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Experimental Study of the Effect of High Length of Glass and Polypropylene Fibers on Asphalt Mixture Characteristics

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Abstract

Fibers are commonly used to improve the performance of bituminous mixtures by addressing issues caused by traffic loads, environmental changes, and material limitations. This manuscript aims to compare the effect of adding various amounts of polypropylene and glass fibers with a length of 35mm on the performance and strength of bituminous mixtures. With an optimal bitumen content of 5% and dry mix method, fiber-reinforced mixtures were prepared by incorporating fibers in amounts ranging from 0.25% to 1.5% of the total aggregate weight, with a constant increase of 0.25%. The effect of high length fibers on the mechanical properties and cracking behavior of bituminous mixtures was evaluated by implementing a laboratory testing program from Marshall stability, volumetric properties analysis, compressive strength, immersion Marshall, freeze-thaw splitting, static creep and Indirect Tensile Asphalt Cracking (IDEAL-CT). Adding 1.5% polypropylene fibers increased stability, flow, and final static creep stiffness by 49%, 14 %, and 39%, respectively, compared to the mixture without fibers. Regarding improving crack resistance, glass fibers demonstrated superior performance in enhancing flexibility and crack propagation resistance compared to polypropylene fibers. The addition of 1% glass fiber increased the Fracture Strain Tolerance (FST) and Crack Resistance Index (CRI) by 134 % and 135%, respectively, compared to the mixture without fibers. Damage cost analysis indicated that incorporating polypropylene and glass fibers in amounts up to 1.5% resulted in an acceptable increase of 18.8% and 13.2%, respectively, the significant improvement in performance and mitigation of damage that reduces pavement lifespan make this approach compelling.

Keywords: Bituminous mixtures; Polypropylene fiber; Asphalt cracking. Glass fiber.

1. INTRODUCTION

Fibers are widely used to reinforce composite materials in civil engineering due to their unique properties that significantly enhance the materials' capacity to withstand external loads [1-2]. Various types of fibers have been incorporated into asphalt mixtures in pavement technology to enhance performance. The primary goal of adding fibers and other addivites is to address deficiencies in asphalt binders that arise from challenges in improving bitumen quality during the refining process. Incorporating fibers into asphalt mixtures significantly enhances their overall properties and extends the lifespan of the pavement [1-3-4-5-6]. Fibers are considered a more effective method for enhancing asphalt performance compared to other materials like rubber, polymers, and fillers, which are commonly used to modify asphalt mixtures. Fibers outperform these materials in improving tensile strength and resisting fatigue cracking, reflective cracking, and permanent deformation [7]. Reflective cracks form due to the significant stresses imposed by traffic loads on the top layer of asphalt pavement. This stress causes considerable bending in the asphalt layer, as the granular layers beneath are less stiff than the asphalt layer above. Cracks begin to develop beneath the surface layer of the asphalt pavement as the tensile strength of the asphalt mixtures decreases. As traffic loads increase, these cracks expand and eventually reach the pavement surface. To prevent the formation and propagation of such cracks, materials with high tensile strength, such as fibers, can be effectively utilized [8-9].

The impact of fiber additions on enhancing various properties of asphalt mixtures depends on several factors, including the geometric attributes of the fibers (such as length and diameter), the quantity of fibers added, the method of integrating the fibers with the asphalt mixture components, and the specific type of fiber used [10]. Laboratory test results indicate that, unlike fiber diameter, fiber length significantly impacts the properties of modified asphalt mixtures. Standardized techniques are used by manufacturers to determine the appropriate fiber

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length [11-12]. Numerous studies have explored the effects of fiber length on the behavior of asphalt mixtures. The findings suggest that fibers of relatively significant length may reduce stability and reinforcement effectiveness within the mixtures. Although some previous studies have indicated that increasing fiber length may lead to a deterioration in certain properties of bituminous mixtures, to the best of the authors' knowledge, no comprehensive study has been conducted to evaluate the overall impact of long fibers on the performance of bituminous mixtures. Conversely, shorter fibers may lead to uneven distribution, fiber agglomeration, and the transformation of fibers into ineffective filler, potentially resulting in an adverse impact on the mixture's properties [13-14]. The investigation into the optimal type and length of fibers for reinforcing bituminous mixtures revealed that basalt fibers, specifically at a length of 6 mm, outperformed lignin and polyester fibers. The basalt fibers with length 6 mm, when added at an optimal concentration of 0.4% by weight, significantly enhanced the mixture's overall engineering properties, such as improved thermal stability, increased crack resistance at low temperatures, and notably better water resistance [10]. A study assessing the interaction between fibers and asphalt mastic, along with fiber distribution in bituminous mixtures, revealed that 20 mm length aramid fibers effectively bond with asphalt mastic and disperse well within the mixtures. When comparing bituminous mixtures enhanced with varying lengths of aramid fibers through uniaxial fatigue and flow number tests, the 19 mm fibers outperformed both shorter and longer fibers in terms of performance[15]. A study thoroughly examined the influence of varying aramid fiber lengths and surface treatments on the performance of bitumen modified with these fibers. Using tools like a dynamic shear rheometer, viscometer, and bending beam rheometer, the research determined that longer aramid fibers notably increase the viscosity of the bituminous binder. From an economic perspective, the enhancement typically achieved with shorter fibers at higher concentrations can be effectively replaced by using longer fibers at lower concentrations [16].

In addition to fiber length, the optimal quantity of added fiber is a critical variable that significantly influences the properties of both the asphalt binder and the resulting asphalt mixture. Regarding the asphalt binder, fiber content affects rheological properties such as dynamic shear modulus and creep rate, as well as fundamental characteristics like viscosity, penetration grade, and softening point. For the asphalt mixture, the quantity of fibers added impacts its resistance to rutting, fatigue, and cracking, along with its stability and flow characteristics [17-18-19]. Fiber content can be calculated using various methods, including as a percentage of the total mixture weight, the weight of the asphalt binder, the aggregate weight in the mixture, or as a percentage of the mixture's mass or the aggregate's mass [20- 21- 22-23].

Previous studies have not established specific criteria for selecting the method to incorporate different fibers into the asphalt mixture. However, two general approaches are commonly used: the dry method and the wet method. In the wet mixing process, fibers are added to the asphalt binder before being mixed with the aggregate, making it particularly effective for fibers with melting points close to the mixing temperature. Asphalt mixtures reinforced with fibers using the wet method demonstrate exceptional durability and resistance to deformation. However, a major challenge of the wet mixing method is the clumping or incomplete dispersion of fibers within the mixture [20-3]. The dry mixing method involves blending fibers with the aggregate before adding bitumen. This approach is suitable for high-melting-point fibers, as it does not require the fibers to melt into the asphalt, unlike the wet mixing method. The dry method minimizes the risk of fiber clumping or clustering in the asphalt mixture, offering simplicity in mixing and ensuring even distribution of fibers throughout the mixture [18-19].

Fibers can be broadly categorized into two main groups: natural fibers and synthetic fibers. Natural fibers are derived from plants, animals, or mineral sources. Synthetic fibers are further classified into organic synthetic fibers, produced through polymerization processes, and inorganic synthetic fibers, which are made from metals via chemical processes [24]. Fig.1 presented the general classification of the fiber.

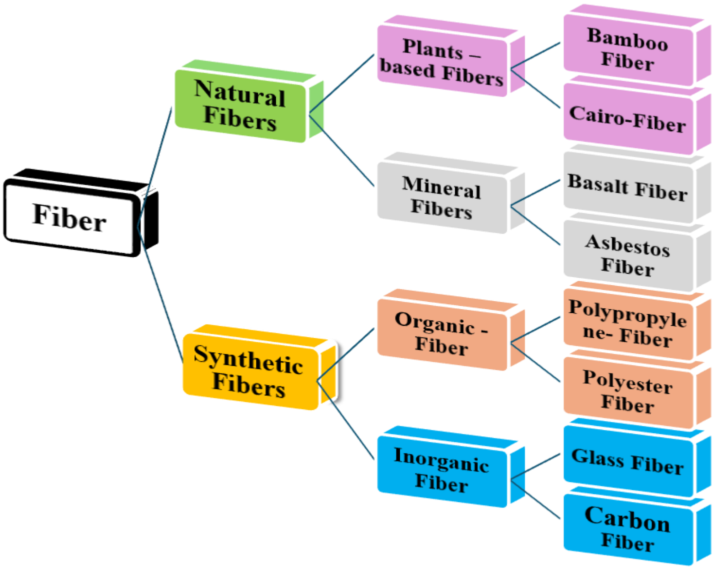

Fig.1. Fiber types are used in bitumen modifications.

Glass fiber is an inorganic synthetic fiber and is one of the most commonly used types for modifying asphalt mixture behavior, primarily due to its exceptional tensile strength [25-26]. Glass fiber possesses several advantageous characteristics, including a high modulus, durability, thermal stability, impact resistance, and chemical resistance. Additionally, glass fiber exhibit high tensile strength and perform exceptionally well at low temperatures. However, their brittleness can be a concern, as it makes them susceptible to breaking when mixed with other components, such as aggregates and asphalt binder, which can affect their effectiveness as performance modifiers in asphalt mixtures[27-28-29]. Asphalt mixtures enhanced with glass fibers demonstrated significant resistance to cracking during the investigation of asphalt concrete fracture characteristics at lower temperatures [30]. The incorporation of glass fibers into modified asphalt concrete mixtures significantly enhances resistance to rutting compared to tensile strength. However, the impact of glass fibers on improving bending strength is limited. As the quantity of glass fibers increases, the strain resulting from flexural failure also rises [24]. Varying lengths of glass fibers have proven to be highly effective in modifying bituminous pavements. Specifically, adding glass fiber with length 12 mm notably improves the mechanical properties of the asphalt mixture, such as Marshall stability and elastic deformation, without altering the bitumen content, thereby reducing risks like rutting and bleeding under high temperatures. Similarly, 10 mm glass fiber doses have shown considerable enhancement in both moisture and rutting resistance of the mixtures. For fracture behavior improvements, 3 mm and 8 mm glass fibers have demonstrated a marked increase in fracture energy and flexibility indices, significantly boosting the modified mixture's overall performance[31-26-32]. The findings confirmed the numerical analyses highlighted the positive effects of glass fiber reinforcement in enhancing the durability of bituminous mixtures. Specifically, J-integral analysis showed that adding glass fibers to reclaimed pavements significantly boosts fracture resistance, particularly under repeated freeze-thaw cycles. A multi-criteria analysis further revealed that incorporating glass fiber with lengths between 4 and 10 mm, and tensile strengths ranging from 2000 to 3000 MPa greatly improved the tensile strength of the mixtures. However, this improvement came with a slight decrease in void content and porosity. Additionally, the inclusion of glass fiber in the bituminous matrix formed a reinforcing network that increased the mixture's resistance to fatigue, rutting, and cracking [33-34].

Polypropylene fibers are synthetic organic fibers commonly used in concrete reinforcement due to their ability to enhance material performance in three dimensions. This multidirectional reinforcement effectively distributes cracks caused by increased loads, improving the overall durability and resilience of the asphalt concrete[35]. Polypropylene fibers are a cost-effective reinforcement material, widely available at a reasonable price. They have demonstrated effectiveness in enhancing the properties of asphalt mixtures by improving resistance to fatigue and rutting, reducing flow, and increasing stability [32]. Polypropylene fibers offer unique three-dimensional reinforcement, distinguishing them from other types of fiber. Assessments of bituminous binders modified with 5% thermally degraded polypropylene fibers revealed reduced heat sensitivity and enhanced mechanical performance. Studies on aged Marshall bituminous samples modified with these fibers showed superior flexibility, durability, and adhesive properties compared to control samples, along with better moisture resistance and fracture performance[25-36-37]. Further investigations demonstrated that shorter polypropylene fibers dispersed more effectively than longer ones, and four-point beam and IDEAL-CT tests confirmed that fiber-reinforced mixtures exhibited improved crack resistance across various temperatures. Additionally, 3D images analysis and response surface methods found that bituminous mixtures with up to 0.2% polypropylene fibers by aggregate weight showed increased peak load and indirect tensile strength while reducing the brittleness index and the percentage of broken aggregates[38- 39].

The concept of hybrid reinforcement has emerged in civil engineering, where various fine materials and fibers are used to modify asphalt and concrete mixtures. This approach aims to combine the benefits of these materials to achieve optimal performance in modified mixtures. Hybrid reinforcement techniques, which involve adding different types of fibers to asphalt mixtures in varying proportions, have been explored to improve the behavior of flexible pavements. The results show that incorporating varying amounts of nano-silica materials into a porous asphalt mixture, along with a hybrid reinforcement made of glass and polypropylene fibers, enhances the mixture's tensile strength and resistance to rutting [40]. The performance of the modified asphalt mixture indicated that the hybrid fiber, composed of aramid and polypropylene fibers, was highly effective in significantly enhancing the mixture's strength. This enhancement allowed for a reduction in the final pavement thickness. The modified mixtures also exhibited substantial resistance to reflective cracking and rutting [41]. The application of hybrid fiber, consisting of various types of glass fibers, including ball-shaped powder and rod-shaped fibers with lengths ranging from 10 to 15 mm, led to a 1.4-fold increase in the tensile strength of asphalt mixtures. Additionally, these reinforced mixtures demonstrated exceptional performance under low-temperature conditions [42].

The key innovations in this research lie in investigating the impact of long fibers (35 mm) of glass and polypropylene on the properties of bituminous mixtures a subject largely overlooked in previous studies, which focused on fiber lengths not exceeding 20 mm [43-44-45-46]. Also, this research uniquely presents a comprehensive study on the impact of long glass and polypropylene fibers on both mechanical properties and cracking behavior in an integrated manner, offering a more accurate evaluation of asphalt mixture performance unlike previous studies that assessed these properties separately. Additionally, the research highlights the economic aspect, aiming to determine whether the performance improvements observed with the proposed fiber modification are economically viable an important consideration that is often neglected in earlier studies on fiber-reinforced bituminous mixtures. Seven different fiber ratios (0, 0.25, 0.5, 0.75, 1, 1.25, 1.5%) of polypropylene and glass fibers were designed for this study. Laboratory tests were conducted to evaluate the effects of varying amounts of these fibers on the performance of bituminous mixtures under different loading, temperature, and moisture conditions.

2. OBJECTIVES

The primary objective of this study is to evaluate the impact of incorporating varying amounts of high length polypropylene and glass fibers on the mechanical properties and crack resistance of asphalt mixtures. Additionally, the study seeks to analyze the economic feasibility of using these high-length fibers as modifiers in bituminous mixtures. To achieve these objectives, a comprehensive laboratory program was implemented. Initially, the physical properties of raw materials, including aggregate, bitumen, and fibers, were assessed. The next phase involved designing the asphalt mixture using the Marshall method to determine the optimum bitumen content for binding aggregate particles. Subsequently, traditional bituminous mixtures and those modified with glass and polypropylene fibers were prepared and subjected to rigorous laboratory testing. This testing regimen included Marshall tests, compressive strength tests, static creep tests, moisture sensitivity tests, and the Indirect Tensile Asphalt Cracking Test (IDEAL-CT). Lastly, the economic feasibility of fiber addition to bituminous mixtures was evaluated. Fig.2 outlines the main steps followed in this research

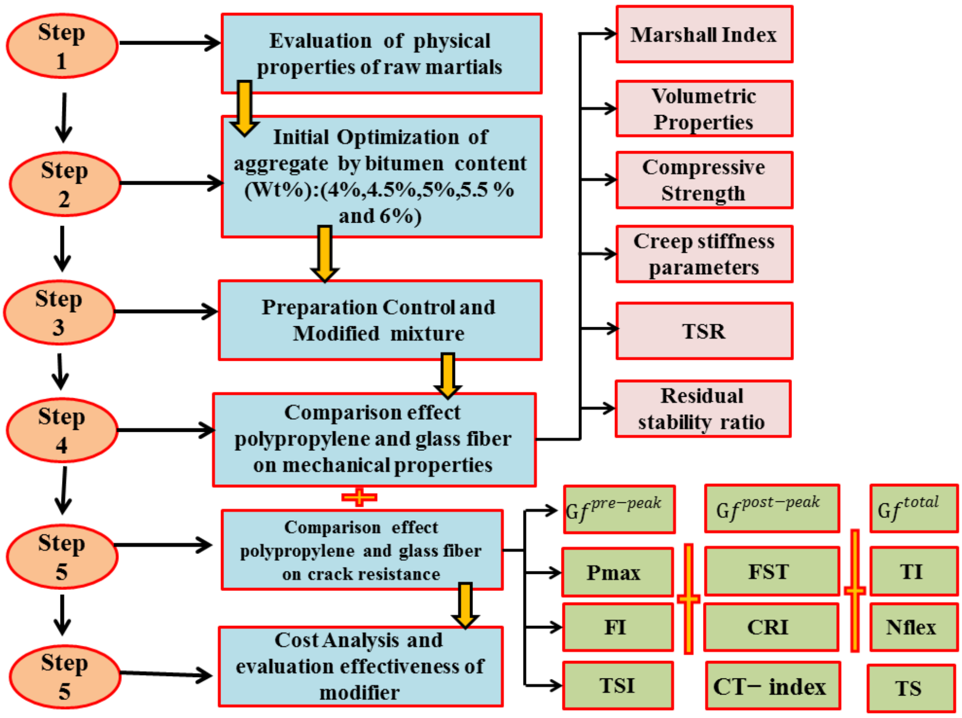

Fig.2.Main steps of the investigation.

3. MATERIALS AND MIXING

3.1. Raw Materials

The primary materials used to prepare the bituminous mixtures in this investigation include coarse and fine aggregates, filler, bituminous binder, polypropylene and glass fiber specimens. These materials underwent various laboratory tests to evaluate their properties according to standard specifications. The engineering properties of these materials, along with the bituminous mixtures, were assessed in accordance with the standards established by the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO).

3.1.1. Aggregate

The aggregate specimens were prepared using crushed limestone as coarse aggregate, natural sand as fine aggregate, and powdered limestone as mineral filler. These materials underwent a series of laboratory tests, including the water absorption test, the Los Angeles abrasion test, and the relative density test. The results of these tests, which were conducted to evaluate the quality of the aggregates, are presented in Table 1.

TABLE 1. COARSE AGGREGATE PHYSICAL CHARACTERISTICS.

Property	Results	Specification	Specification Limit
Bulk relative density	2.69	*ASTM C 127*	------------
Apparent relative density	2.71	*ASTM C 127*	------------
Water absorption (%)	2.40	*ASTM C 127*	*<2.6*
Los Angeles Abrasion (%)	25	*ASTM C 131*	*<28*

To meet the gradation requirements for dense asphalt mixtures as specified by AASHTO, the coarse aggregate, fine aggregate, and filler were mixed in precise proportions. Fig. 3 presents the gradation test results for the aggregate mixture used in the study specimens, along with the specification limits according to AASHTO criteria.

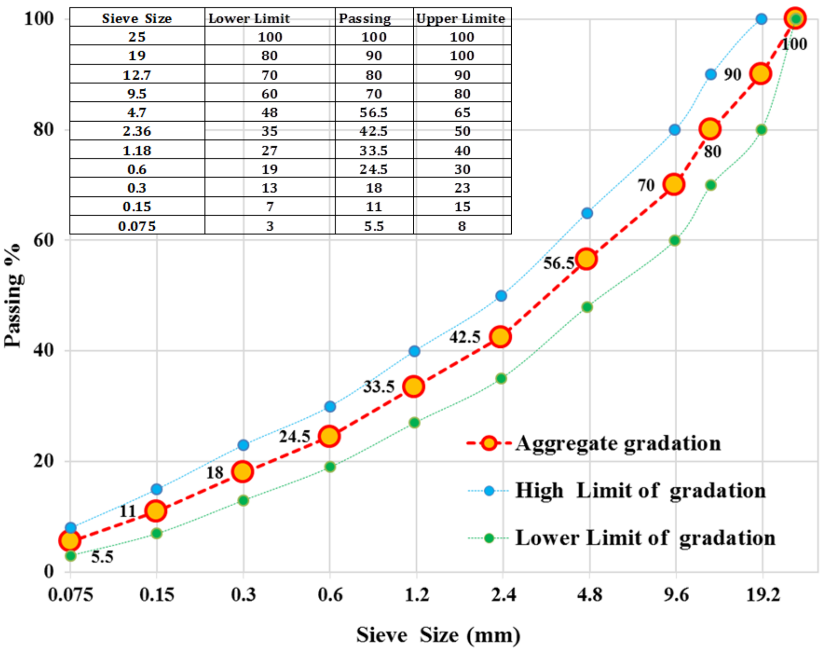

Fig.3.Aggregates gradation curve and specification limits.

3.1.2. Bitumen

The bituminous mixtures were prepared by combining aggregate specimens with a 60/70 penetration grade bituminous binder, commonly used in Egypt. The bituminous binder sample was sourced from the Suez Refinery. Tests for specific gravity, penetration, softening point, and kinematic viscosity were conducted on the asphalt binder used in this study. The results of these tests are presented in Table 2.

TABLE 2. BITUMEN BINDER PHYSICAL PROPERTIES.

Property	**Results**	**Specification**	**Specification Limit**
Specific gravity	1.02	ASTM D5	1–1.03
Penetration at 25 °C (0.1 mm)	65	ASTMD0005–13	60–70
Softening point (°C)	54	ASTM D36	48–56
Kinematic Viscosity. (at 135°C), Cst	330	ASTM D 2196	≥ 320

3.1.3. Fiber

Hot asphalt mixtures were reinforced with two types of synthetic fibers: polypropylene and glass fibers. A description of these fibers, provided by the manufacturer, is presented in Table 3.

TABLE 3: POLYPROPYLENE AND GLASS FIBERS PHYSICAL CHARACTERISTICS.

Property	Unite	Polypropylene Fiber	Glass Fiber
Length	mm	35	35
Tensile Strength	MPa	467 - 548	-----------
Color	-----------	Transparent	White
Specific Weight	g/cm3	0.91	2.53
Cross Section	-----------	Circular	Rectangular
Melting Point	°C	160	> 300
Elongation	%	20 - 25	-----------
Chemical Resistance	-----------	Transparent	-----------
Water Absorption	%	0.01	< 0.2

Fig. 4 shows images of the polypropylene and glass fibers, both of considerable length, incorporated into the research mixtures. These images illustrate how the different manufacturing processes for the two fiber types influence their diameters. Glass fiber has a coarser granular structure compared to polypropylene fiber, a contrast that is reflected in the physical and mechanical properties of the mixtures. The variation in fiber diameter also suggests specific challenges encountered during the production of specimens

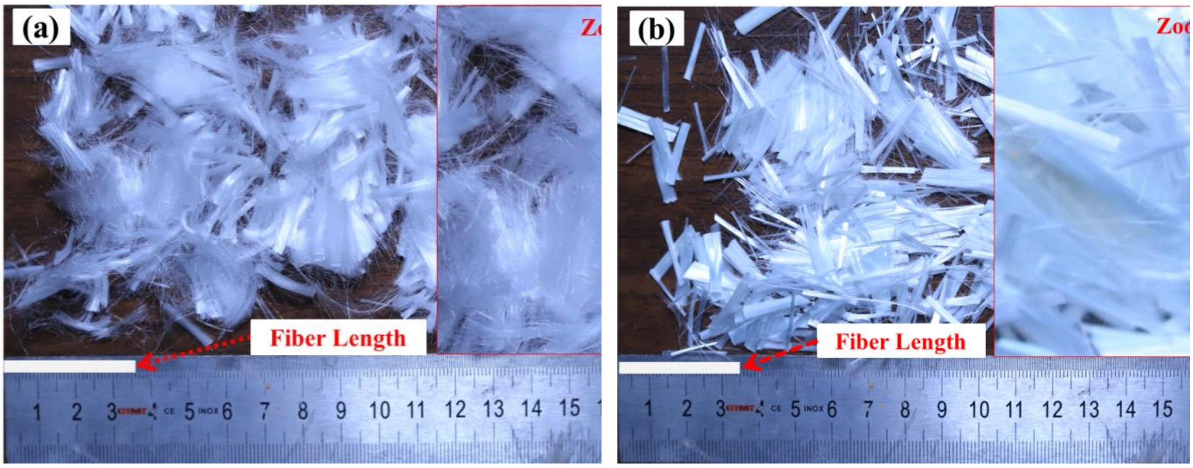

Fig.4. Types of fibers in this investigation, (a) Polypropylene fiber and (b) Glass fibers.

The bituminous mixtures were modified with polypropylene and glass fibers, incorporating fiber quantities ranging from 0.25% to 1.5% by the weight of the aggregate, with a consistent incremental increase of 0.25%. Various volumetric and engineering properties of the fiber-modified mixtures were measured and compared against the conventional mixture without fibers.

3.2. Mixing

3.2.1. Optimum Asphalt Content

The Marshall mix design method was used to prepare the asphalt mixture in accordance with AASHTO T-166 specifications. Five different hot asphalt mixtures were prepared with varying asphalt binder contents (4%, 4.5%, 5%, 5.5%, and 6%). For each binder content, three cylindrical samples, measuring 101.6 mm in diameter and 63.5 mm in height, were compacted with 75 blows on each face. The average properties of the specimens in these binder contents were evaluated using a Marshall apparatus. Measurements included stability, flow, specific gravity, voids in the mineral aggregate (VMA), voids filled with bitumen (VFB), and voids in the mixture (VM). The optimal binder content, determined to be 5%, was selected based on maximizing stability, achieving the highest unit weight, and meeting the target of 4% air voids in the entire mixture. This optimal content was then applied to both the control and fiber-modified mixes. Table 4 presents the Marshall test results (stability, flow, Marshall quotient) and various volumetric properties of the traditional asphalt mixture at the optimal bitumen content.

TABLE 4. ASPHALT MIXTURE PROPERTIES AT OPTIMUM BITUMEN CONTENT

Property	Results	Specification limits
Unit Weight (g/cm3)	2.395	-----------
%Air voids in total mix (VM)	4.0	3-5 %
% Voids Filled with Bitumen (VFB)	79	---------------
% Voids in Mineral Aggregate (VMA)	15.15	----------------
Marshall Stability (Kg)	1090	900 kg (min)
Marshall Flow (mm)	3.80	2-4 mm
Marshall Quotient (Kg/mm)	302.8	300 -500

3.2.2. Fiber Mixing Method

Both polypropylene and glass fibers were added to the bituminous mixture as supplementary modifiers without replacing any portion of the aggregate components. The primary objective of this addition is to enhance the tensile strength properties of the asphalt binder, thereby improving the overall performance of the bituminous mixture. The dry mixing method was used to incorporate various amounts of high length polypropylene and glass fiber into the asphalt mixture components, including the aggregate and the optimal asphalt binder content, as shown in Fig. 5. In this process, the fiber contents were mixed with the aggregate for 90 Sec [47]. Subsequently, the mixture was heated in an oven to 160°C, which is 10°C above the mixing temperature. The optimal asphalt content, preheated in the oven at 150°C, was then added to the mixture. The mixing was carried out using a mixer at 700 rpm. The specimen was mixed and compacted at a temperature not lower than 143°C, following the ASTM D1559-76 specifications.

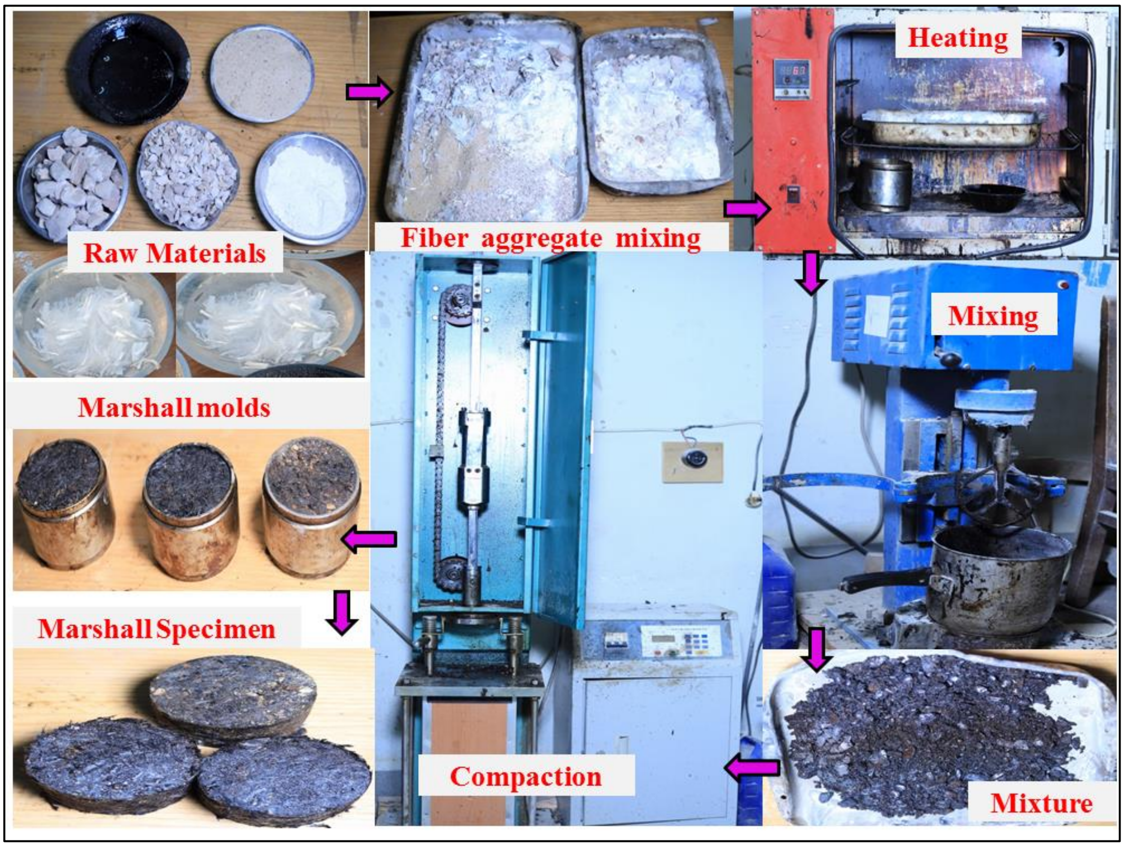

Fig. 5. Illustrates the stages of mixing for fiber-modified asphalt specimens.

Fig.6 illustrates the influence of the physical properties of high length polypropylene and glass fibers on the asphalt mixture's external appearance. In Fig.6a, the surface of the asphalt mixture modified with polypropylene fibers appears uniform, with no visible fibers on the surface. This homogeneity is due to the melting of polypropylene fibers within the bituminous matrix, attributed to their relatively low melting point, which is close to the mixing temperature. In contrast, Fig.6b shows clearly visible glass fibers on the surface of the bituminous mixture. This visibility is due to the high melting point of glass fibers, significantly above the mixing temperature, which prevents them from melting during mixing and compaction. Additionally, the high stiffness of glass fibers makes full integration into the bituminous matrix challenging, causing them to protrude on the surface. Moreover, the surface energy properties of glass fibers may result in less effective bonding with the bitumen, leading to their visible presence on the surface of the asphalt mixtures.

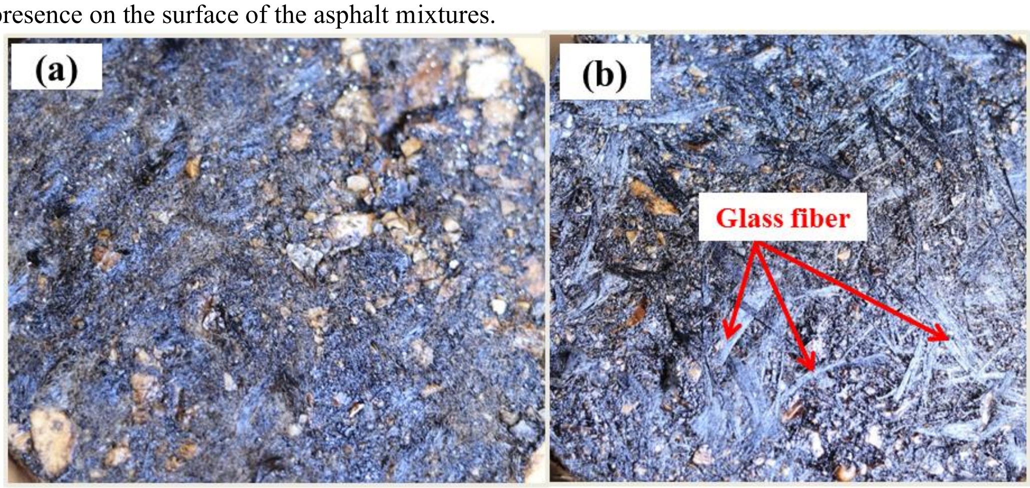

Fig.6.The effect of adding synthetic fibers on the external appearance of bituminous mixtures: (a) Polypropylene fibers and (b) Glass fibers.

4. TESTING METHODS

4.1. Physical Properties of Fiber

4.1.1. Water Absorption Test

The resistance of fibers to water absorption is a desirable property for protecting bituminous mixtures from moisture-related risks during the operational stage. To evaluate the behavior of the investigated fibers under varying moisture conditions, a Water Absorption (WA) test was conducted on both glass and polypropylene fibers. A 20 g specimen of each fiber type was prepared and placed in dry containers, with their initial average weight recorded as (W0). The specimens were then exposed to air at 90% relative humidity and a temperature of 20°C for 5 days. The weights of the glass and polypropylene fiber specimens were measured at regular intervals (every 5 h) during the test period to assess the change in weight due to water absorption (W1), as calculated using Eq. 1

$$\textit{Water Absorption (\%)} = \frac{W1-W0}{W0} * 100 \tag{1}$$

4.1.2. Loss in Heating Test

The loss in heating test was used to evaluate the weight loss due to the evaporation of moisture and other volatile substances from synthetic glass and polypropylene fibers when exposed to heat. This procedure helps assess the thermal stability of synthetic fibers through short-term aging techniques. A specimen of each fiber type (initial weight W0 = 30 g) was prepared and placed in a container, then kept in an oven at a constant temperature of 160°C, equivalent to the asphalt mixture production temperature, for a continuous duration of 5 hours (final weight W1 = 30 g). The rate of weight change for each fiber specimen was recorded at regular intervals, following the calculation method outlined in Eq.2

$$\textit{Mass Loss (\%)} = \frac{W0-W1}{W0} * 100 \tag{2}$$

4.2. Marshall Test

The Marshall Stability test for both control and fiber-modified specimens was conducted under uniform conditions according to ASTM D 1559. The bituminous specimens were submerged in a water bath at 60°C for 30 min, with the loading head maintained at 40°C. The specimens were then tested at a loading rate of 50.8 mm/min within 30 Sec of removal from the water bath to evaluate the stability of the bituminous mixtures at elevated temperatures, where the bitumen loses some of its viscosity and adhesion [48]. Stability and flow parameters were measured as the maximum compressive load the mixture could withstand during the test and the corresponding displacement at that maximum load.

4.3. Compressive Strength Test

The compressive strength of the Marshall specimens from the investigated mixtures was tested according to ASTM D1074. The test was conducted at temperatures of 25°C and 60°C to assess the effect of temperature on compressive strength loss. The procedure began by submerging three specimens from each mixture in a water bath for 30 min at 25°C and 60°C to ensure uniform temperature distribution. The test was conducted within 30 Sec of removing the specimens from the water bath using UTM, applying a constant loading rate of 50 mm/min, as shown in Fig. 7a. The specimen was carefully centered on the lower plate of the device to ensure proper alignment for the test. The applied load was continuously recorded until failure occurred, as illustrated in Fig. 7b. The compressive strength of the mixture was calculated by dividing the maximum applied load by the cross-sectional area of the specimen.

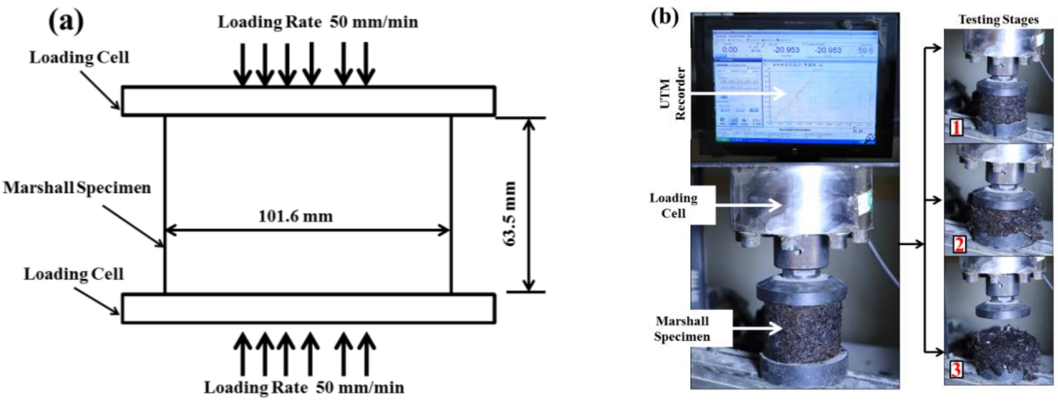

Fig.7. Compressive strength test data (a) Loading applied mechanism and (b) Testing set-up and deformation stages.

4.4. Static Creep Test

The static creep test is conducted to assess the role of high length added fibers in enhancing the deformation properties of bituminous mixtures under sustained loading. This test helps determine creep compliance and resistance to permanent deformation. The static creep test is performed on Marshall specimens using a UTM, following ASTM D6992. After conditioning the specimens for 4 h at 40°C, a static load of 100 kPa is applied. Initial creep stiffness values are recorded at the end of the pre-loading phase, while strain and final creep stiffness values are measured at the conclusion of the actual loading phase for each mixture under investigation.

4.5. Moisture Susceptibility Test

4.5.1. Immersion Marshall Test

Bituminous mixtures are prone to deterioration when exposed to water due to their porous structure. Therefore, enhancing the water stability of these mixtures through the addition of fibers is essential for assessing the effectiveness of synthetic fibers as modifiers [49]. The submerged Marshall test is conducted to assess the moisture resistance of the mixtures by conditioning two groups of specimens (each group consisting of three specimens per mixture) in a water bath at 60°C for 30 min and 24 h, as shown in Fig. 8a. Subsequently, the Marshall apparatus is used to measure the average stability values for each group, as illustrated in Fig. 8b. The residual immersion stability is then calculated using Eq. 3

$$MSR = \frac{MS2}{MS1} \times 100\ \% \qquad (3)$$

Where MSR is the Immersion Residual Marshall Stability (%); MS2 is the Marshall stability after 24 h of immersion (kg), and MS1 is the Marshall stability of the fresh mixture after 30 min of immersion (kg). MSR values are utilized to assess the moisture susceptibility of the bituminous mixture, with higher MSR values indicating greater resistance to moisture-induced damage.

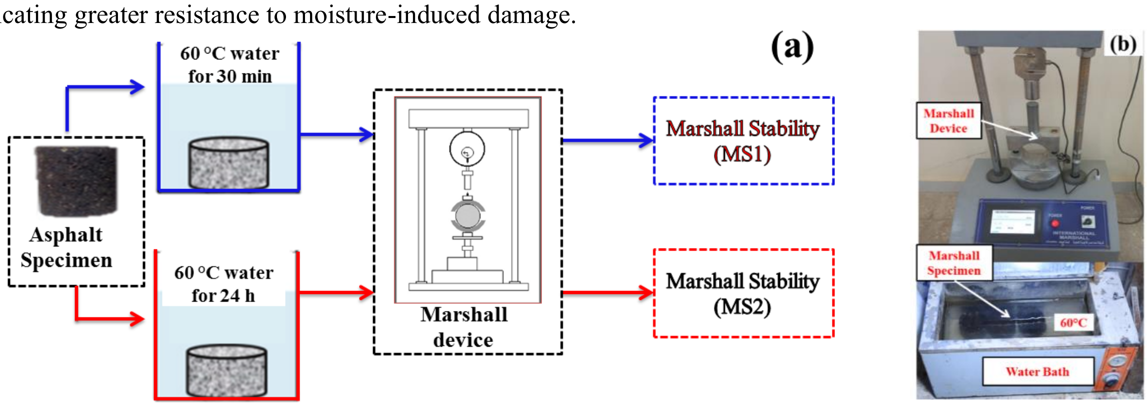

Fig.8: Immersion Marshall test information (a) Test procedures diagram and (b) Specimen set-up and devices.

4.5.2. Tensile Strength Ratio (TSR)

The effect of incorporating high length polypropylene and glass fibers on the moisture resistance of bituminous mixtures was assessed using the modified Lottman test, as per AASHTO T283. Enhancing moisture resistance is critical for evaluating the effectiveness of fibers as modifiers in bituminous mixtures. Moisture damage is one of the most common failure mechanisms in bituminous pavements, caused by the decreased adhesion between aggregate particles and the bituminous binder. This test is regarded as one of the most accurate methods for assessing the moisture sensitivity of bituminous mixtures [50-51]. Fig.9a outlines the primary steps for conducting the Tensile Strength Ratio (TSR) test. In this procedure, prepared Marshall specimens from each mixture were divided into two groups: dry and wet, with each group consisting of three specimens. The dry group was prepared by placing the specimens in a plastic bag and then submerging them in a water bath at +25°C. The wet group underwent several steps: first, the mixtures were saturated to approximately 70-80% using a vacuum device; next, the specimens were placed in a plastic bag containing 10 ± 0.5 ml of water. The wrapped specimens were kept in a vacuum-sealed condition in a cooling device at a stable internal temperature of -18°C for 16 h. After cooling, the specimens were submerged in a water bath at +60°C for 24 h. In the final conditioning stage, the specimens were placed in a water bath at +25°C for an additional 2 hours, as shown on Fig.9b. Following conditioning, the dry and wet specimens were tested to calculate the Indirect Tensile Strength (ITS) of the bituminous mixtures, and the TSR was calculated using the formula in Eq.4.

$$TSR = \frac{ITSwet}{ITSdry} \times 100\ \% \qquad (4)$$

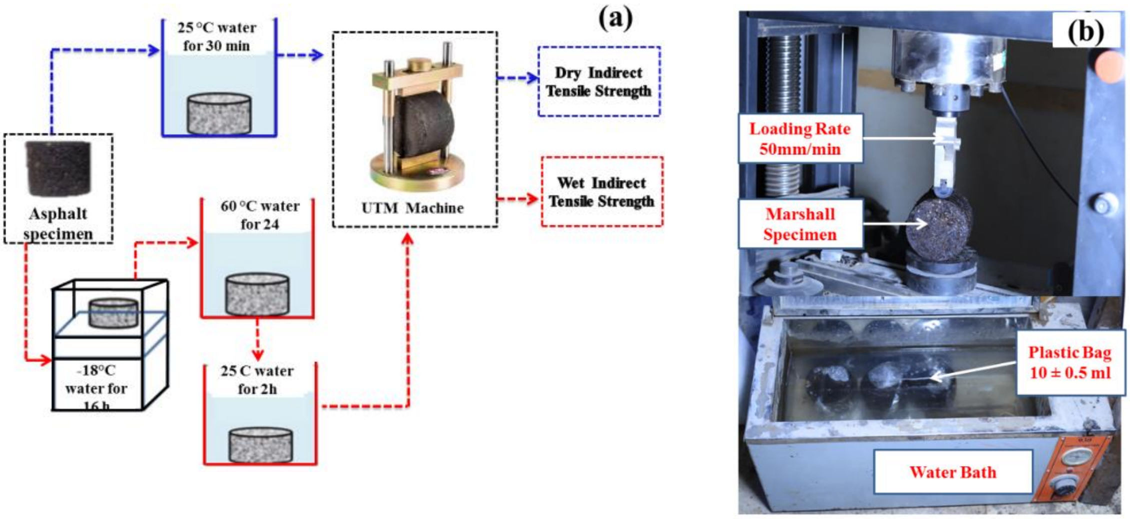

Fig.9.Tensile Strength Ratio information (a) Test procedures diagram and (b)Specimen set-up and devices.

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

The influence of the type and quantity of high length synthetic fibers added on the cracking behavior and fractures specifications of bituminous mixtures at an intermediate temperature of 25°C was assessed using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) according to ASTM D8225. The IDEAL-CT test is a modern technique known for its simplicity, eliminating the need for complex specimen cutting and notching. It is widely utilized as a quality control tool related to the performance of bituminous mixtures during the design and production processes. According to standard specification limits, the bituminous mixtures were prepared with a targeted air void content of 7.0 ± 0.5%, and standard dimensions of 101.6 mm in diameter and 63.5 ± 1 mm in thickness. Before testing, three replicates of each mixture, meeting the targeted air void content, were conditioned in a water bath at 25°C for 2 h. The test was conducted on all specimens under uniform conditions at a temperature of 25°C and a loading rate of 50 mm/min using UTM, as shown in Fig.10a. The load-displacement curves for all specimens were recorded and analyzed to characterize the fracture parameters.

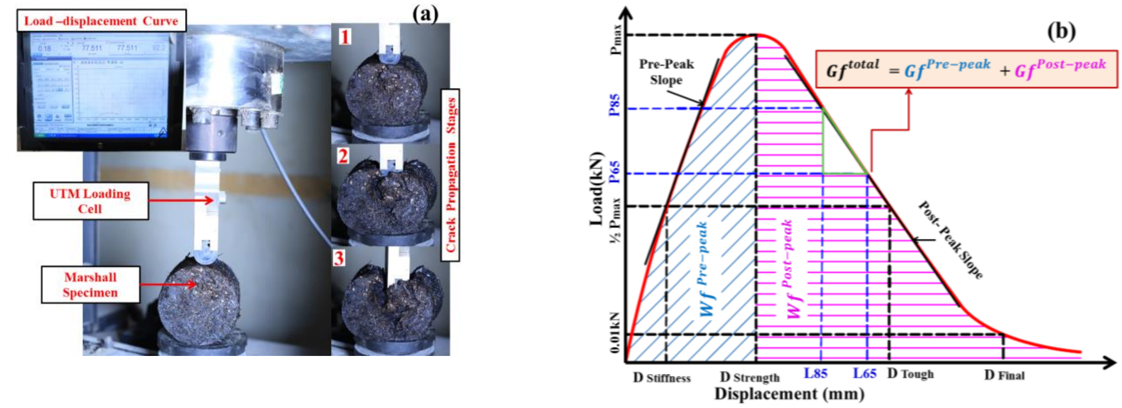

Fig.10. (a) IDEAL-CT set-up and deformation stages and (b) IDEAL-CT load-displacement curve with different fracture parameters definitions.

To analyze the impact of fibers on the fracture behavior of the mixtures, the load-displacement curve of the specimens was divided into pre-peak and post-peak load stages, as illustrated in Fig. 10b. The total fracture energy, along with the energy at the conclusion of each stage, was calculated using the following formulas:

$$Gf^{total} = \frac{Wf^{total}}{t * D} \quad (5)$$

$$Gf^{pre-peak} = \frac{Wf^{pre-peak}}{t * D} \quad (6)$$

$$Gf^{post-peak} = \frac{Wf^{post-peak}}{t * D} \quad (7)$$

Where Gf^{total}, $Gf^{pre-peak}$ and $Gf^{post-peak}$ are total fracture energy, fracture energy at pre-peak stage (before fracture) and fracture energy at post - peak stage (after fracture) in J/m². Wf^{total} , $Wf^{pre-peak}$ and $Wf^{post-peak}$ are total fracture work, fracture work at pre-peak stage (before fracture) and fracture work at post- peak stage (after fracture) in J. D and t are specimen diameter and thickness respectively in m. Additional parameters were also calculated to estimate the cracking potential of the bituminous mixtures. The values of these indices and the extent of their variation determine the cracking performance classification of the bituminous mixtures. The indices evaluated include CT-index, Flexibility Index (FI), Crack Resistance Index (CRI), Fracture Strain Tolerance (FST), Toughness Index (TI), N*flex* factor, Tensile Stiffness Indicator (TSI) and Tensile Strength (TS) all of which are used to predict the cracking resistance of the bituminous mixture. These indices were calculated using the following formulas:

$$CT - \text{index} = \frac{Gf^{total}}{|m75|} * \frac{L75}{D} \quad (8)$$

Where |m75| is the slope at point 75% peak at post peak load stage, L75 is the displacement value at point 75% peak at post peak load stage in (mm).

$$|m75| = \left| \frac{(P85 - P65)}{L85 - L65} \right| \quad (9)$$

$$FI = A \frac{Gf^{total}}{|m75|} \quad (10)$$

where A is the calibration coefficient (0.01).

$$CRI = \frac{Gf^{total}}{Pmax} \quad (11)$$

where Pmax is the peak load value in (N).

$$FST = \frac{Gf^{total}}{St} \quad (12)$$

Where St is indirect tensile strength of asphalt mixture in N/mm² according following formulas:

$$St = \frac{2\,Pmax}{\pi t D} \quad (13)$$

$$TI = Gf^{post-peak} * (Dtough - Dstrength) * .001 \quad (14)$$

$$N\mathit{flex}\ \text{factor} = \frac{TI}{|s|} \quad (15)$$

where |s| is the slope of the post peak load displacement curve at the inflection point (kN/mm), TI is the toughness up to the post peak load displacement curve inflection point.

$$TSI = \frac{0.5Pmax}{Dstiffness} \quad (16)$$

$$TS = \frac{Pmax}{D*t} \tag{17}$$

5. RESULTS

In general, the values presented in all subsequent laboratory test results represent the average of three replicates for each mixture to enhance reliability in the results.

5.1. Physical Properties of Fiber

Table 5 presents the water absorption test results for polypropylene and glass fibers, showing absorption percentages of 0.03% and 0.04%, respectively. These results indicate that both polypropylene and glass fibers exhibit low moisture sensitivity. However, polypropylene fibers demonstrate superior resistance to wet environments, likely due to their non-polar nature, which prevents water molecules from adhering to their surface. Overall, both polypropylene and glass fibers are considered excellent modifiers for bituminous mixtures exposed to wet conditions, with polypropylene fibers being the preferred choice.

TABLE 5. WATER ABSORPTION TEST RESULTS OF POLYPROPYLENE AND GLASS FIBERS

Fiber type	Dry weight (g) W0	Wet weight (g) W1	Average water absorption (%)
Polypropylene fiber	20	20.006	0.03
Glass fiber	20	20.008	0.04

Table 6 presents the thermal stability results of polypropylene and glass fibers after being heated for 5 h at 160°C. Both fibers demonstrate considerable thermal stability, with minimal mass loss. Glass fibers exhibit a lower mass loss rate of 0.68%, which can be attributed to their high silica content, known for its high melting point and strong thermal stability. These characteristics help the fibers retain their mass and structural integrity at elevated temperatures. On the other hand, polypropylene fibers show a higher mass loss of 5.3% due to the softening and decomposition of polypropylene when exposed to heat, leading to the breakdown of polymer chains. Evaluating the thermal stability of fibers is crucial in selecting the appropriate mixing technique and temperature to optimize their effectiveness as modifiers in bituminous mixtures.

TABLE 5. MASS LOSS TEST RESULTS OF POLYPROPYLENE AND GLASS FIBERS.

Fiber type	Weight before heating (g) W0	Weight after heating (g) W1	Mass loss (%)
Polypropylene fiber	30	28.41	5.3
Glass fiber	30	29.80	0.68

5.2. Marshall Index

Fig.11 presents the Marshall test results for the control and fiber-modified mixtures. The error bars indicate one standard deviation above and below the mean values of the replicates. A 15% significance threshold was used to identify and exclude outliers from the analysis. After removing outliers, each mixture had at least three replicates. As shown in Fig11a, the addition of high length polypropylene fibers significantly enhances the stability of asphalt mixtures, with a peak improvement of 49% at 1.5% fiber content compared to the control, indicating better load-bearing capacity. As the polypropylene fiber content increases, flow values decrease, suggesting increased deformation resistance, which is beneficial for pavement durability. As highlighted by earlier studies focused on the use of short and medium-length polypropylene fibers[32]. The maximum reduction in flow is observed at 13% for 1.5% fiber content compared to the control. High length glass fiber also improves stability, peaking at 18% improvement at 0.5% fiber content, but this effect diminishes at higher contents. Unlike polypropylene fibers, increasing glass fiber content beyond 0.75% leads to higher flow values compared to the control, indicating reduced deformation resistance. Overall, polypropylene fibers are more effective than glass fibers in enhancing stability and reducing flow, as they reinforce the asphalt binder, making the mixture more rigid and durable. However, while glass fibers enhance stability, they may increase brittleness and susceptibility to deformation, which is consistent with previous literature that examined the impact of glass fibers on the performance of bituminous mixtures. [52- 30].

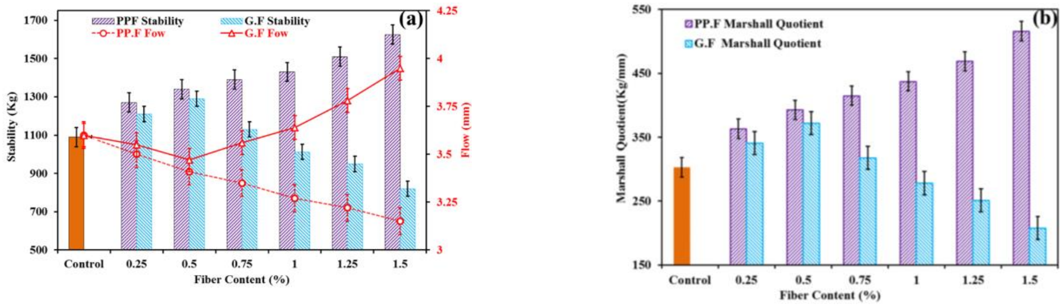

Fig.11.Marshall test results versus with different polypropylene and glass fiber amount (a) Stability and flow and (b)Marshall Quotient. (*Notes PP. F: Polypropylene Fiber, G.F: Glass Fiber*).

In Fig.11b, the incorporation of high length polypropylene fibers markedly enhances the Marshall Quotient values of asphalt mixtures, achieving a 70% improvement at a 1.5% fiber content over control mixture, indicating increased stiffness and resistance to deformation. While high length glass fibers also contribute to higher Marshall Quotient values, their impact is less pronounced than that of polypropylene fibers. The maximum improvement observed with glass fibers is 13% at a 0.5% fiber content compared to the control mixture. However, mixtures with glass fiber contents exceeding 0.75% show Marshall Quotient values lower than the control mixture, suggesting reduced stiffness. The Marshall Quotient, which measures stiffness and stability under load, is crucial for predicting the performance and durability of asphalt pavements. Overall, polypropylene fibers demonstrate a more substantial positive effect on the Marshall Quotient, indicating superior performance compared to glass fibers.

5.3. Volumetric Properties

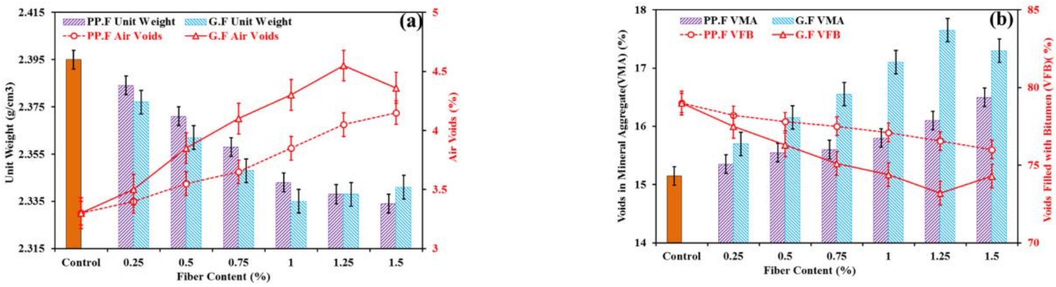

Fig.12.Effect of synthetic fibers on the various volumetric properties of the asphalt mixture (a) Unit weight, and air voids and(b) VMA and VFB.

The following concise summary encapsulates the findings from Fig.12, highlighting the relationship between various volumetric properties of asphalt mixtures modified with different weight proportions of high-length glass and polypropylene fibers:

a) Firstly, the addition of high length polypropylene fibers significantly improves the volumetric properties of the asphalt mixture compared to glass fibers [53-54-55].
b) The unit weight values of the modified mixtures decreased with the addition of up to 1.5% high length of polypropylene fibers, resulting in a reduction of approximately 2.50% compared to the control mixture without fibers. In the glass fiber mixtures, increasing the fiber content leads to a decrease in unit weight values up to 1% glass fiber content, with this reduction being around 2.3%. Beyond this point, the unit weight values begin to increase again. The reduction in unit weight with the addition of polypropylene fibers is less pronounced compared to glass fibers at the same fiber content.
c) The addition of high length polypropylene fibers results in an approximate 25% increase in air void values compared to the control mixture, with the increase observed at a 1.50% fiber content. Glass fiber exhibit a different pattern; the air void values increase by 38% up to 1.25% fiber content, after which a noticeable decrease is observed.
d) The effect of high length polypropylene and glass fibers on the values of voids in the mineral aggregate (VMA) shows a pattern like that observed for air void values. In mixtures modified with polypropylene fibers, there is a 9% increase in VMA at a fiber content of 1.5%. For mixtures modified with glass fibers, the increase is 16% at a fiber content of 1.25%
e) Asphalt mixtures modified with polypropylene fibers show a continuous decrease in the values of voids filled with bitumen (VFB), with a reduction of 4% compared to the control mixture at a polypropylene

fiber content of 1.5%. Glass fibers exhibit a similar trend up to a 1.25% addition, showing an 8% decrease, followed by an increase at higher fiber contents.

f) The differences in the physical properties of glass and polypropylene fibers significantly contribute to their varying effects on the volumetric properties of asphalt mixtures. High-length polypropylene fibers tend to exhibit a more consistent influence on these properties, likely due to their lower density and greater flexibility, which promotes a more uniform distribution within the asphalt matrix. In contrast, glass fibers display less consistent behavior, particularly at higher contents, where clustering and uneven distribution can occur due to their increased stiffness and brittleness. These distinctions underscore the importance of selecting the appropriate type and dosage of fibers to optimize the volumetric properties and overall performance of asphalt mixtures.

5.4. Compressive Strength

Fig. 13a illustrates the effects of varying doses of high length polypropylene and glass fibers on the compressive strength of asphalt mixtures. The addition of polypropylene fibers notably enhances the compressive strength compared to the unmodified mixture. The compressive strength for traditional asphalt mixtures and those modified with 1.5% polypropylene fibers ranges from 26.7 to 35.6 kg/cm² at 25°C and from 53.4 to 61.9 kg/cm² at 60°C. As shown in Fig.13b, the percentage increase in Index of retained compressive strength is substantial, reaching 74% and 98% at 25°C and 60°C, respectively, with the addition of 1.5% polypropylene fibers. Overall, polypropylene fibers demonstrate superior resistance to compressive strength loss at elevated temperatures compared to the control mixture.

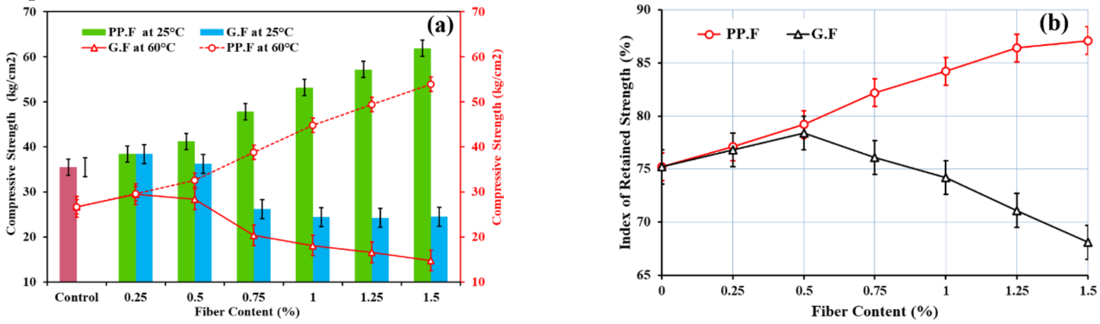

Fig.13. Effect of synthetic fibers on compressive strength test results (a) compressive strength values, and (b) Index of retained strength.

The addition of high-length glass fiber enhances compressive strength compared to the control mixture, with the most significant improvement observed at a 0.5% fiber content. The mixture modified with 0.25% glass fibers exhibits the highest compressive strength values, ranging from 29.5 to 38.4 kg/cm² at 25°C and 60°C, respectively. However, it was noted that mixtures with glass fiber doses exceeding 0.5% displayed lower compressive strength than the control mixture. This reduction may be attributed to fiber clumping at higher dosages, which can degrade the mechanical properties of the sample. High compressive strength is crucial for helping asphalt mixtures withstand heavy loads without deforming, thereby reducing the risk of rutting. Additionally, enhanced compressive strength contributes to resistance against cracks caused by repeated traffic loads, ultimately extending the pavement's lifespan.

5.5. Static Creep Test

Figure14 presents the results of the static creep test for asphalt mixtures reinforced with varying doses of high-length glass and polypropylene fibers, including accumulated strain, initial creep stiffness, and final creep stiffness. At contents 1% glass fibers and 1.5% polypropylene fibers were added, the specimens exhibited the lowest accumulated strain values after 70 min of static creep testing, compared to the control mixture without fibers. All mixtures modified with glass and polypropylene fibers showed lower accumulated strain values than the control mixture, indicating enhanced resistance to deformation. The mixture with 1.5% polypropylene fibers recorded a final accumulated strain value of 3638.3 με, approximately 21% lower than the control asphalt specimen's final strain accumulation of 4658.8 με. Similarly, the mixture modified with 1% glass fibers exhibited a final accumulated strain value of 4000.5 με, reflecting a reduction of about 14%. The difference between this value and that of the 1.5% polypropylene fiber-modified mixture is only 362.2 με, which is not significant from a pavement engineering perspective.

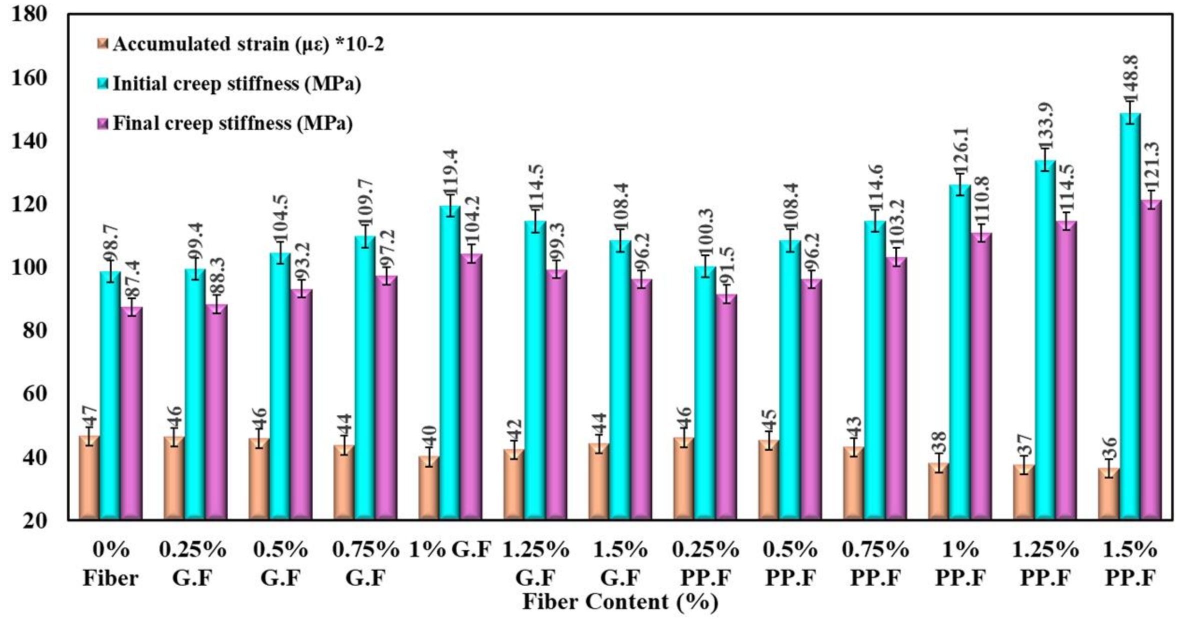

Fig.14. Effect of different amounts of polypropylene and glass fibers on static creep test results.

The examination of the initial and final creep stiffness values of the investigated mixtures at the same dosages reveals that polypropylene fiber-reinforced mixtures outperform those modified with glass fibers. Like the trends observed with accumulated strain, the optimal fiber content for enhancing initial and final creep stiffness parameters is 1.5% for polypropylene and 1% for glass fibers. Conventional asphalt exhibits initial and final creep stiffness values of 98.7 MPa and 87.3 MPa, respectively. In contrast, the mixture modified with 1.5% polypropylene fibers shows values of 148.8 MPa and 121.3 MPa, reflecting a 51% increase in initial creep stiffness and a 39% increase in final creep stiffness. The mixture reinforced with 1% glass fibers demonstrates initial and final creep stiffness values of 119.4 MPa and 104.2 MPa, marking a 21% increase in initial stiffness and a 19% increase in final stiffness, which is significant. These findings indicate that polypropylene fibers are more effective than glass fibers in enhancing the mechanical properties of asphalt mixtures. This indicates the consistency of results for mixtures reinforced with long polypropylene fibers and prepared using the Marshall method in improving static creep behavior, with previous studies that examined the creep performance of bituminous mixtures prepared using other methods[56]. These results are crucial for evaluating the effectiveness of fibers as asphalt modifiers, showing that higher creep stiffness and lower accumulated strain lead to better resistance to permanent deformation and improved pavement durability.

5.6. Moisture Susceptibility Test

5.6.1. Immersion Marshall Test

Fig.15 presents the submerged stability values and residual stability ratio for the control mixture and asphalt mixtures modified with varying doses of polypropylene and glass fibers after immersion in water at 60°C for 24 hours. The results show that the control mixture has the lowest residual Marshall stability after immersion compared to polypropylene fiber-reinforced mixtures. The addition of 1.5% polypropylene fibers enhances the residual Marshall stability by 17% compared to the control mixture. In contrast, asphalt mixtures reinforced with glass fibers exhibit mixed results. Mixtures modified with up to 0.75% glass fibers display higher residual Marshall stability values than the control mixture, but mixtures with higher fiber content show decreased values. The mixture containing 0.5% glass fibers demonstrates the best residual Marshall stability performance, with a 6% improvement over the control. It is well-known that immersing asphalt mixtures in water for 24 hours can lead to increased adhesion loss between the aggregate and the bitumen binder. However, the results of the submerged Marshall test indicate that the incorporation of fibers significantly enhances the mixture's resistance to water-induced damage, underscoring the advantages of fiber reinforcement. Polypropylene fibers better resist stability loss due to 24-hour water immersion compared to glass fibers, maintaining higher stability ratios. Improving residual stability is crucial for asphalt mixtures to resist water infiltration, prevent issues such as potholes, cracks, and ruts, extend pavement lifespan, and reduce maintenance costs [25].

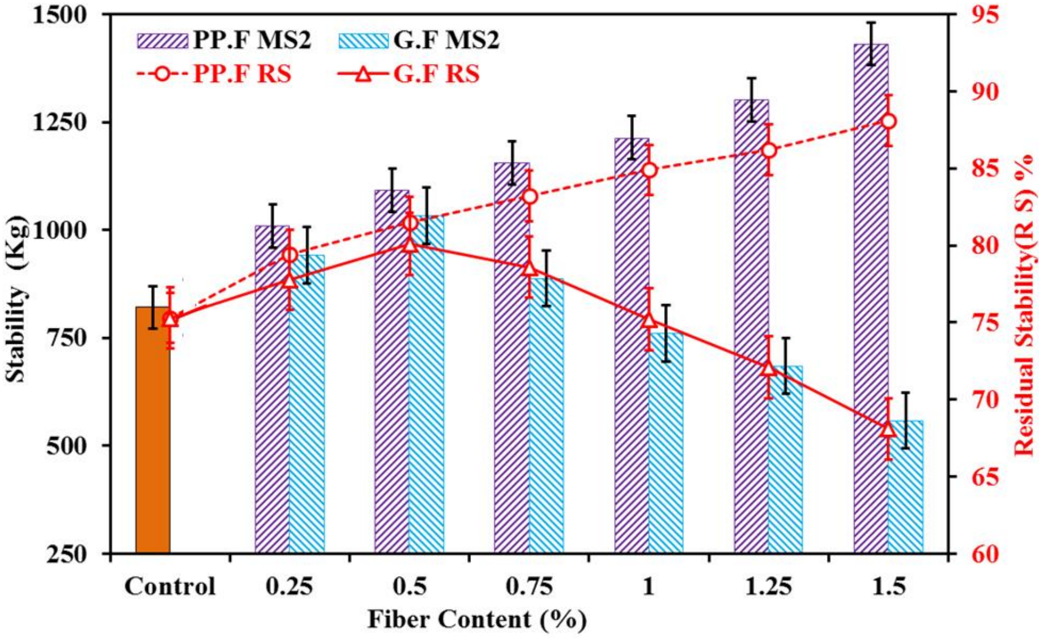

Fig.15. Effect of various amount synthetic fibers in immersion Marshall test results.

5.6.2. Tensile Strength Ratio (TSR)

Fig.16a presents the ITS values for all investigated mixtures under both wet and dry conditions. Mixtures modified with polypropylene fibers demonstrate a significant improvement in tensile strength compared to those with glass fibers and the control mixture in dry conditions. Similarly, in wet conditions, polypropylene fibers exhibit strong resistance to tensile strength loss due to moisture. To assess moisture resistance, the TSR was calculated for traditional bituminous mixtures and those modified with varying contents of polypropylene and glass fibers. Fig.16b shows the TSR values for the mixtures under study. The traditional bituminous mixture without fibers had a TSR value of 0.70%. The TSR values for mixtures modified with high length polypropylene fibers increased with fiber dosage up to 1.5%, showing a 24% improvement over the control mixture. This confirms the effectiveness of polypropylene fibers in enhancing the moisture resistance of the mixture.

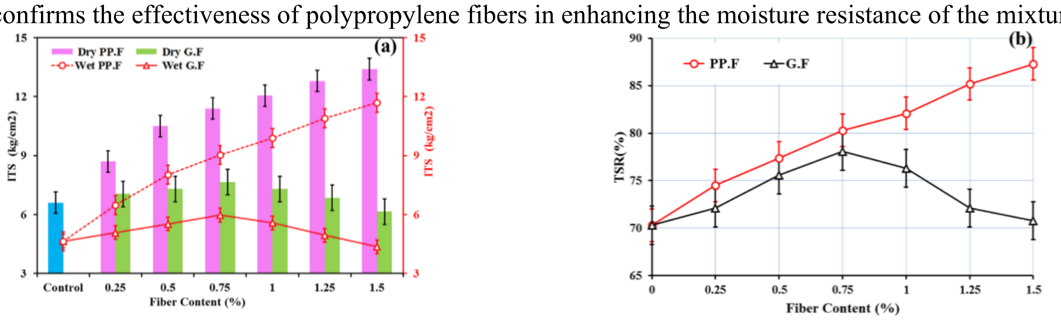

Fig.16.The results of TSR test (a) ITS values in dry and wet conditions and (b) TSR values.

Mixtures modified with high length glass fibers show an increase in TSR values as fiber dosage increases up to 0.75%, after which the values start to decline. All glass fiber-modified mixtures exhibit higher TSR values compared to the control mixture, with the mixture containing 0.75% glass fibers showing an 11% improvement over the control. Polypropylene fibers offer better resistance to tensile strength loss than glass fibers, indicating superior performance after water exposure. High tensile strength is crucial for preventing cracks and ensuring the durability of asphalt pavements, thereby reducing maintenance needs and extending service life. The freeze-thaw cycle that the saturated specimens underwent can cause damage to bituminous mixtures, such as asphalt stripping and softening, due to the thermal contraction of the bituminous material and the thermal expansion of moisture at low temperatures. Enhancing tensile strength and strain capacity is essential to counteract the detrimental effects of moisture. Previous studies have shown that the presence of fibers improves the properties of bituminous mixtures, such as strain capacity and fracture energy, while also increasing the mixture's stability, thus enhancing its resistance to the effects of freeze-thaw cycles [53-57-39].

5.7. Indirect tensile asphalt cracking test (IDEAL-CT)

5.7.1. Fracture energy parameters

The results of the effect of varying amounts of high length glass and polypropylene fibers on the fracture energy properties of hot mix asphalt are presented in Fig.17. It is evident that the $Gf^{pre-peak}$ decreases with the addition of more than 0.25% glass fibers, indicating increased flexibility of the mixture. Conversely, for polypropylene fibers, doubling the fiber content increases the $Gf^{pre-peak}$ values, reaching 150% of the control mixture at a 1% fiber addition, before decreasing again while remaining above the control values. The improvement in $Gf^{pre-peak}$ energy for polypropylene fiber mixtures compared to glass fiber mixtures can be attributed to the enhanced cohesion of the asphalt matrix due to fiber-aggregate interlocking , as indicated by previous studies [58-59-60]. The results also indicate that mixtures containing 0.75% polypropylene fibers, and 1 % glass fibers exhibit the highest Gf^{total} and $Gf^{post-peak}$ values among both fiber groups. The mixture of 0.75% polypropylene fibers showed a 77% and 71% increase in Gf^{total} and $Gf^{post-peak}$, respectively, compared to the control mixture. These increases were 87% and 218% for Gf^{total} and $Gf^{post-peak}$, respectively, for the mixture with 1% glass fibers. All glass fiber mixtures demonstrated higher $Gf^{post-peak}$ than the control specimen, surpassing polypropylene fibers. This can be attributed to the relative improvement in the mixture's flexibility with the addition of glass fibers, which reduces the crack propagation rate after reaching peak load.

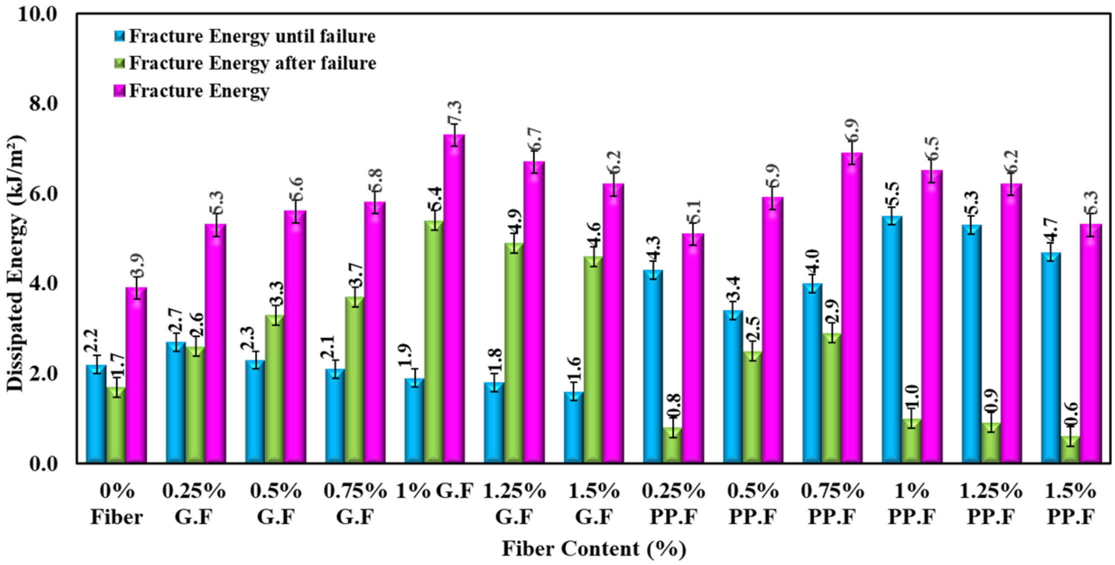

Fig.17. Effect of the addition of different amounts of polypropylene and glass fibers on fracture energy parameters of bituminous mixtures.

5.7.2. Peak load (Pmax), Fracture strain tolerance (FST)and Toughness index (TI)

Fig.18 illustrates the effect of varying amounts of high length from glass and polypropylene fibers on the parameters of peak load, FST, and TI of hot asphalt mixtures. Polypropylene fibers significantly increase peak load values compared to the same doses of glass fibers, likely due to their homogeneous distribution within the bituminous mixture, which enhances stiffness and resistance to elastic deformations before fracturing. In contrast, glass fibers increase the mixture's flexibility, resulting in higher deformation under lower loads. All glass fiber specimens exhibited lower peak loads than the control specimen, while adding 1.0% polypropylene fibers led to an 84% increase in peak load compared to the control. Conversely, the FST indices for glass fiber samples were much higher than those for polypropylene fiber specimens, reflecting the role of glass fibers in enhancing flexibility. The average FST values for glass fiber specimens ranged from 7 to 11.3, compared to 4.4 to 5.1 for polypropylene fiber specimens, with the control mixture showing an FST value of 5.2. The TI is a crucial measure of the asphalt mixture's brittleness, as previous literature concluded [58-59]. The results indicate that adding polypropylene fibers significantly increased the TI values of the mixture compared to glass fibers. This increase is attributed to the formation of a cohesive network within the asphalt, which enhances the mixture's stiffness and resistance to deformation. The mixture modified with 1% polypropylene fibers demonstrated the highest TI increase, showing a 470% rise over the control specimen without fibers, indicating a more brittle behavior in the tested specimens.

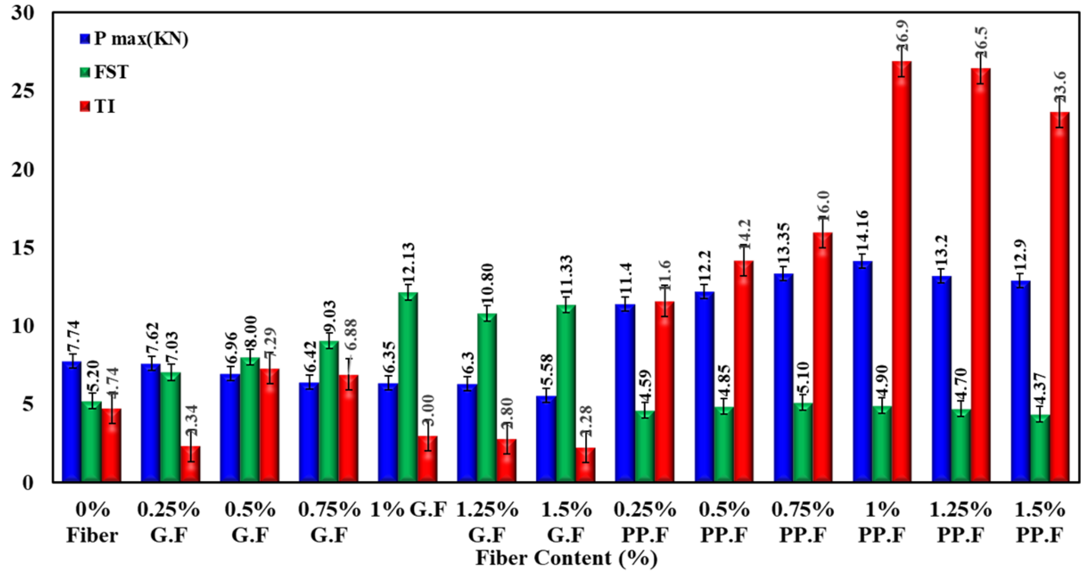

Fig.18. Effect of the addition of different amounts of polypropylene and glass fibers on fracture resistance indexes of Pmax, FST and TI of bituminous mixtures.

5.7.3. Flexibility Index (FI), Crack Resistance Index (CRI)and Nflex factor

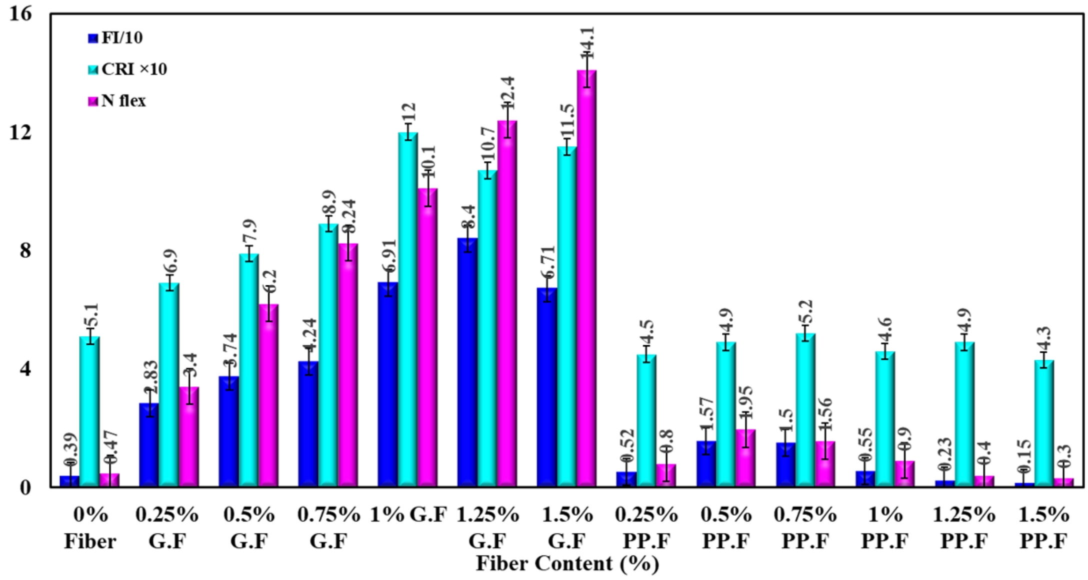

Fig.19. Effect of the addition of different amounts of polypropylene and glass fibers on fracture resistance indexes of FI, CRI and N_{flex} of bituminous mixtures.

Fig.19 presents the results for the indices of FI, CRI, and Nflex factors for both control and modified asphalt mixtures evaluated in this study. The glass fiber-modified mixtures exhibit higher FI values compared to both the polypropylene fiber mixtures and the control mixture, suggesting that glass fibers enhance the mixture's flexibility and crack resistance. The highest FI values for the fiber types were observed in mixtures with 0.5% polypropylene fibers and 1.25% glass fibers, with values of 15.7 and 84, respectively, compared to the control mixture value of 3.9. The CRI results also show a significant increase in flexibility and crack resistance for glass fiber specimens, as indicated by higher CRI values compared to the control mixture and the polypropylene fiber specimens, which exhibited greater stiffness and lower crack resistance[61]. The highest CRI value was achieved in the specimen with 1% glass fibers, representing a 135% increase over the control mixture. Among the polypropylene fiber group, the specimen with a 0.75% fiber addition exhibited the highest CRI value, showing a 2% increase compared to the control. The Nflex factor, evaluated as an indicator of the mixture's crack resistance, is known as the brittleness slope and is calculated by dividing the specimen's toughness by the slope at the inflection point in the post-peak section of the load-displacement curve [62]. According to the Nflex results, specimens with polypropylene fibers exhibited significantly lower Nflex values compared to those with glass fibers. This difference is attributed to the high brittleness slope observed in the polypropylene fiber samples, indicating reduced crack resistance. The mixture containing 1.5% glass fibers demonstrated the highest Nflex value, 36 times greater than the control mixture, whereas the same content in the polypropylene fiber group yielded the lowest Nflex value. Overall, glass fibers outperform polypropylene fibers in enhancing the flexibility of the mixture and **improving** crack resistance after the peak load.

5.7.4. CT- Index, Tensile Stiffness Indicator (TSI) and Tensile Strength (TS)

Fig.20 illustrates the average values of the CT-Index, TSI, and TS indicators from the IDEAL-CT test results for both the control sample and the fiber-reinforced specimens studied. High CT-Index values indicate enhanced crack resistance in the modified specimens, reducing the likelihood of field cracking. The glass fiber-reinforced specimens showed higher CT-Index values compared to those reinforced with polypropylene fibers. Notably, all glass fiber mixtures achieved a CT-Index above the minimum recommended threshold in Virginia (i.e., 70), while only the polypropylene fiber mixtures with 0.5% and 0.75% additions reached this benchmark. However, it is recommended to use locally determined CT-Index values to evaluate the success or failure of mixtures, considering regional climate variations [63]. The CT-Index values for the glass fiber specimens range from 133 to 448, significantly higher than the control mixture value of 12.63 and the polypropylene fiber mixture values, which range from 12.7 to 84.5. In contrast, there was a noticeable improvement in the TS and TSI values for the polypropylene fiber-reinforced mixtures as fiber content increased, compared to the glass fiber mixtures. This highlights the role of polypropylene fibers in enhancing the stiffness of the specimens and their resistance to elastic deformation during the pre-peak load phase, as reflected in the higher TS and TSI values [64-65]. Specifically, the TS values for polypropylene fibers ranged from 1.77 to 2.3, for glass fibers from 1.18 to 0.86, and for the control specimen, 1.2. Meanwhile, the TSI values for polypropylene fiber specimens ranged from 2.5 to 4.82, for glass fibers from 1.4 to 2.85, and for the control specimen, 2.38.

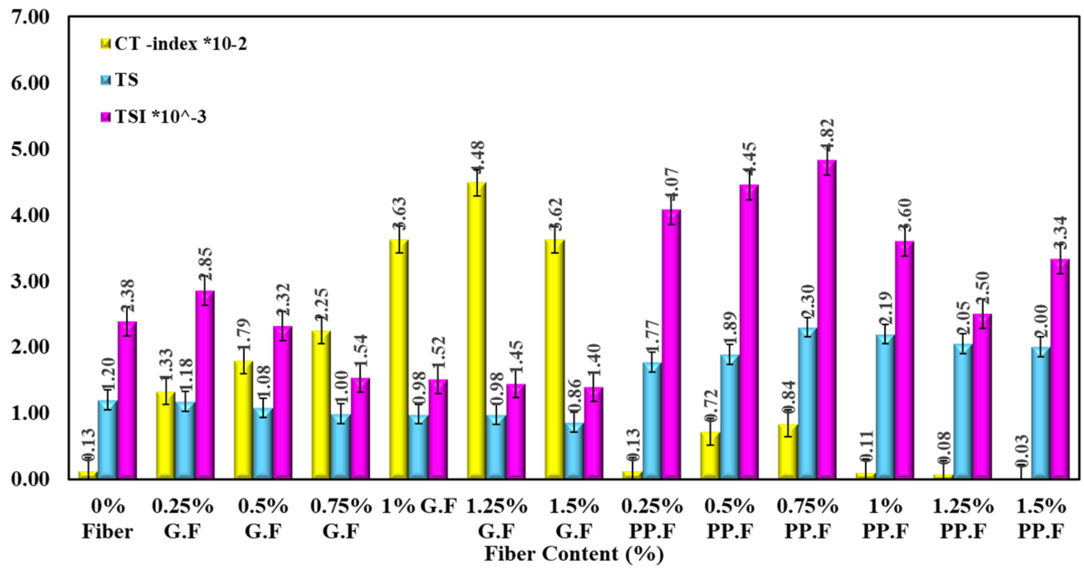

Fig.20. Effect of the addition of different amounts of polypropylene and glass fibers on fracture resistance indexes of CT- index, TSI and TS of bituminous mixtures.

6. STATICALLY ANALYSIS

In addition to the standard error indicators shown in Fig.11 through 20, this study includes a comprehensive statistical analysis. This analysis examines the average of both standard deviation (SD) and coefficient of variation (COV) for both glass and polypropylene fiber mixtures to compare the variability within the two groups. The results of this analysis are presented in Table 7.

TABLE7. THE AVERAGE OF SD AND COV FOR THE MECHANICAL PROPERTIES AND FRACTURE RESISTANCE PARAMTERS OF MIXTURES WITH POLYPROPYLENE AND GLASS FIBER

Parameter		Polypropylene fibers mixtures		Glass fibers mixtures	
		SD	COV%	SD	COV%
Marshall Indexes	Marshall Stability	120.6	7.5	132.2	8.3
	Flow	0.26	8.1	0.32	9.5
	Marshall quotient	44.3	8.2	45.3	8.9

Volumetric Properties	unit weight	0.15	10.1	0.18	11.2
	Air voids	0.25	7.5	0.29	9.5
	VMA	1.05	8.9	1.12	10.3
	VFB	4.1	9.3	4.65	11.5
Compressive Strength	At 25 °C	3.1	6.5	2.5	9.4
	At 60 °C	2.8	7.8	2.4	11.2
Static Creep indexes	Accumulated strain	280.3	9.5	350.1	12.3
	Initial creep stiffness	7.2	11.6	9.2	13.6
	Final creep stiffness	6.2	10.3	8.6	12.8
Moisture Susceptibility	Immersed Marshall stability	101.3	8.1	98.2	10.1
	ITS dry	0.72	7.1	0.44	11.5
	ITS wet	0.61	9.3	0.35	10.8
Indirect tensile asphalt cracking test (IDEAL-CT)	$Gf^{pre-peak}$	146	12.1	184	13.7
	$Gf^{post-peak}$	111.2	8.5	280.1	11.1
	Gf^{total}	325.1	7.1	295.1	10.2
	Pmax	1.05	9.1	0.41	10.3
	FST	0.61	8.7	0.38	12.7
	TI	1.1	10.1	0.22	11.1
	FI	0.61	7.9	2.2	11.6
	CRI	0.04	8.3	0.08	9.8
	N*flex*	0.07	6.7	0.09	10.3
	CT- index	1.54	7.4	9.8	9.5
	TSI	0.22	8.6	0.12	10.3
	TS	0.15	7.7	0.07	11.1

The bituminous mixtures modified with fiber polypropylene exhibit average COV for Marshall indices and mechanical properties, with COV of stability 7.5%, 8.9% VMA, 10.3% final creep stiffness and 7.1% ITS dry %, compared to 8.3% ,10.3%,12.8% and 11.5% respectively for glass fiber mixtures. The reduction in the coefficient of variation values for polypropylene fiber mixtures is attributed to their more uniform distribution, resulting in more consistent performance at evaluating the mechanical properties of the specimens. Similarly, the fracture resistance parameters of polypropylene fiber-reinforced mixtures show a decrease in the average COV values compared to glass fiber-reinforced mixtures. The average COV for polypropylene fiber mixtures is 7.1% Gf^{total},8.7 % FST,8.3% CRI and 7.7% TS compared to 10.2%,12.7%,9.8% and 11.1%% respectively for glass fiber mixtures. This reduction in the average COV values for polypropylene fiber-reinforced mixtures is attributed to the lower melting point of polypropylene fibers, which is closer to the mixing temperature. This proximity allows the fibers to melt and blend more smoothly during the mixing process, resulting in a more homogenous mixture. This homogeneity reduces variability in the fracture properties of the mixtures.

7. COST ANALYSIS

Conducting an economic benefit analysis is essential when assessing the impact of fibers as modifiers in bituminous mixtures. This analysis evaluates the economic feasibility and cost-effectiveness of fiber incorporation by comparing the costs associated with different types and quantities of fibers against the benefits they offer, such as improved mechanical properties and enhanced durability. Such assessments enable researchers and engineers to determine if the investment in fibers is justified, supporting informed decision-making for infrastructure projects and facilitating government approvals. This study examines the cost of raw materials for the surface layer, incorporating polypropylene and glass fibers to improve field performance. A comprehensive cost analysis was conducted for the control mixture and mixtures modified with various fiber amounts. The analysis included raw material costs such as bituminous binder, aggregates, and filler alongside manufacturing costs, which encompass production, transportation, and application of the mixture. Raw material costs were guided by quotes from reputable local companies in Egypt's asphalt paving industry, while fiber costs were obtained from the Egyptian Fiber Company. Table 8 shows the proportions of raw materials required for the mixtures, and Table 9 details the raw material costs per ton in $-USA.

TABLE 8. THE PROPORTIONS OF RAW MATERIALS NECESSARY FOR PREPARING CONTROL AND FIBER – MODIFIED BITUMINOUS MIXTURE.

Materials	Control	0.25% fiber	0.5% fiber	0.75% fiber	1.0% fiber	1.25% fiber	1.5% fiber
Asphalt binder	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Coarse aggregates	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Fine aggregates	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Mineral Filler	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Fiber	0.00	0.0025	0.005	0.0075	0.01	0.0125	0.015

TABLE 9. THE COST OF 1- TON OF BITUMINOUS BINDER, AGGREGATE, FILLER,AND FIBER IN ($-USA).

Materials	bituminous	Coarse aggregates	Fine aggregates	Mineral Filler	Fiber
Control mixture	550	6	5.5	10	0
Polypropylene fiber mixture	550	6	5.5	10	600
Glass fiber mixture	550	6	5.5	10	430

Table 10 outlines the quantities of bituminous binder, aggregates, filler, and synthetic fibers required to rehabilitate a bituminous pavement section measuring 1 km in length, 12 m in width, and 0.05 m in thickness. The cost of raw materials for the bituminous mixtures was calculated by multiplying the required quantities for paving 1 km, as detailed in Table 10, by the approved prices per ton of raw materials listed in Table 9. To determine the total cost of the bituminous mixtures, the manufacturing cost was added to the raw material cost. Table 11 presents the final costs for various fiber-reinforced mixtures and the control mixture needed to cover 1 km.

TABLE 10: THE AMOUNTS OF RAW MATERIALS REQUIRED FOR PAVING 1-KM OF CONTROL AND POLYPROPYLENE / GLASS FIBER MIXTURES.

Mixtures	0% Fiber	0.25% Fiber	0.50% Fiber	0.75% Fiber	1.0% Fiber	1.25% Fiber	1.50% Fiber
Volume (m3)	600	600	600	600	600	600	600
Specific gravity	2.395	2.384/ *2.377*	2.371/ *2.362*	2.358/ *2.348*	2.343/ *2.335*	2.338/ *2.337*	2.334/ *2.341*
Asphalt mixture weight (ton)	1437	1430.4/ *1426.2*	1422.6/ *1417.2*	1414.8/ *1408.8*	1405.8/ *1401*	1402.8/ *1402.2*	1400.4/ *1404.6*
Asphalt weight (ton)	71.9	71.5/*71.3*	71.1/*70.9*	70.7/*70.4*	70.3/*70.1*	70.1/*70.1*	70/*70.2*
Coarse aggregates weight (ton)	718.5	715.2/ *713.1*	711.3/ *708.6*	707.4/ *704.4*	702.9/ *700.5*	701.4/ *701.1*	700.2/ *702.3*
Fine aggregates weight (ton)	632.3	629.4/ *627.5*	625.9/ *623.6*	622.5/ *619.9*	618.6/ *616.4*	617.2/ *616.9*	616.2/ *618.0*
Mineral Filler weight (ton)	86.2	85.8/*85.6*	85.4/*85.0*	84.9/*84.5*	84.3/*84.0*	84.2/*84.1*	84.0/*84.3*
Polypropylene / *Glass*	0	3.58/ *3.57*	7.11/ *7.09*	10.6/ *10.57*	14.06/ *14.01*	17.54/ *17.53*	21/ *21.07*

TABLE 11. THE TOTAL COST OF REQUIRED FOR PAVING 1-KM OF CONTROL AND POLYPROPYLENE / GLASS FIBER MIXTURES.

		0% Fiber	0.25% Fiber	0.50% Fiber	0.75% Fiber	1.0% Fiber	1.25% Fiber	1.50% Fiber
Raw Materials	Asphalt	39545	39325/ *39215*	39105/ *38995*	38885/ *38720*	38665/ 38555	38555/ *38555*	38500/ 38610
	Coarse aggregates	4311	4291.2/ *4278.6*	4267.8/ *4251.6*	4244.4/ *4226.4*	4217.4/ *4203*	4208.4/ *4206.6*	4201.2/ *4213.8*
	Fine aggregates	3477.65	3461.7/ *3451.25*	3442.45/ *3429.8*	3423.75/ *3409.45*	3402.3/ *3390.2*	3394.6/ *3392.95*	3389.1/ *3399*
	Mineral filler	862	858/*856*	854/*850*	849/*845*	843/*840*	842/*841*	840/*843*
	Polypropylene / *Glass*	0	2148/ *1535.1*	4266/ *3048.7*	6360/ *4545.1*	8436/ *6024.3*	10524/ *7537.9*	12600/ *9060.1*
Manufacturing Procedures	Preparation	7500	7500	7500	7500	7500	7500	7500
	Transportation	2700	2700	2700	2700	2700	2700	2700
	Laying	1800	1800	1800	1800	1800	1800	1800
Total cost		60195.65	62083.9/ *61335.9*	63935.25/ *62575.1*	65762.2/ *63745.9*	67563.7/ *65012.5*	69524/ *66533.5*	71530.3/ *68125.9*
The increasing ratio in polypropylene/*glass* Mixtures cost (%)		0	3.1 / *1.8*	6.2/ *3.9*	9.2 / *5.9*	12.2/ *8.0*	15.5/ *10.5*	18.8/ *13.2*

The results indicate that the overall cost of the control mixture is slightly lower than that of bituminous mixtures containing polypropylene and glass fibers. The increased cost of fiber-reinforced mixtures is solely due to the inclusion of these fibers. Notably, polypropylene fiber mixtures are marginally more expensive than glass fiber mixtures. Adding 1.5% polypropylene fibers by weight of the aggregate led to significant improvements in Marshall stability, volumetric properties, freeze-thaw resistance, compressive strength, permanent deformation, and cracking resistance, with an acceptable 18.3% increase in cost. This enhancement in bituminous mixture properties justifies the additional expense. Similarly, incorporating 1% glass fibers increased the mixture's flexibility and provided high resistance to crack propagation by creating a three-dimensional network that reduces deformation, extends pavement service life, and lowers maintenance costs, though it resulted in an 8% increase in overall cost.

8. CONCLUSIONS

This work investigated the influence of high length from polypropylene and glass fiber on the performance of bituminous mixtures. Marshall test, compressive strength, static creep test, susceptibility moisture tests and IDEAL-CT were conducted to evaluate the previous fibers effects. The following conclusions were reached from laboratory investigation results:

- Low dosages of long glass and polypropylene fibers significantly improved the overall performance of the bituminous mixture (mechanical properties and fracture behavior), supporting their use alongside the fiber lengths proposed in previous studies.
- The quantitative comparison of the mechanical properties and fracture characteristics demonstrated the superiority of polypropylene fibers over glass fibers in enhancing the performance of the bituminous mixture, thereby supporting the use of polypropylene fibers in improving pavement infrastructure.
- The various properties of bituminous mixtures, including stability, flow, Marshall quotient, volumetric properties, compressive strength, stability, residual stability ratio, and tensile strength ratio, significantly improve with increasing polypropylene fiber content. With the addition of 1.5% polypropylene fibers, the properties of the bituminous mixture reached their maximum enhancement by (49%) Marshall stability,(14%) flow, ,(70%)Marshall quotient, (25%) VM, (9%) VMA, (4%) VFB, (17%) residual stability,(24%) tensile strength ratio, and(74%),(101%) compressive strength at 25°C and 60°C, respectively, compared to the control mixture.
- The incorporation of glass fibers good enhances the mechanical properties of bituminous mixtures, although these improvements diminish with increasing fiber content. At a 0.5% fiber addition, the properties reached their maximum enhancement by (18%) Marshall stability, (4%) flow, and (6%) residual stability. Increasing fiber content to 1.25%, the volumetric properties also peaked, with improving by (38%) VM, (15%) VMA, and (8%) VFB.
- The addition of polypropylene and glass fibers to bituminous mixtures significantly enhances resistance to permanent deformation, as evidenced by the static creep test results. The maximum improvement in permanent deformation resistance was achieved with the addition of 1.5% polypropylene fibers and 1% glass fibers. Adding 1.5% polypropylene fibers resulted in a reduction in accumulated strain by approximately 22%, and the final creep stiffness values increased by 39% from control mixture results. In contrast, the improvement in these parameters was 14% and 19%, respectively, with the addition of 1% glass fiber.
- The incorporation of glass fibers exhibits distinct post-peak behavior compared to polypropylene fibers in enhancing the flexibility of bituminous mixtures and resistance to crack propagation, as demonstrated by the results of the IDEAL-CT test. A content of 1% glass fibers corresponded to the maximum enhancement of Gf^{total} and CRI by 87% and 135%, respectively. With fiber content increasing to 1.25%, the flexibility indicators, FI and CT-index, showed maximum values 84 and 447.95 compared to 3.9 and12.6 respectively for the control mixture.
- The polypropylene fiber-modified mixtures exhibited notable pre-peak fracture behavior. At a fiber addition rate of 0.75%, the mixture showed the maximum improvement values compared to control mixture, with (77%) Gf^{total} , (51%) TSI and (92%) TS.
- The economic evaluation revealed that incorporating polypropylene and glass fibers at a rate of 1.5% led to an acceptable increase in the overall cost of asphalt pavement by 18.8% and 13.2%, respectively, compared to the control mixture. However, this increase in cost is justified by the significant improvement in the performance of the asphalt mixtures, extending the pavement lifespan. Therefore, fiber reinforcement proves to be a worthwhile investment in the field of pavement.

ABBREVIATIONS

G.F, Glass Fiber; PP.F, Polypropylene Fiber; UTM, Universal Testing Machine; TSR, Tensile Strength Ratio;

VMA, Voids in Mineral Aggregate; VFB, voids filled with bitumen; VM, void in mixture ;IDEAL-CT, Indirect Tensile Asphalt Cracking ;FST, Fracture Strain Tolerance; CRI, Crack Resistance Index; TI, Toughness Index; FI, Flexibility Index; TSI, Tensile Stiffness Indicator; TS, Tensile Strength.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

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The authors confirm that the final version of the manuscript has been reviewed, approved, and consented to for publication by all authors.

Competing interests

The authors declare no competing interests.

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