHTO specifications. Figure 1a presents the outcomes of the aggregate gradation.

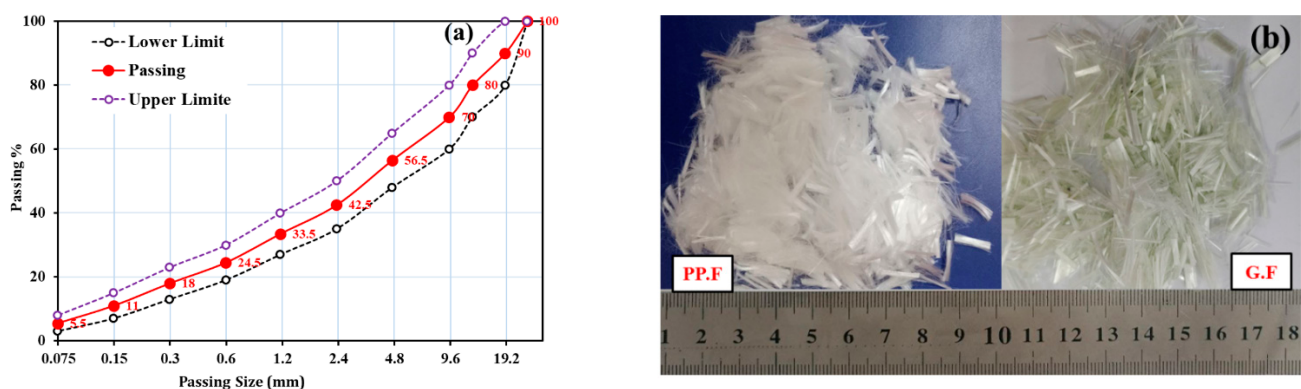


Figure 1. Material properties: (a) gradation of HMA aggregates and AASHTO specification limits and (b) general appearance of the fibers.

A series of laboratory tests were conducted on the aggregate used in the study to measure various properties and ensure compliance with standard specifications. Table 1 presents the results of these laboratory tests. The engineering properties of the aggregate materials and the bituminous mixture were assessed in accordance with the standards established by the American Society for Testing and Materials (ASTM).

Table 1. Characteristics of the materials used in the study.

Aggregate:			
Property	Results	Specification	Specification Limit
Bulk relative density	2.695	ASTM C 127	-----
Apparent relative density	2.713	ASTM C 127	-----
Water absorption (%)	2.40	ASTM C 127	<2.6
Los Angeles abrasion (%)	25	ASTM C 131	<28
Bitumen:			
Property	Test Results	Test Method	
Specific gravity	1.02	ASTM D70	
Penetration at 25 °C (0.1 mm)	65	ASTM D5	
Softening point (°C)	54	ASTM D36	
Kinematics viscosity (at 120 °C), (cSt)	745	ASTM D2170	
Kinematic viscosity (at 135 °C), (cSt)	330	ASTM D2170	
Kinematic viscosity (at 160 °C), (cSt)	103	ASTM D2170	
Flash point (°C)	319	ASTM D92	

Table 1. Cont.

Fiber Type	Fiber Length (mm)	Fiber:			
		Specific Gravity	Modulus of Elasticity (GPa)	Tensile Strength (GPa)	Fracture Deformation
PP.F	18	0.91	4.048–5.674	0.467–0.548	-----
G.F	18	2.60	70–80	2.40	2–3.5

Bitumen: Bitumen of B 60/70 grade from the Suez refinery was used in the study. Various physical tests for the binder are detailed in Table 1.

Synthetic Fiber: Two types of synthetic fibers, widely recognized in the literature as effective modifiers for HMA, were introduced to reinforce the asphalt mixture. The physical and mechanical properties of the G.Fs and PP.Fs used in this study are presented in Table 1, with specifications provided by the manufacturer (Egyptian Fiber Company, Cairo, Egypt). While manufacturers offer various lengths of G.Fs and PP.Fs, this research specifically utilized an 18 mm fiber length for both types, based on recommendations from previous investigations [33,58].

Figure 1b illustrates the general appearance of the G.Fs and PP.Fs added to the study mixtures. The photos highlight the impact of different production methods on the fiber diameters, showing that G.Fs have a coarser granular structure compared to PP.Fs. This structural difference is reflected in the physical and mechanical properties of the mixtures, with the variation in fiber diameter potentially leading to mixing difficulties during specimen production.

2.2. Manufacturing Method

The initial stage of the study involved determining the optimal asphalt content suitable for the specified aggregate gradation using the Marshall method. This optimal asphalt content was then utilized to prepare the necessary specimens for fracture testing, which was the primary focus of the study. The SCB, IDEAL-CT, and 3-PB tests were employed to evaluate the fracture performance of the HMA. Figure 2a illustrates the methodology followed in this study.

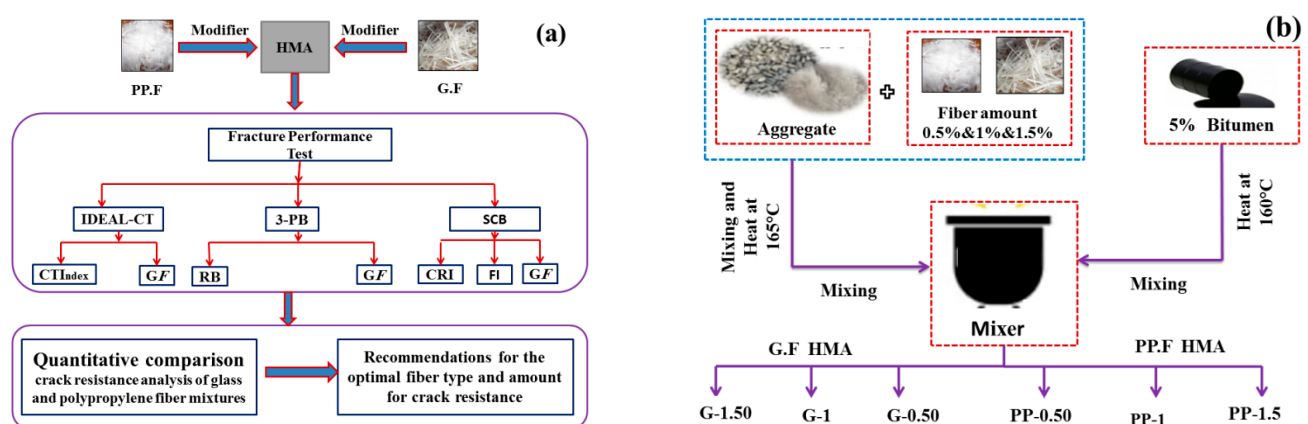


Figure 2. (a) Research flowchart and (b) dry mixing method in adding fiber in HMA.

Marshall Mix Design: To evaluate trial mixtures of lab-mixed, lab-compacted (LMLC) asphalt mixtures, the Marshall stability and flow test values, along with the density and air voids in both the mix and the mineral aggregate, are assessed. Additionally, Marshall stability and flow tests can monitor the production of asphalt mixtures through both plant-mixed and laboratory-compacted (PMLC) samples [59]. Initially, the optimal bitumen content was determined by conducting Marshall stability tests on asphalt mixtures with five different bitumen levels (4%, 4.5%, 5%, 5.5%, and 6%). Beyond assessing stability and

flow, the fundamental physical properties of the asphalt specimens such as air voids in the mixture (Va), voids in the mineral aggregate (VMAs), compacted density, and voids filled with bitumen (VFBs) were also evaluated. The highest unit weight, maximum stability, and a requirement of 4% air voids led to selecting 5% as the optimal binder content. Using this optimal binder content, investigation specimens were prepared with PPFs and GFs, each 18 mm in length, at three different fiber contents (0.50%, 1.00%, and 1.50%) by weight of the aggregate, while accounting for the minimal bitumen absorption by the fibers during mixing, as suggested by previous research [49,60–62]. Consequently, Marshall stability tests were conducted on these specimens prepared with varying fiber dosages. Table 2 presents the naming of the investigated mixtures according to the quantity and type of fibers added.

Table 2. Tested mixture types and their corresponding nomenclature.

Mixture	Dosage of synthetic fibers added to the asphalt mixture
Control	Asphalt mixture without fiber modifier
PP-0.5	Asphalt mixture enhanced with 0.5% polypropylene fiber
PP-1	Asphalt mixture enhanced with 1% polypropylene fiber
PP-1.5	Asphalt mixture enhanced with 1.5% polypropylene fiber
G-0.5	Asphalt mixture enhanced with 0.5% glass fiber
G-1	Asphalt mixture enhanced with 1% glass fiber
G-1.5	Asphalt mixture enhanced with 1.5% glass fiber

Fiber Mixing Methods: The dry mixing technique was utilized to incorporate G.Fs and PP.Fs into the mixture components to compare their effects on the fracture performance of HMA. Despite the melting point of PP.Fs (165 °C) being close to the asphalt mixing temperature, the dry mixing method was chosen due to its distinct advantages. This technique is favored for several critical reasons: it ensures superior fiber dispersion within the aggregate before the bitumen binder is added, minimizing the risk of fiber clumping and promoting a more consistent mixture. Additionally, the dry mixing method is straightforward and cost-efficient, making it ideal for large-scale production. These benefits highlight the effectiveness of dry mixing in achieving uniformity and economic feasibility in creating fiber-reinforced asphalt mixtures. The G.Fs and PP.Fs were mixed with the aggregate for 90 Sec, the minimum duration necessary to achieve proper fiber dispersion, as suggested by previous studies [63]. The mixture was then heated to 160 °C, approximately 10 °C higher than the conventional asphalt mixture temperature (150 °C), to fully remove moisture from the aggregate mixture. Following this, the heated asphalt binder, also at 160 °C, was combined with the fiber–aggregate mixture using a low-shear mechanical mixer at a speed of 700 rpm. The study specimens were then compacted using various techniques based on the specimen geometry, following ASTM D1559-76 specifications, at a minimum temperature of 143 °C. Figure 2b illustrates the laboratory preparation method for the fiber-modified asphalt mixture. Challenges were encountered with G.Fs during the mixing process, particularly in specimens with higher fiber content, compared to PP.F mixtures. The analysis revealed issues such as clumping and the need for additional bitumen in G.F specimens, especially at higher fiber levels, leading to uneven distribution within the mixture. Consequently, physical tests indicated undesirable outcomes in parameters like air voids and bulk density compared to PP.F mixtures. These findings suggest that polypropylene fibers outperform glass fibers in enhancing the overall behavior of bituminous mixtures, consistent with previous studies [47,64,65].

2.3. Mechanical Testing

2.3.1. Semi-Circular Bending (SCB) Test

The fracture test was conducted on asphalt mixtures modified with GFs and PPFs using SCB specimens, which have recently gained popularity among researchers in the field of

HMA. The procedures for preparing SCB test specimens are outlined in Figure 3a. Asphalt mixture samples with a diameter of 101.6 mm and a height of 63.5 mm were compacted by delivering 75 blows to each side of the specimen, strictly adhering to ASTM D6926 specifications to maintain the integrity of the bituminous mixture's properties. Compaction was performed using a mechanical compactor equipped with a 4.5 kg hammer, dropped from a height of 45 cm at a consistent rate of 60 blows per minute. The target air void content for these test samples was set at 7.0%, following ASTM D8044 specifications. The Marshall specimen was then cut in half with a diamond saw to produce two half-cylinder samples, each with dimensions of 101.6 mm in loading length, 50.8 mm in height, and 63.5 mm in width. A notch, 10 mm deep and 1.5 mm wide, was created in the middle of the specimen to ensure it did not affect the stress distribution within the specimen, as indicated by previous studies [51,62].

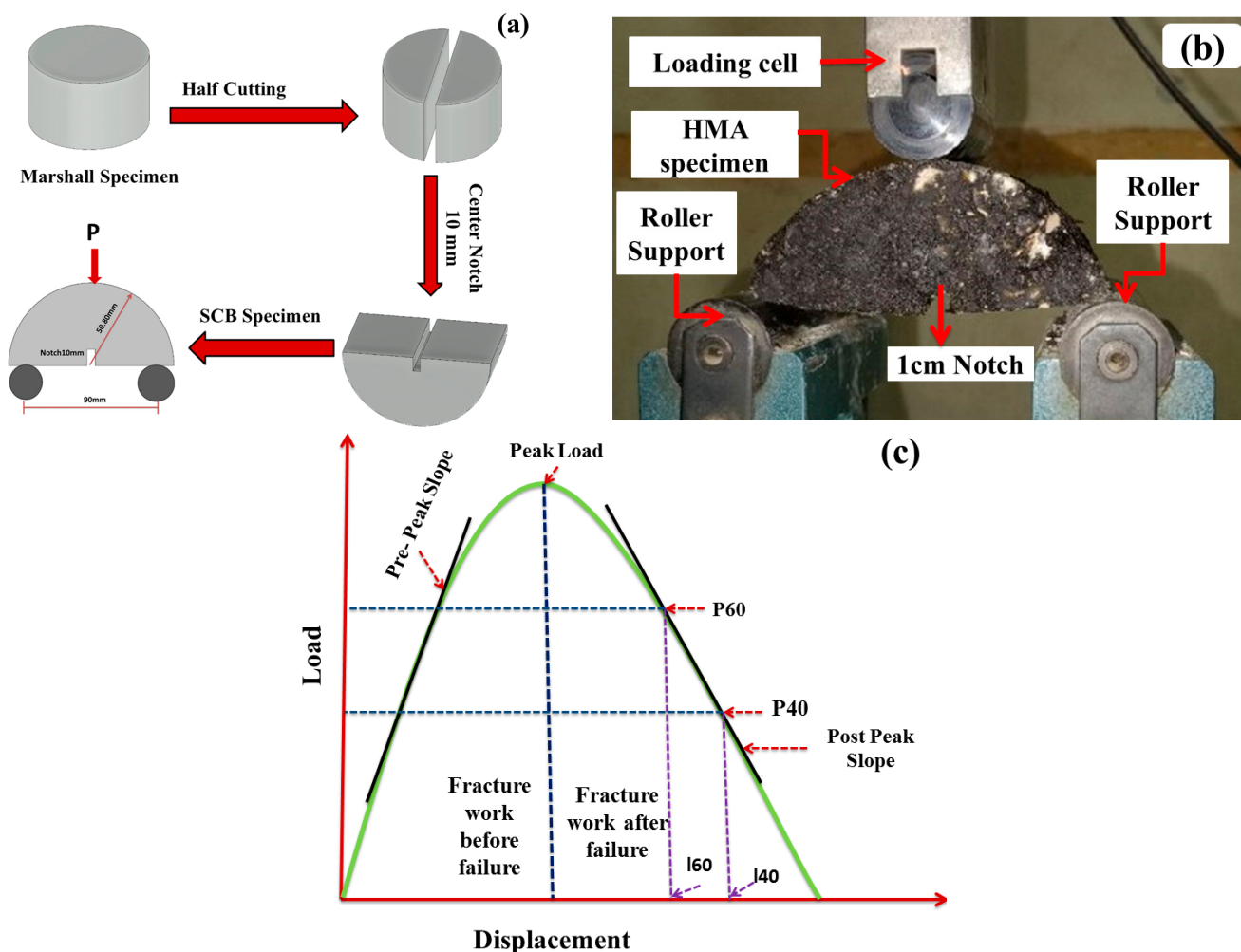


Figure 3. SCB test information: (a) preparing of SCB test specimens, (b) specimen set-up during loading, and (c) standard load–displacement curve of SCB test with fracture parameter definitions.

After completing the preparation stages, the specimen is conditioned at the target temperature of 25 °C for a minimum of 8 h. It is then placed in the Universal Testing Machine (UTM), with a support distance of 90 mm, and subjected to a loading rate of 5 mm/min. The peak load and fracture energy are recorded for each specimen [40] (see Figure 3b). The UTM is a computer-controlled electromechanical machine with the following specifications: machine model WDW-300D, voltage 380 V, 50 Hz, 3-phase, and a maximum load capacity of 100 kN/mm, used for tensile, compression, and bending tests (Serial No. 0771, production date: 25 December 2007). During the test, the load–displacement curve for

each specimen was recorded using the UTM for three specimens of each mixture under investigation. The fracture energy of the HMA was calculated using Equation (1), placing greater emphasis on fracture parameters rather than on the mixture's homogeneity and linear elasticity characteristics.

$$G_f = \frac{W_f}{t * (r - a)} \quad (1)$$

Here, G_f is the fracture energy value (J/m^2); W_f indicates the area below the load–displacement curve ($N.mm$). The symbols of r , t , and a are the SCB specimen's radius, thickness, and notch length in (m), respectively. Equations (2) and (3) were utilized to determine the parameters of the FI and CRI for HMA specimens reinforced with G.Fs and PP.Fs.

$$CRI = \frac{G_f}{\text{Peak Load}} \quad (2)$$

$$FI = 0.01 * \frac{G_f}{\text{Post - peak slope}} \quad (3)$$

The load–displacement curve of the tested specimens was analyzed to determine the pre-peak load slope, peak load, fracture energy, and post-peak load slope. The post-peak slope was determined by finding the slope of a line drawn between points at 60% and 40% of the peak load value in the post-peak phase [66] (see Figure 3c).

2.3.2. Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The Indirect Tensile Asphalt Cracking (IDEAL-CT) test is performed to evaluate and compare the effects of GFs and PPFs on enhancing the cracking resistance of asphalt mixtures. This test, recognized as a standard procedure in asphalt pavement technology, involves applying compressive loads to cylindrical Marshall specimens with target air voids of 7.0%, following ASTM D 8225. The loading mechanics generate indirect tensile stress along the length of the loading axis, with failure observed along the circumferential diameter of the specimen. The test was conducted using a UTM, applying a vertical load at a rate of 50 mm/min at a temperature of 25 °C (see Figure 4a). The specimen deforms under the increasing load until reaching the peak load, after which the load value decreases until it reaches 0.01 kN, marking the end of the test [67].

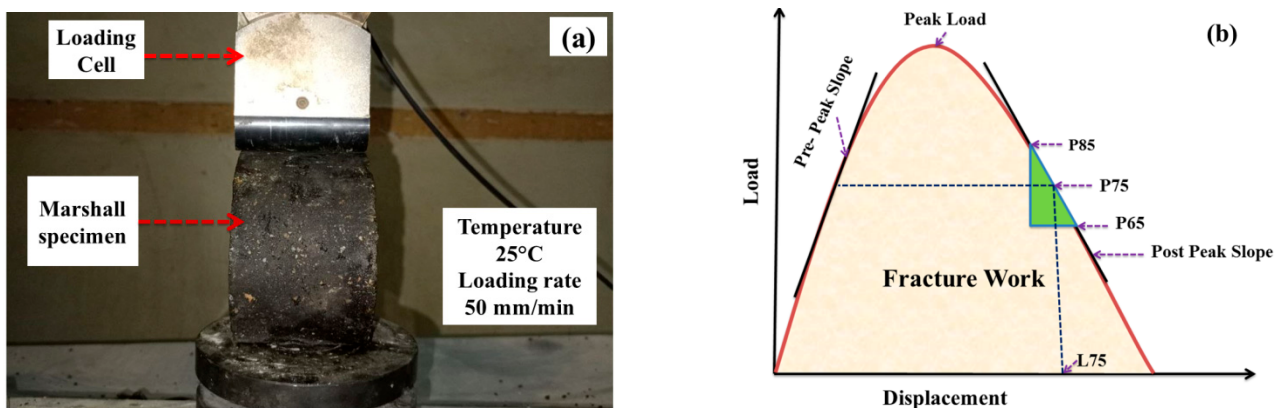


Figure 4. IDEAL-CT information: (a) specimen set-up during IDEAL-CT loading and (b) load–displacement curve of IDEAL-CT with fracture parameter definitions.

The load–displacement curve for the IDEAL-CT was captured during the testing process. Dividing the curve into two parts, pre-peak load and post-peak, facilitated the derivation of the CT Index, which indicates the resistance of HMA to crack propagation. As the CT Index value increases, the rate of crack propagation in the mixture decreases (see Figure 4b). The CT Index value for the tested specimen is determined according to Equations (4) and (5).

$$|m75| = |(P85 - P65)/(L85 - L65)| \quad (4)$$

$$CT - Index = \frac{t}{62} * \frac{Gf}{|m75|} * \frac{L75}{D} \quad (5)$$

Here, Gf is the fracture energy (J/m^2), $|m75|$ is the slope at point 75% peak in the post-peak load phase, $L75$ is the displacement value at point 75% peak in the post-peak load phase (mm), $P85$, $P75$, and $P65$ are the applied load values at points 85%, 75%, and 65% of the peak load value in the post-peak load stage (kN), D is the diameter of the IDEAL-CT specimen (mm), t is specimen thickness (mm), and CT Index is the specimen cracking index [24].

2.3.3. Three-Point Bending (3-PB) Tests

The impact of G.Fs and PP.Fs on the fracture behavior of HMA was evaluated using specimens from the 3-PB test. For each fiber dosage, three beams measuring $250 \times 100 \times 50$ mm, cut from a compacted asphalt mixture slab with a diamond saw, were tested to assess the tensile behavior of the reinforced mixtures, including bending strength and maximum tensile stress. To ensure precision and reliability, the bituminous mixture in this test was engineered with a targeted air void content of 7% of the total sample volume, in accordance with ASTM D8237 specifications. The specimens were placed in a UTM, where each beam was supported on two rollers and subjected to a load applied at the center of the beam at a rate of 5 mm/min until failure occurred [27]. Figure 5a illustrates the geometric shape of the specimen, while Figure 5b shows the specimen preparation during the test. In this test, both the displacement at the midpoint of the test beam and the maximum load were recorded.

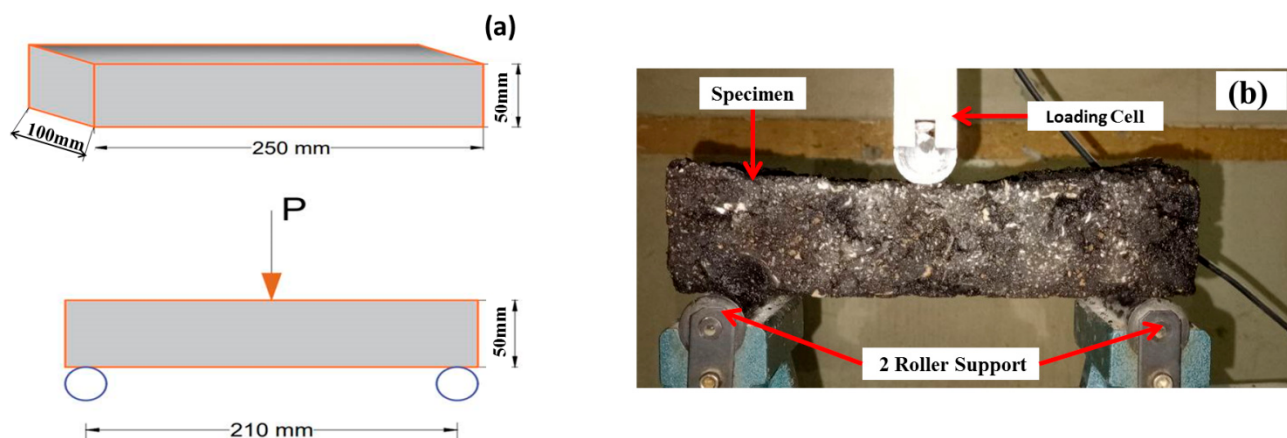


Figure 5. The 3-PB test information: (a) Specimen geometry of 3-PB test. (b) Specimen set-up during 3-PB test loading.

The maximum bending stress was calculated as follows:

$$RB = \frac{3 L P}{2bh^2} \quad (6)$$

where RB is the maximum bending stress (MPa), L is the total length of the specimen (250 mm), P is the maximum load in case of a failure (N), b is the specimen width (100 mm), and h is the specimen height (50 mm) [63].

3. Results and Discussion

The results in this section represent the average of three repetitions for each mixture. Outliers, defined as values exceeding 20% of the mean, were excluded to ensure accuracy. To further minimize uncertainty, error bars representing the standard error have been

included in the graphical representations. The standard error was calculated by dividing the standard deviation by the square root of the number of repetitions.

3.1. Physical Properties and Marshall Results of Fiber HMA

The influence of PP.Fs and G.Fs on the unit weight and air voids of various asphalt mixtures (PP-0.50, PP-1, PP-1.50, G-0.50, G-1, and G-1.50) is illustrated in Figure 6a. The unit weight of PP.F mixtures ranges from 2.365 to 2.330 g/cm³, generally decreasing as the PP.F percentage increases compared to the control mixture. Similarly, G.F mixtures show unit weights ranging from 2.362 to 2.341 g/cm³, with all tested samples exhibiting slightly lower unit weights than the control mix, although without a consistent trend. The air voids in G.F mixtures follow a similar pattern, with G-0.50 showing approximately 3.85% and G-1.50 around 4.35%. The addition of G.Fs initially decreases unit weight and increases air voids, as the fibers create additional void spaces and affect compaction. However, exceeding the optimal fiber content reverses these trends due to poor dispersion and clumping, leading to increased density and reduced effective air voids. In PP.F mixtures, the air void content increases with higher PP.F content, ranging from 3.55% (PP-0.50) to nearly 4.15% (PP-1.50) compared to 3.3% for the control mixture. These results suggest that adding PP.F and G.F to asphalt mixtures reduces unit weight and increases air voids, which may influence durability but could also enhance flexibility and crack resistance. These findings are consistent with previous research on fiber-reinforced asphalt mixtures [36,46,68].

Figure 6b displays the effect of PP.Fs and G.Fs on VMAs and VFBs in asphalt mixtures. VMAs in PP.F mixtures range from 15.55% to 16.5%, increasing as the fiber content increases. Similarly, G.F mixtures show an upward trend in VMAs, with G-1.50 reaching the highest VMA at 17.3%. The increase in PP.F content is associated with a reduction in VFBs compared to the control mixture. In the G.F group, the G-0.5 and G-1 mixtures exhibit a pattern similar to that of the PP.F mixtures. However, the G-1.5 mixture shows an increase in VFBs compared to the G-1 mixture, likely due to the higher air void content mentioned earlier. These findings highlight the influence of fibers on the internal structure of the asphalt mixture, affecting air void distribution and bitumen content. Generally, higher VMA values indicate more internal air voids, impacting compaction and durability, while lower VFB values suggest decreased bonding ability and moisture resistance. VMA and VFB properties are critical in asphalt mixture design as they directly impact pavement durability, stability, and overall performance. Achieving an optimal balance between these factors is essential for enhancing the efficiency and longevity of asphalt mixtures.

The Marshall stability and flow test results for the control asphalt specimen and those modified with G.Fs and PP.Fs at contents of 0.5%, 1.0%, and 1.5% are presented in the subsequent section of the study. The results clearly demonstrate that, compared to the control specimen and G.F mixtures, PP.F mixtures yield superior outcomes in terms of increased stability and reduced flow, up to a fiber content of 1.5%. Conversely, for G.F mixtures, stability and flow properties improve at a 0.5% fiber content, but performance declines as the G.F content increases beyond this point. The superior performance of PP.F-reinforced asphalt mixtures is attributed to the even distribution of PP.Fs and the absence of clumping during mixing, unlike G.Fs. This improved performance enhances the asphalt mixture's resistance to deformation during the Marshall test (see Figure 6c). Marshall stability measures the asphalt mixture's resistance to deformation and cracking under load, with fibers reinforcing the mixture and helping to distribute the load more evenly, thereby increasing its strength and durability. The studies of [69,70] suggest that the effectiveness of fiber reinforcement varies based on factors such as the type of asphalt, the type and content of fiber, and other material properties. Research indicates that adding fibers can enhance Marshall stability by up to 30%. Although the exact mechanism by which fibers improve Marshall stability is not fully understood, it is believed that fibers form a three-dimensional network within the mixture, which enhances its overall strength and resistance to deformation [59].

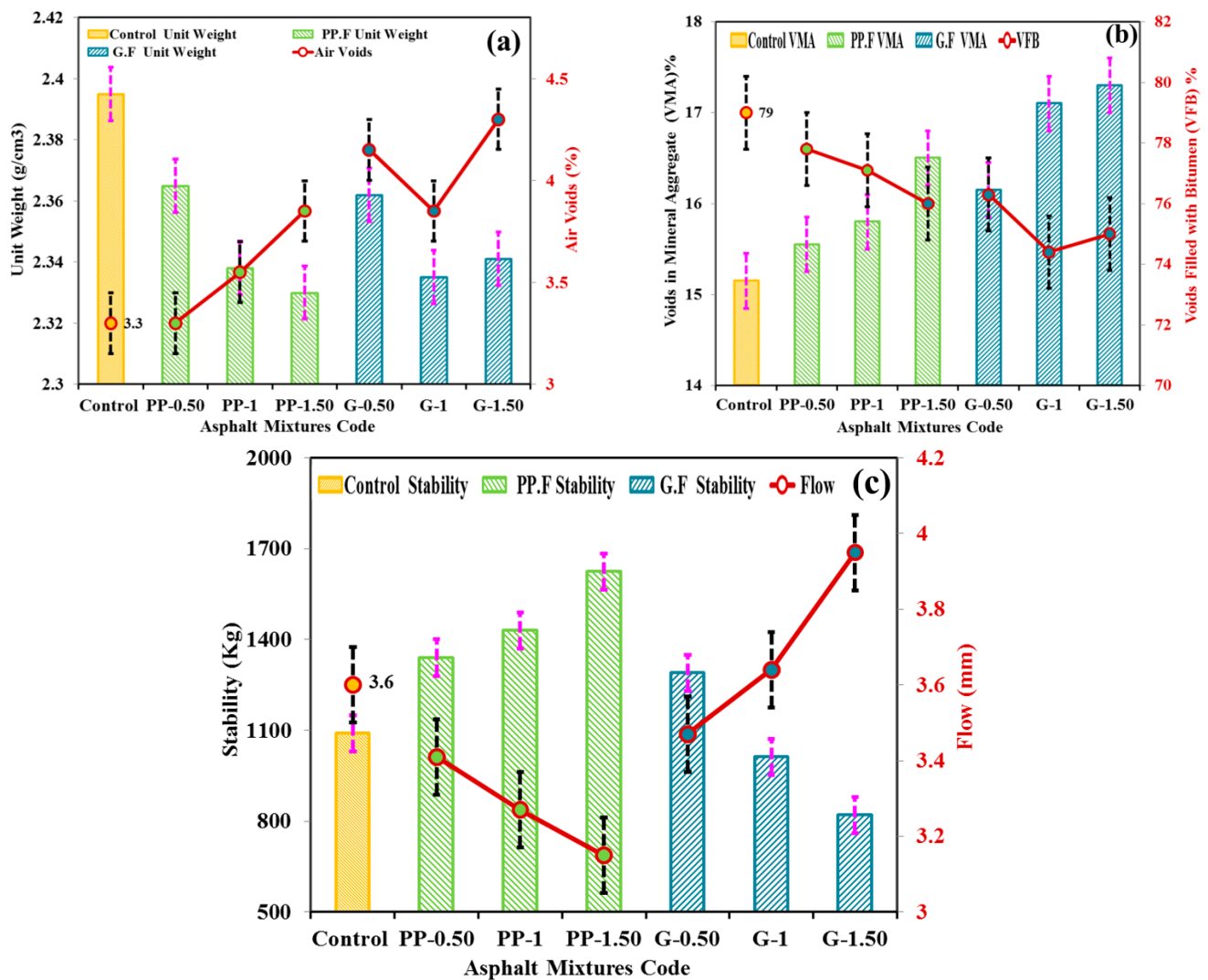


Figure 6. Effect of fiber on physical properties and Marshall results. (a) Unit weight and air voids, (b) VMAs and VFBs, and (c) Marshall stability and flow.

3.2. Semi-Circular Bending (SCB) Test Results

The progression of cracking in an asphalt mixture during the SCB test is illustrated in Figure 7a. By examining the stages of crack initiation, propagation, and final failure, the mixture's structural integrity and failure mechanisms become evident. The first image highlights the onset of cracking under loading, marking the initial loss of tensile strength in the mixture. The subsequent image shows crack propagation, demonstrating the material's resistance to deformation under constant load and the role of fiber reinforcement in distributing stress. The final image depicts the complete fracture of the mixture, characterized by multiple breakages, indicating the ultimate failure of the reinforced mixture under load, though with controlled performance due to the presence of fibers. These stages of failure in the bituminous mixture during the SCB test can be clearly observed in Figure 7a. The failure of the bituminous mixture can be categorized into three types based on the influence of tensile and shear stresses. These include the following: Tensile Failure (Mode I): This type of failure occurs when the crack propagates perpendicular to the direction of the applied load. It happens at the beginning of the load application under the high influence of tensile stresses. Shear Failure (Mode II): This failure occurs when the crack propagates parallel to the direction of the applied load. It takes place after some time of load application, where the shear stresses have a more significant impact on the SCB specimen. Mixed-Mode Failure (Mode I–II): This type of failure occurs when both tensile and shear stresses are

present. It can be observed at the end of the test. These classifications help in understanding the complex stress interactions within the bituminous mixture during the SCB test [10]. Figure 7b displays the load–displacement curves for asphalt mixtures with varying doses of G.Fs and PP.Fs during the SCB test. The pre-peak slope of PP.F mixtures increases with the fiber content, with the PP-1.5 mixture exhibiting the steepest slope and the highest initial stiffness. Similarly, the pre-peak slope in G.F mixtures also increases with fiber content, but it is generally less steep than in PP.F mixtures. After the peak, the slope in PP.F mixtures drops sharply, indicating a rapid loss of load capacity after cracking. In contrast, G.F mixtures show a more gradual decline, with G-1.5 demonstrating better load retention and resistance to cracking. This enhances the deformation and cracking resistance of G.F-reinforced mixtures, thereby improving pavement durability. The load–displacement curve from the SCB test provides critical insights into the effects of fibers on asphalt, particularly in terms of stiffness and cracking behavior [71].

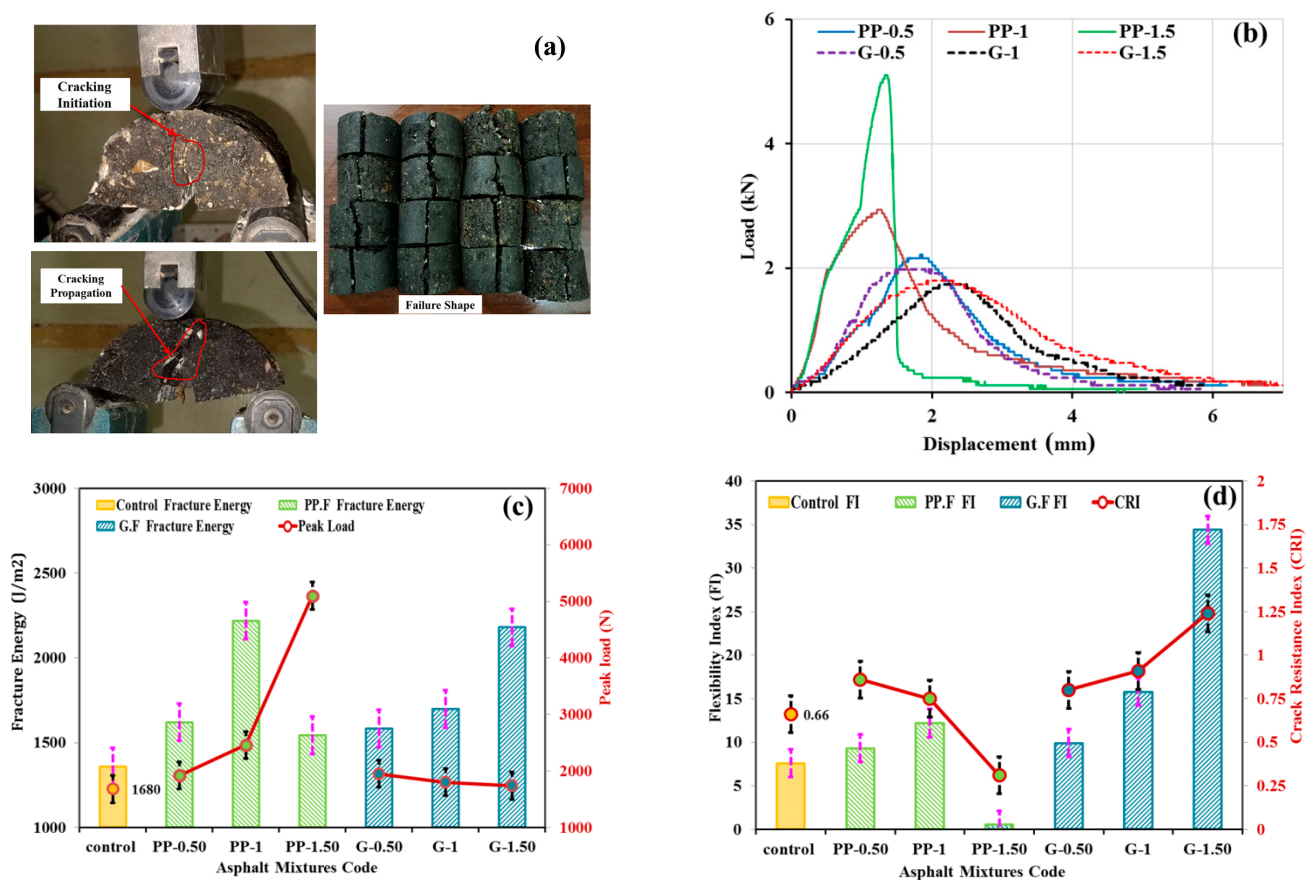


Figure 7. Effect of fiber amount on SCB test results: (a) crack development, (b) load–displacement curves, (c) fracture energy and peak load, and (d) FI and CRI.

Analyzing fracture energy and peak load is essential for assessing the impact of fibers on asphalt's crack resistance. Higher values indicate a stronger mixture with better crack resistance, while lower values suggest less effective reinforcement. It was observed that PP.Fs enhanced peak load values more effectively than G.Fs. Peak load values were highest in the PP.F and G.F mixtures at fiber dosages of 1.5% and 0.50%, respectively. The PP-1.5 and G-0.5 mixtures showed peak load increases of 203.6% and 16.1%, respectively, compared to the control mixture. The highest peak load in the PP-1.5 mixture exceeded that in the G-0.5 mixture by 161.5%. As shown in Figure 7c, peak load values for G.F mixtures decrease as the fiber addition rate increases, although they remain higher than the control specimen, likely due to fiber clumping at higher G.F contents. Conversely, in the PP.F-reinforced mixtures, peak load values increase with higher fiber content, attributed to the homoge-

neous distribution of PP.Fs even at higher dosages. Figure 7c also illustrates the average fracture energy values for HMA specimens modified with G.Fs and PP.Fs. The addition of G.Fs significantly enhances fracture energy, with the highest value observed in the G-1.5 mixture, showing a 60.4% increase compared to the control. In PP.F-reinforced mixtures, the highest fracture energy was recorded in the PP-1 mixture, with a 63.2% increase over the control, making it 1.8% higher than the G-1.5 mixture. This significant increase in the PP-1 mixture is attributed to the optimal amount of PP.Fs, which enhances tensile strength and improves energy absorption. Better distribution and bonding of PP.Fs result in more effective load transfer and crack bridging, increasing fracture energy. However, in the PP-1.5 mixture, fracture energy decreases due to uneven fiber distribution and clumping at higher contents, leading to increased brittleness. Overall, the PP-1 mixture exhibits the highest fracture energy, indicating that this fiber content is optimal for enhancing fracture resistance, demonstrating that fiber reinforcement positively impacts the fracture toughness of asphalt pavement. According to a previous study [32], adding an amount of fiber to an asphalt mixture improves its low-temperature fracture performance. The positive impact of fiber content is both clear and consistent. G.Fs notably enhance resistance to I-II compound cracks, though their effect on I cracks is less significant. Additionally, another study found that adding fibers improved the low-temperature cracking behavior of asphalt mixtures by increasing both fracture energy and tensile strength [72].

Figure 7d presents the CRI values for the specimens modified with G.Fs and PP.Fs, as well as the control specimen. An increase in CRI indicates improved mix flexibility and enhanced crack resistance [66]. The G.F mixtures display better crack resistance behavior compared to the PP.F mixtures. Increasing the G.F content significantly boosts the CRI value, with the highest value observed in the G-1.50 mixture, which shows an 87.9% increase from the control mixture. In contrast, the highest CRI value in the PP.F mixtures occurs in the PP-0.50 mixture, with a 30.3% increase compared to the control, followed by a sharp decrease. The CRI value for G-1.50 (the optimal mixture in the G.F group) exceeds that of PP-0.50 (the optimal mixture in the PP.F group) by 44.2%. The PP-1.50 mixture showed a CRI value lower than the control sample, indicating a negative effect when the fiber addition rate exceeds 1%. Laboratory tests revealed that the G-1.50 mixture exhibited the highest FI value among all study mixtures. As shown in Figure 7d, increasing the G.F content significantly increases FI values, with the FI values in the G-0.5, G-1, and G-1.50 mixtures increasing by 6.1%, 69.9%, and 269.8%, respectively, compared to the control specimen. In the PP.F mixtures, the highest FI value is observed in the PP-1 mixture, with a 31.2% increase over the control, after which it sharply declines. Increasing PP.F content to 1.50% reduces the FI value below that of the control specimen. The significant FI decrease in the PP-1.5 mixture is likely due to poor fiber dispersion and clumping in the asphalt matrix, resulting in ineffective reinforcement and increased brittleness. While fibers can enhance tensile strength and flexibility up to an optimal content, exceeding this amount—as in the PP-1.5 mixture—diminishes performance. The optimal fiber content in PP-1 improves properties, but adding more fibers, as in PP-1.5, exceeds the beneficial limit, leading to lower CRIs and FIs at constant bitumen binder content [73].

3.3. Indirect Tensile Asphalt Cracking Test (IDEAL-CT) Results

The fracture energy parameters and Flexibility Indexes of the specimen increase as the applied load on the specimen intensifies until failure occurs, according to an analysis of the IDEAL-CT results. As a result, the asphalt mixture becomes more effective at resisting deformation. The sequence of images in Figure 8a illustrates the progression of cracks during the IDEAL-CT in an asphalt mixture modified with either G.Fs or PP.Fs. Similar to the SCB test, the stages observed include crack initiation, propagation, and eventual failure. Initially, a visible crack forms under tensile stress. As the load continues to be applied, the crack propagates, indicating the mixture's ability to resist further deformation. The final stage shows a complete fracture, demonstrating how fiber reinforcement delays failure and enhances the tensile strength and crack resistance of asphalt mixtures. This

process underscores how fiber modifications contribute to controlled crack development, ultimately improving the durability of the mixture.

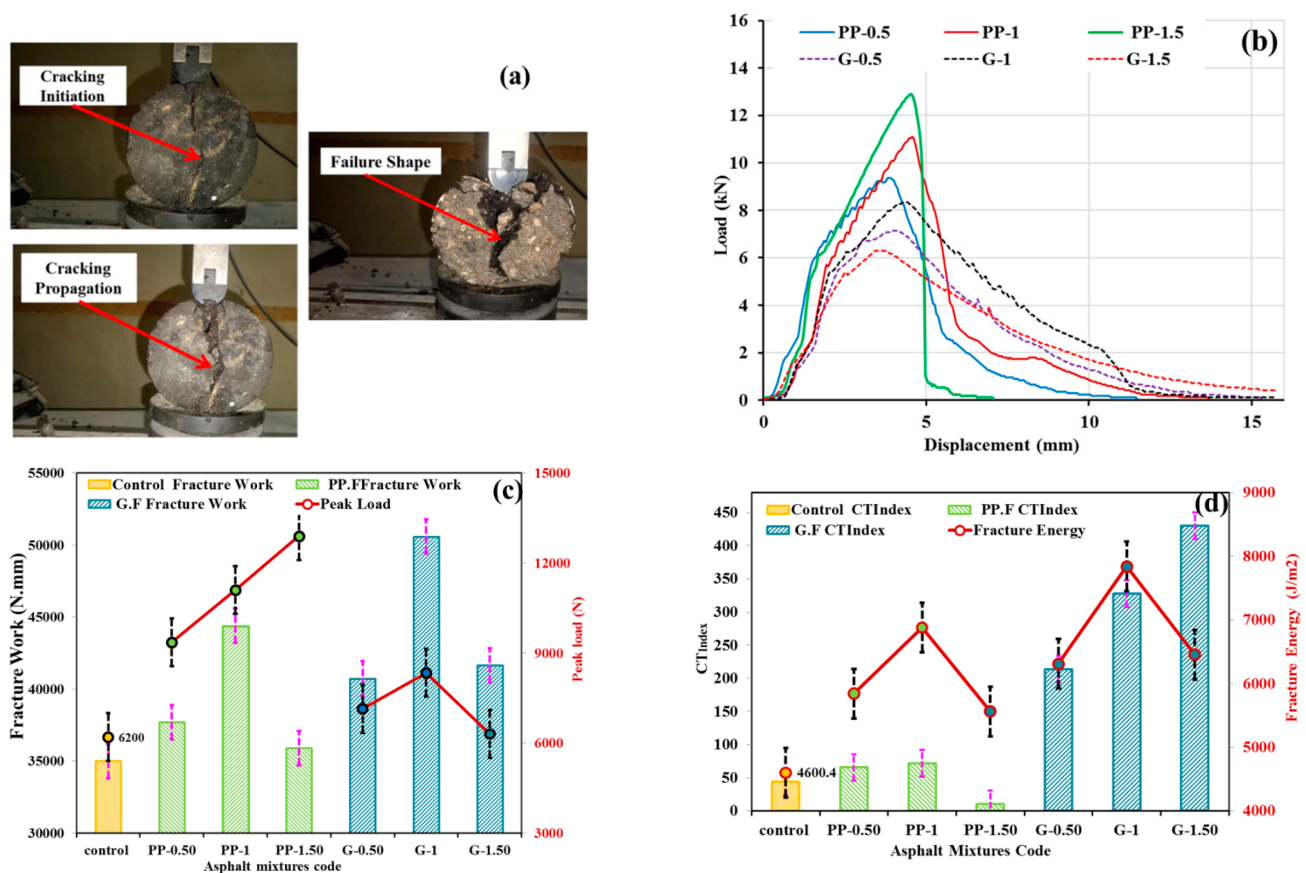


Figure 8. Effect of fiber amount on IDEAL-CT results: (a) crack development, (b) load–displacement curves, (c) fracture work and peak load, and (d) fracture energy and CT Index.

Figure 8b presents the load–displacement curves for asphalt mixtures modified with PP.Fs and G.Fs during the IDEAL-CT. As fiber content increases, the pre-peak slope of PP.F mixtures steepens, with PP-1.5 exhibiting the highest stiffness and resistance to initial deformation. Similarly, G.F mixtures show increased pre-peak slopes with additional fiber content, although these slopes are generally less steep than those of PP.F mixtures, with G-1.5 demonstrating the greatest stiffness. After reaching peak load, the PP.F mixtures experience a sharp decline in load-carrying capacity, particularly in PP-1.5, indicating a rapid loss of strength after cracking. In contrast, G.F mixtures display a more gradual reduction in load post-peak, with G-1.5 maintaining relatively stable load retention, suggesting superior post-cracking resistance and load retention. These load–displacement curves are essential for understanding crack formation in asphalt mixtures, where the pre-peak slope indicates initial stiffness and deformation resistance, and the post-peak portion reflects the mixture’s ability to resist crack propagation. While the addition of PP.F increases initial stiffness, it leads to a rapid loss of load capacity post-cracking. Conversely, G.Fs offer a better balance between stiffness and post-cracking durability, enhancing overall asphalt performance. This analysis is crucial for designing more durable and resilient pavements.

In Figure 8c, the effect of PP.Fs and G.Fs on peak load and fracture work parameters is depicted. The highest peak load value was observed in the PP.F-reinforced mixture group for PP-1.5, showing a 108% increase compared to the control mixture. G-1 exhibited the highest peak load value in the G.F-reinforced mixture group, with a 34.5% increase from the control mixture value. All mixtures modified with G.F and PP.F demonstrated higher peak load values compared to the control specimen. In PP.F mixtures, the peak load value

consistently increased with the fiber addition rate. However, in G.F mixtures, the peak load values increased with the fiber dosage in G.F-0.5 and G.F-1 mixtures but decreased in the G.F-1.5 mixture due to the clumping previously mentioned in Section 3.2. All investigated mixtures in the IDEAL-CT exhibited higher peak load values than those observed in the SCB test, which can be attributed to the geometry of the tested specimen and the mechanism of load application during the test [22]. The results in Figure 8c show that the fracture work values for mixtures reinforced with G.Fs and PP.Fs follow similar trends. Fracture work values for mixtures modified with 0.5% and 1% fiber doses increase compared to the control mixture but then decrease at the 1.5% addition rate. In G.F mixtures, fracture energy values increase by 16.3% and 44.5% for G.F-0.5 and G.F-1, respectively, compared to the control sample. In PP.F mixtures, fracture work values increase by 7.7% and 26.8% compared to the control mixture. Although the mixtures with 1.5% fiber content in the PP.F and G.F groups show lower fracture work values than those with 1% fiber content, they are still higher than the control sample, with increases of 18.9% and 2.5% for G.F and PP.F mixtures, respectively.

The behavior of mixtures reinforced with G.Fs and PP.Fs in enhancing fracture energy values is comparable, as illustrated in Figure 8d. Fracture energy values increased with the addition of G.Fs and PP.Fs up to a 1% addition rate, after which they declined. The highest fracture energy values were observed in the G-1 and PP-1 mixtures within their respective groups, showing improvements of 26.1% and 44.2%, respectively, over the control mixture. Additionally, the fracture energy value of the G-1 mixture was 12.2% higher than that of the PP-1 mixture. Figure 8d also demonstrates that increasing the G.F addition rate enhances the CT Index, with the highest CT Index observed in the G-1.5 mixture, showing an increase of 886% compared to the control value. In the PP.F-reinforced mixtures, the CT Index values increase with the addition of PP.F up to 1% in the PP-1 mixture, which shows an increase of 64.9% over the control mixture, before declining. Notably, the PP-1.5 mixture exhibits a lower CT Index value than the control mixture, indicating increased stiffness of the bituminous mixture at PP.F contents higher than 1%. All G.F mixtures achieved CT Index values above the minimum recommended threshold in Virginia (i.e., 70), unlike the PP.F and control mixtures [24]. These results indicate that the fracture resistance of asphalt mixtures can be significantly enhanced by incorporating fibers. However, PP.Fs are less effective in reinforcing flexibility compared to G.Fs. This difference may be attributed to the toughening effect of the fiber–asphalt interface, which helps dissipate concentrated stress. The surface adhesion strength between fibers and the asphalt binder, which varies depending on the type of fiber used, plays a crucial role in determining the fracture resistance of the asphalt mixture, even when the same quantity of fiber is added [74].

3.4. Three-Point Bending (3-PB) Test Results

Figure 9a presents the results of the 3-PB test, showing that the fracture work and peak load values follow a similar trend with varying contents of G.Fs and PP.Fs. As the fiber addition rate increases, both peak load and fracture work parameters decrease. However, all PP.F mixtures achieve higher fracture work and peak load values compared to the control sample. In the G.F mixture group, the G-1 and G-1.5 mixtures exhibit lower fracture work and peak load values than the control mixture. The mixture modified with a 0.5% fiber dosage shows a 20% increase in fracture work for G-0.5 and 37.2% for PP-0.5, and an 11% increase in peak load for G-0.5 and 470% for PP-0.5 compared to the control mixture. The peak load results from the 3-PB test differ from the IDEAL-CT results presented in Section 3.3 due to the different loading conditions: the IDEAL-CT better utilizes tensile strength under compressive load, resulting in higher peak load values. The 3-PB test, which applies a bending load, makes the asphalt mixture more prone to cracking and less effective for fiber reinforcement. In contrast, the compressive load in the IDEAL-CT aligns the fibers more effectively, enhancing reinforcement. While the 3-PB test induces bending

stresses that make cracks form more easily, reducing peak load values, the IDEAL-CT delays cracking and failure due to effective fiber bridging.

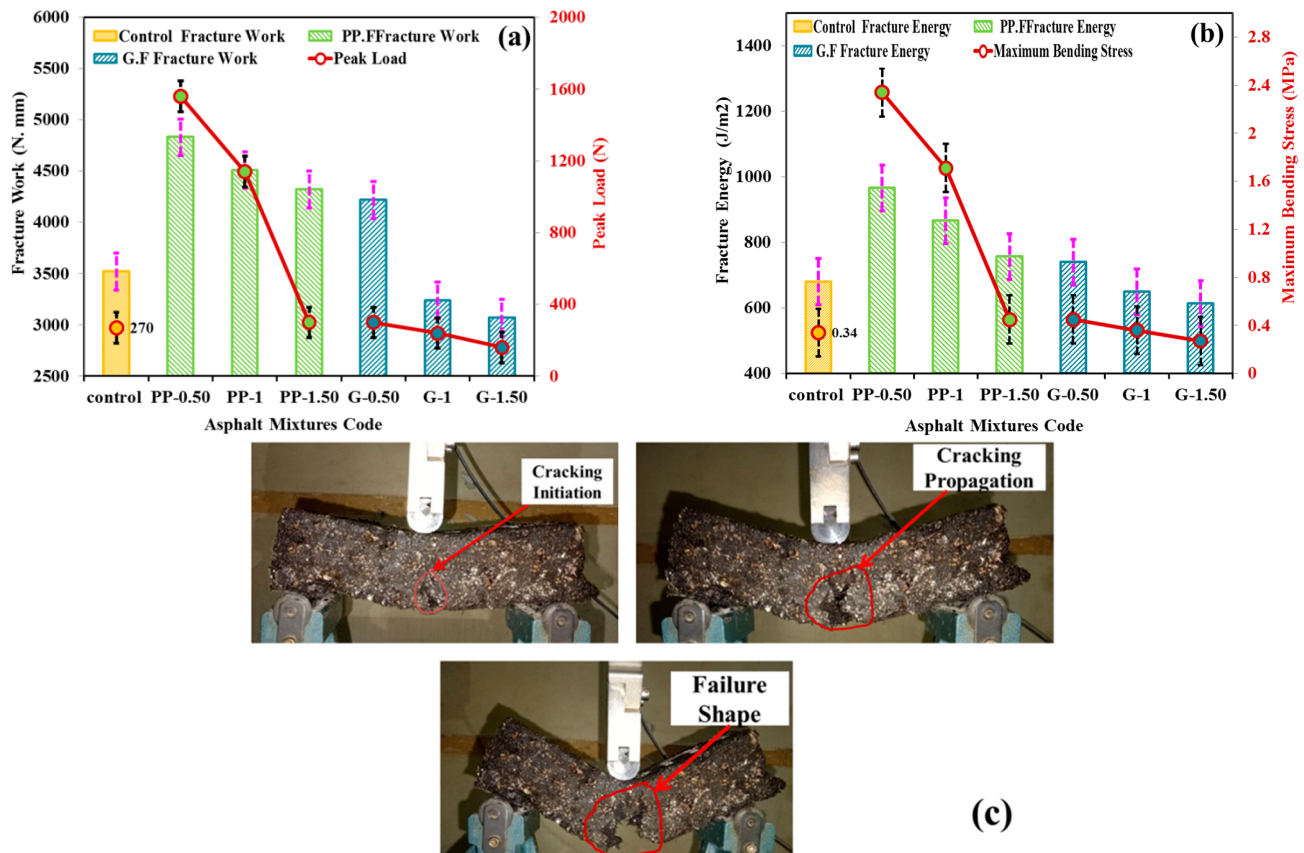


Figure 9. Effect of fiber amount on 3-PB test results: (a) fracture work and peak load, (b) fracture energy and maximum bending stress, and (c) crack development.

Figure 9b illustrates the impact of increasing fiber doses on the fracture energy of bituminous mixtures in the 3-PB test. The results show that fracture energy values decrease with higher rates of both PP.F and G.F additions. The PP-0.5 and G-0.5 mixtures achieved the highest fracture energy values within their respective groups. Compared to the control mixture, the PP-0.5 and G-0.5 mixtures showed increases in fracture energy by 42% and 8.8%, respectively. All PP.F-modified mixtures exhibited higher fracture energy values than the control. However, within the G.F group, the G-1 mixture showed lower fracture energy values than the control. Figure 9b illustrates that increasing the rate of fiber addition reduces the maximum bending stress values in both G.F and PP.F mixtures. In PP.F mixtures, higher fiber content results in a significant decrease in maximum bending stress values, whereas the rate of decrease is lower in G.F mixtures. The highest maximum bending stress is observed in the PP-0.5 and G-0.5 mixtures, with increases of 588.2% and 32.3%, respectively, compared to the control mixture. The results suggest that adding PP.Fs and G.Fs does not significantly improve the maximum bending stress of bituminous mixtures due to several factors. These factors include the non-ideal direction and distribution of fibers within the asphalt matrix, which leads to ineffective reinforcement. Additionally, higher fiber content can cause clumping and poor dispersion, creating weak points. Stress concentration during bending, coupled with weak bonding between fibers and the asphalt binder, further reduces effectiveness. Moreover, fibers can make the asphalt matrix stiffer and more brittle, negating any potential strength gains [75]. Figure 9c illustrates the mode of ductile failure that occurs in the bituminous mixture during the 3-PB test. This type of failure is characterized by significant plastic deformation before the sample cracks, indicating a high level of deformation prior to final failure. This failure mode can also be

classified as longitudinal cracking, which occurs parallel to the direction of the applied load and is primarily caused by tensile stresses that develop as the asphalt mixture bends [53].

The findings reveal different values for parameters such as fracture work, fracture energy, and peak load across the SCB, IDEAL-CT, and 3PB tests used to investigate asphalt mixtures. These differences can be attributed to the variations in stress application and testing set-ups in each test. The IDEAL-CT results show high fracture energy and peak load values due to its focus on tensile strength and initial crack resistance. In contrast, the SCB test generally shows lower fracture work and fracture energy values compared to the IDEAL-CT, primarily due to its sample geometry. The 3PB test, which evaluates overall structural integrity rather than specific crack behavior, results in lower values for fracture energy and peak load as it mainly assesses flexural strength. These variations stem from the specific stress applications and measurement methods in each test, providing distinct perspectives on the performance of the asphalt mixture.

4. Conclusions

This study investigates the effects of PP.Fs and G.Fs on improving the fracture behavior of HMA using SCB, IDEAL-CT, and 3-PB tests to compare fibers' impact on enhancing asphalt mixture cracking resistance. The key findings are summarized below:

- The results showed that both PP.Fs and GFs significantly affected the fracture behavior and mechanical properties of bituminous mixtures. Comparing and testing various specimen geometries in SCB, IDEAL-CT, and 3-PB tests highlighted how these fibers influence the fracture characteristics of the asphalt mixture.
- Fracture energy in bituminous mixtures was significantly enhanced with the addition of PP.Fs and G.Fs based on all study tests. The SCB test showed optimal results at 1–1.5% fiber content, with increases of 63.2% (PP-1) and 60.4% (G-1.5). Similarly, IDEAL-CT results peaked with PP-1 and G-1 at 49.6% and 70.4%, respectively. However, in the 3-PB test, optimal fiber content dropped to 0.5%, achieving 42% (PP-0.5) and 8.8% (G-0.5). Therefore, maintaining fiber content between 0.5% and 1% is recommended for optimal fracture energy.
- The addition of G.Fs significantly augmented the crack resistance of bituminous mixtures, over both the control and PP.F mixtures. The G-1.5 mixture achieved the highest CRI values, increasing by 87.9% over the control, while the PP-0.5 mixture in the PP.F group observed a 30.3% increase. However, increasing PP.F dosage by more than 1% reduced CRI values below the control, indicating reduced crack resistance and increased brittleness in PP.F mixtures.
- G.Fs notably enhanced the flexibility of the bituminous mixture over PP.Fs, with the G-1.5 mixture achieving peak FI and CT Index values, increasing by 269.8% and 886%, respectively, over the control. The PP-1 mixture in the PP.F group showed increases of 31.2% and 64.9%, but higher PP.F dosages beyond 1% led to reduced flexibility, indicating a decline in the mixture's resistance to elastic deformations.
- The 3-PB test results indicate that increasing doses of PP.Fs and G.Fs reduce maximum bending stress, with 0.5% being the optimal dosage for both fiber types. The PP-0.5 and G-0.5 mixtures show significant increases in maximum bending stress by 588.2% and 32.3%, respectively, compared to the control mixture.
- High doses of PP.F notably improve mechanical properties but result in poor fracture behavior. A 1% dosage of PP.F is optimal, offering a balanced enhancement in both mechanical properties and fracture resistance.
- G.Fs are more effective than PP.Fs in boosting fracture resistance and flexibility in asphalt mixtures. Reinforcing with 1% G.F is an optimal strategy for improving crack resistance while maintaining acceptable mechanical properties in G.F reinforcement applications.

The SCB test is ideal for detailed mixed-mode fracture analysis in fiber-reinforced asphalt, while the IDEAL-CT offers a quicker assessment of tensile cracking resistance. The 3-PB test focuses on evaluating flexural strength and stiffness, making it essential

for understanding the overall structural benefits of fiber reinforcement. The choice of test depends on the fracture properties of interest and the intended application of the asphalt mixture. Future studies should consider including more detailed comparisons of the effects of PP.Fs and GFs on fracture properties by incorporating additional mixtures with reduced fiber dosages and varying aggregate gradations. Expanding the range of fracture tests to include methods such as asymmetrical edge-notched disc bend (AENDB), Short Bend Beam (SBB), Brazilian Disc (BD), and Hollow Center Cracked Disc (HCCD) would provide a more comprehensive evaluation of fiber reinforcement. Additionally, modeling techniques could offer further insights into the impact of fibers on deformation resistance in bituminous mixtures.

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Abbreviations

HMA, Hot-Mix Asphalt; G.F, glass fiber; PP.F, polypropylene fiber; SCB, Semi-Circular Bending; IDEAL-CT, Indirect Tensile Asphalt Cracking Test; 3-PB, Three-Point Bending; UTM, Universal Testing Machine; FI, Flexibility Index; CRI, Crack Resistance Index.

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