

Enhancement of Hot Asphalt Mixture Performance through the Incorporation of Carbon and Polyester Microfibers

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Abstract

This study explores the performance enhancement of hot asphalt mixtures by integrating carbon (MCF) and polyester (MPF) microfibers. Conventional asphalt mixtures (M0) encounter issues such as rutting, moisture damage, and thermal cracking due to increasing traffic and environmental stressors. Fiber-reinforced asphalt mixtures (CFRAMs and PFRAMs) were created with fiber contents from 0.25% to 1.5% by weight. Laboratory evaluations assessed Marshall properties, moisture susceptibility (through immersion Marshall and freeze-thaw splitting tests), and high-temperature rutting resistance (wheel tracking tests at 40°C and 60°C). The results indicated that both types of fibers enhanced mechanical performance, reaching optimal results at 0.75% fiber content. CFRAMs displayed the highest Marshall stability (17.5 kN compared to 12.5 kN for M0) and Marshall stiffness (6.18 kN/mm), as well as greater moisture resistance (tensile strength ratio >85% in contrast to 80% for M0). Polyester fibers showed a higher water absorption rate (2.43% versus 1.87%) and reduced thermostability compared to carbon fibers. Wheel tracking tests verified the outstanding rutting resistance of CFRAMs (with a proportional rut depth of 0.067 at 40°C compared to 0.211 for M0), particularly at high temperatures. The study concludes that microfibers significantly improve the durability of asphalt, with carbon fibers demonstrating superior performance for sustainable pavements in challenging conditions.

Keywords: Carbon fiber; fiber-reinforced asphalt; moisture damage; rut resistance; sustainable pavements; wheel tracking test.

Introduction

Flexible pavements are made of asphalt mixtures containing three main components: asphalt binder, mineral aggregate, and air voids. Because of their ability to adapt to various conditions and distribute loads efficiently, asphalt mixtures are the primary material used in creating flexible pavements (Ezzat et al., 2023). Increasing traffic volume, heavier axle loads, and severe climate have increased pavement distress due to thermal crack formation, rutting, stripping, and hardening under age (Jasim et al., 2019). In addition, other factors, such as water infiltration and high variances in temperature, have intensified the deterioration of the conventional structural integrity of asphalt mixtures. Therefore, because of the growing number of modern pavement durability requirements (Al et al., 2022), standard asphalt pavements will be unable to fulfil those requirements thus requiring further modifications to improve mechanical performance and environmental toughness (Ismael et al., 2021; Jasim et al., 2026).

Asphalt concrete is the top choice worldwide for constructing roads due to its speed of installation, maintenance ease, and ability to ensure safe driving. Nevertheless, the new demands for longer service life under severe mechanical and environmental stresses reveal the limitations of the traditional formulation of asphalt concrete. To address these limitations, many researchers have taken an interest in the development of innovative asphalt mixtures with improved performance characteristics through innovative materials. Many recent studies have developed reinforcing fibers

(AlSaadi et al., 2023; Ismael et al., 2022; Khaled et al., 2024; Yousif et al., 2022) for use in asphalt mixtures, especially using reinforcing fibers made from carbon or polyester, as a means to reduce the most common failure types. Many of the technologies used to develop innovative asphalt formulations have tested many materials, aside from polyester and carbon, for their effects on improving asphalt performance (Zahedi et al., 2017). For example, cellulose fiber is most often used as an additive in stone mastic asphalt (SMA) mixtures and has shown to prevent binder drain down and increase moisture resistance (AlSaadi et al., 2023). Additionally, basalt fiber has been shown to increase crack resistance, tensile strength, and durability of asphalt (Hui et al., 2022; Wang et al., 2022). Nano silica and carbon nanotube nanomaterials are examples of additives that have been used together with asphalt to improve its performance (Ezzat et al., 2023; Moeini et al., 2020; Yao et al., 2013). Polymer-modified binders are, in particular, SBS modifier asphalt, well known for providing improved performance at high temperatures and increased resistance to fatigue (Yildirim, 2007). There have, however, been very few studies that have performed direct comparisons between micro carbon fibers and micro polyester fibers in laboratory-controlled testing environments; however, extensive testing has been conducted using Carbon Fiber Reinforced Asphalt Mixtures (CFRAMs) and Polyester Fiber Reinforced Asphalt Mixtures (PFRAMs), both of which have shown to provide significant improvements in tensile strength, crack resistance, and durability compared to conventional asphalt mixtures (Sultan et al., 2026; Zahedi & Zarei, 2016; Zarei, Akbarinia, et al., 2020).

Asphalt mixtures' performance is significantly affected by carbon fibers' tensile strength (Jing et al., 2023), low density (Hao et al., 2023), and thermal/electrical conductivity (Baeza et al., 2018; Liu et al., 2021). When carbon fibers are integrated into asphalt mixtures, they increase resistance to fatigue, rutting and reflective cracking (Khattak et al., 2013; Zarei et al., 2022) and allow for self-healing properties when used with conductive additives (Ye et al., 2024). Khattak et al. (2013) found that carbon nanofibers increase the stiffness and deformation resistance of asphalt mixtures and Ye et al. (2023) found that waste carbon fibers increase the efficiency of crack-healing. Similar to carbon fibers, polyester fibers are synthetic polymers made from petroleum and have a high level of compatibility with asphalt binders due to their similar chemical make-up. Polyester fibers, like carbon fibers, have high ductility and energy absorption capabilities, which can mitigate moisture susceptibility and thermal stress build-up in pavements.

It is important to note that difference between microfibers and microfibrs in asphalt mixtures is primarily determined by their length relative to the maximum aggregate size. Fibers with lengths shorter than the maximum aggregate size are categorized as microfibers, whereas those exceeding this threshold are classified as macrofibers. Microfibers predominantly affect the asphalt binder or mastic phase, contributing to enhanced material properties at the microstructural level. Despite their potential benefits, the underlying mechanisms and performance contributions of microfibers in asphalt mixtures remain insufficiently understood. Therefore, this study investigates the influence of microfiber incorporation on the moisture damage resistance under freeze and thaw condition and rutting response of asphalt mixtures under elevated service temperatures. As well, the performance of mixtures reinforced with micro carbon fibers and polyester fibers has been evaluated and compared to that of unreinforced control mixtures, in order to develop optimized, cost-effective, and sustainable fiber-reinforced asphalt pavements capable of withstanding modern traffic demands and extreme environmental challenges, thereby offering practical solutions to enhance pavement durability and service life (Wang et al., 2025).

While there is an increasing amount of interest in fiber-reinforced asphalt mixtures, many research gaps exist. Previous studies focused on assessing different types of fiber but have not compared the performance of micro-carbon and micro-polyester fibers beside each other using the same design and testing methods. In addition, while many of these studies assess traditional mechanical properties, few studies have conducted complete assessments regarding moisture susceptibility, freeze-thaw resistance, or high-temperature rutting performance (Shi et al., 2025). Additionally, existing literature does not have an established optimal microfiber content for achieving a balance between mechanical performance, durability, and volumetric nature. The purpose of this research is to fill these gaps by systematically assessing the performance of asphalt mixtures with micro-carbon versus micro-polyester fiber over a broad range of fiber contents. The originality of this research includes a complete experimental evaluation of both fiber types using tests for Marshall stability, immersion Marshall, freeze-thaw splitting, water absorption, thermal stability and wheel tracking. This research will formally identify the optimal amount of both types of fibers as well as provide a side-by-side performance comparison of two fiber types, thereby providing practical guidelines for the design of durable asphalt pavements in hot-climate regions.

Materials

Aggregate

In this paper, the materials used to prepare asphalt mixtures are crushed quartz aggregates of different sizes with mineral filler powder, such as ordinary Portland cement. The essential properties of coarse, fine aggregates, and mineral filler powder are summarized in Table 1. The aggregate gradation was chosen at the mid-point, which achieves a dense grading to produce the asphalt pavement layer with enough strength to carry high traffic, with the lower and upper limits according to the Iraqi specification (SCRB, 2003) as presented in Figure 1.

Table 1 Essential Properties of Aggregates

Test	Unit	Standard	Results
The bulk specific gravity of coarse aggregates	gm/cm ³	ASTM C-127	2.603
Water absorption of coarse aggregates	%	ASTM C-127	0.463
Los Angeles abrasion Value (LSV)	%	ASTM C-131	18.3
Sodium sulfate soundness (SS)	%	ASTM C-88	2.98
Flat and elongated Particles	%	ASTM D-4791	1.6
Fractured face (two-face)	%	ASTM D-5821	97
The bulk specific gravity of fine aggregates	gm/cm ³	ASTM C-128	2.651
Water absorption of fine aggregates	%	ASTM C-128	0.733
The bulk specific gravity of mineral filler	gm/cm ³	ASTM C-128	2.794
Mineral filler passing sieve No.200	%	----	95

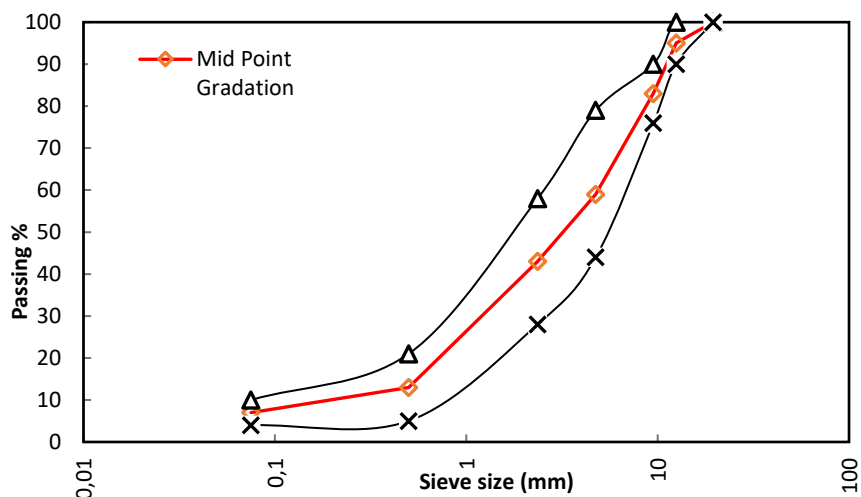


Figure 1 Gradation of Aggregates

Asphalt Binder

The asphalt binder with the performance grade (PG 70-16) produced by the Daurah refinery was used to prepare all experimental mixtures. In the current study, the fundamental physical characteristics of asphalt are determined depending on the ASTM specification and summarized in Table 1.

Table 2 Physical Characteristics of Asphalt Binder

Materials	Tests	Unit	Standard	PG 70-16	
				Results	IQ-Specification
Pure Asphalt Binder	Penetration at 25°C	0.1 mm	ASTM D5	46	40-50
	Kinematic viscosity at 135°C	Centistoke	ASTM D2170	410	
	Softening point	°C	ASTM D36	51	
	Ductility at 25°C	cm	ASTM D113	130	>100
	Flash point	°C	ASTM D92	272	>232
	Specific gravity	-	ASTM D70	1.04	
RTFO Binder	Retained penetration	%	ASTM D5	60	>55
	Ductility at 25 °C	cm	ASTM D113	80	>25

Additive Materials

Micro Polyester Fiber (MPF)

Micro polyester fiber (MPF) is a synthetic organic material produced from crude oil and asphalt is one of the components. It is smooth, straight, and resilient, with lower absorbency, and higher melting point fiber. It is supplied by the Sika Company in Iraq. MPF plays a significant role in increasing the adhesion between the aggregate and the asphalt binder, making asphalt concrete strong, stable, durable, and suitable in regions with high temperatures. MPF was added in various percentages (0.25, 0.5, 0.75, 1, 1.25, 1.5) of the mixture weight based on some recommended papers in this filed (Albayati & Ismael, 2023; Alfalah et al., 2021; Morea & Zerbino, 2018). Figure 2 displays the MPF under microscopic. The basic properties of MPF are provided in Table 3.

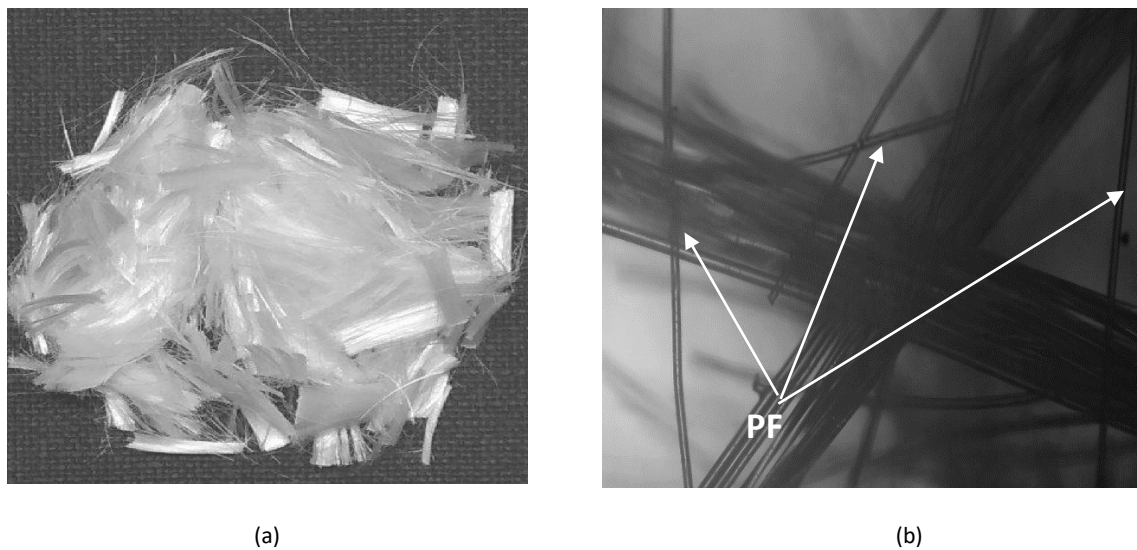


Figure 2 Micro Polyester Fiber (MPF) (a) Shape of MPF, (b) MPF under Microscope.

Table 3 Physical Properties of Fiber

Property	Unit	Standard	Micro Polyester Fiber Results	Micro Carbon Fiber Results
Length	mm	ASTM D204	10±2	10±2
Width	µm	ASTM D2130	32	20
Color	-	-	White	Black
Shape	-	-	Circle	Circle
Specific gravity	gm/cm ³	ASTM D792	1.4	1.8
Softening point	°C	ASTM D7138	≥258	≥550
Tensile Strength	MPa	ASTM D5035	750	1300
Modulus of Elasticity	GPa	-	30	30

Micro Carbon Fiber (MCF)

Micro carbon fiber (MCF), also known as graphite fiber, is made of organic materials and produced from either polyacrylonitrile (PAN) or pitch precursors in the form of thin strands having high tensile strength, extremely stiff, and very lightweight. It is supplied by the Sika Company in Iraq. It is used in processes to successfully create Fiber Reinforced Asphalt Concrete (FRAC) due to increased tensile strength and properties related to mixtures caused by the asphalt and aggregates, essentially bonded together by fibers. This is another reason carbon fiber is favored as reinforcement in asphalt concrete due to its advantages and compatibility. Carbon fiber is composed of carbon, and asphalt is a hydrocarbon suitable for saving energy and resources. MCF was added in various percentages (0.25, 0.5, 0.75, 1, 1.25, 1.5) of the mixture weight based on some recommended papers in this field (Albayati & Ismael, 2023; Alfalah et al., 2021). Figure 3 displays the MCF under a microscope. The basic properties of MCF are provided in Table 3.

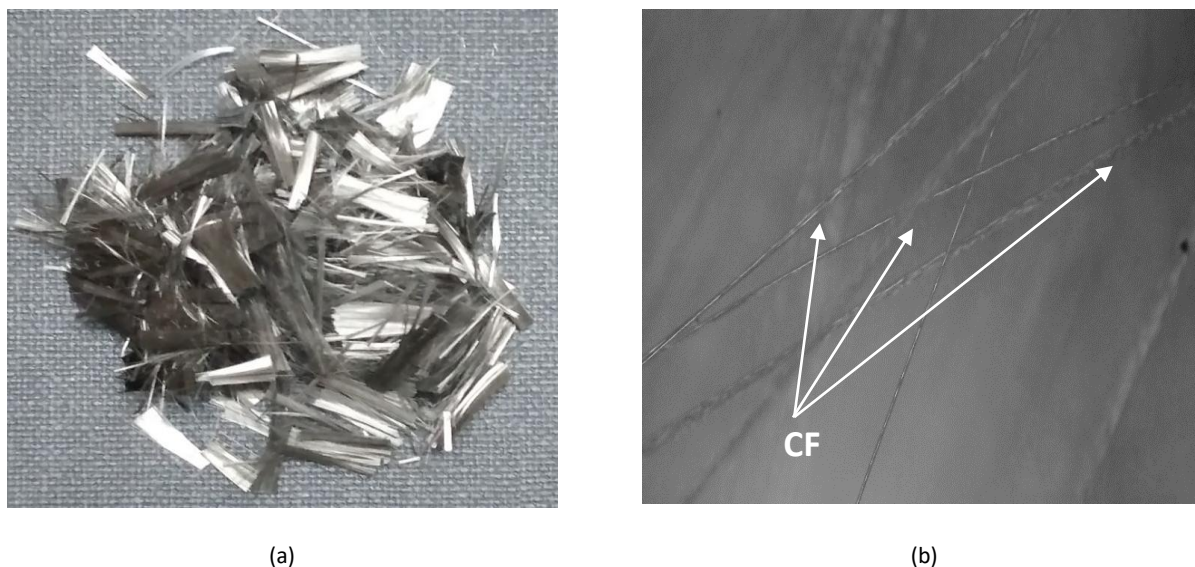


Figure 3 Micro Carbon Fiber (MCF) (a) Shape of MCF, (b) MCF under Microscope.

The percent weights of microfiber for this study were calculated based on the percent weights of the total asphalt mixture and consisted of 0.25%, 0.50%, 0.75%, 1.00%, 1.25%, and 1.50% as indicated in order to evaluate the influence of increasing fiber dosage on mixture performance. The percent weights of the microfibers chosen were based on previous test results of fiber-reinforced asphalt mixtures as well as on preliminary laboratory observations made after trial mixing. The lower percent weights of 0.25% and 0.50% were chosen to determine the initial reinforcing characteristics of microfibers, while the intermediate percent weights of 0.75% and 1.00% were chosen to identify the possible optimum ranges of percent weights for the fiber. The higher percent weights were used to evaluate the effectiveness of excess fiber addition on the workability, dispersion, homogeneity and volumetric properties of the mixture. During the performance of the trial preparation, the greater percent weights of 1.25% and 1.50% were shown to exhibit more clustering and less mixture workability. The resultant range of percent weights provided a systematic means of evaluating both the positive and negative effects of incorporating microfibers into the asphalt mixture and provided a means of determining the optimal amount of microfibers to be utilized in the asphalt mixture.

Experimental Method

The following tests were performed on two types of fibers and different asphalt mixture specimens to investigate their performance, as shown below.

Physical Properties of Fibers (Tests and Results)

Water Absorption Test

The water absorption test (WAT) involved three specimens of polyester and three of carbon fibers, each weighing 30 g and kept in dry beakers. These samples were stored in a curing chamber at 20 °C with 90% relative humidity for five days. During this period, the beakers containing the fibers were weighed every five hours. The weights recorded were used to determine water absorption, calculated via Eq. (1).

$$\text{Water Absorption (\%)} = \frac{W_1 - W_0}{W_0} \times 100 \quad (1)$$

where W1 is the wet weight in (gm), W0 is the dry weight in (gm).

Table 4 shows the fibers' water absorption test results. The water absorption ratios for carbon and polyester fiber are 1.87% and 2.43%, respectively. Meanwhile, it was observed that polyester fiber adsorbed much more water than carbon fibers after 5 days in a moisture condition, which can be detected with fingers. This indicator also suggests that polyester fiber is more sensitive to a humid environment than carbon fiber by about 30%.

Table 4 Water Absorption (WAT) results of fibers

Fiber Type	Dry Weight (g)	Wet Weight (g)	Average Water Absorption (%)
	W_0	W_1	
Micro Polyester Fiber	30	30.74	2.43
Micro Carbon Fiber	30	30.56	1.87

Oven Heating Test

To evaluate the thermal stability of polyester and carbon fibers, a simple Oven Heating Test (OHT) was performed. For each fiber type, three specimens weighing 50 g each were placed in beakers and heated in a laboratory oven at 163 °C for 5 hours, mimicking asphalt mixing conditions. The fiber weight changes were continuously tracked, recorded, and calculated using Eq. (2).

$$\text{Mass Loss (\%)} = \frac{W_0 - W_1}{W_0} \times 100 \quad (2)$$

where W_0 and W_1 are the weight before and after heating, respectively.

The oven heating test results, shown in Table 5 with water absorption data, reveal that carbon fiber and polyester fiber lost 0.54% and 0.92% of their mass, respectively. Polyester fiber's higher loss indicates lower thermal stability—about 70% less than carbon fiber. A color change from white to light yellow was seen in polyester fiber after heating, while carbon fiber kept its original color due to its material differences.

Table 5 Thermostability of Fibers Results

Fiber Type	Before Oven Heating (gm)	After Oven Heating (gm)	Mass Loss (%)
	W_0	W_1	
Micro Polyester Fiber	50	49.54	0.92
Micro Carbon Fiber	50	49.73	0.54

Asphalt Mixture Design

The Marshall method was used to design both the Conventional Asphalt Mixtures (CAM) and Fiber-Reinforced Asphalt Mixtures (FRAM). The Optimum Asphalt Content (OAC) was determined by averaging the asphalt content that best balances three important factors: maximum stability, maximum density, and 4% air voids in the mixture.

The CAM and the FRAM are produced with a maximum size of (12.5 mm) with five different asphalt content (4%, 4.5%, 5%, 5.5%, and 6%) and seven different micro fiber (carbon and polyester) contents (0, 0.25, 0.5, 0.75, 1, 1.25, 1.5) by the weight of the mixture to initialize specimens volumetric properties and determine the OAC. Table 6 describes the two fiber-reinforced asphalt mixtures produced in this study, using carbon and polyester fibers, in addition to the conventional asphalt mixture. These specimens will be used to investigate the effect of micro carbon fiber and micro polyester fiber contents in the laboratory on the mechanical and volumetric properties, then determine the optimum fiber-reinforced asphalt mixtures (carbon and polyester) and compare them with the control asphalt mixture.

Table 6 Type of Asphalt Mixtures

Code	Description	Function	Objective
M0	Conventional asphalt mixture prepared with five different asphalt contents (4%, 4.5%, 5%, 5.5%, and 6%)	Used to determine the OAC	Control asphalt mixture (M0)
M1-PF to M6-PF	O.M.C prepared with different percentages of PF (0.25, 0.5, 0.75, 1, 1.25, 1.5) respectively	Determine the optimum polyester fiber content as a result of comparing PFRAM.	The optimum polyester fiber-reinforced asphalt mixture PFRAM
M1-CF to M6-CF	O.M.C prepared with different percentages of CF (0.25, 0.5, 0.75, 1, 1.25, 1.5) respectively	Determine the optimum carbon fiber content by comparing CFRAM.	The optimum carbon fiber-reinforced asphalt mixtures CFRAM

Preparation of Fiber-Reinforced Asphalt Mixtures

Mixtures with asphalt that were reinforced with either micro polyester fibers (referred to as PFRAMs) or micro carbon fibers (denoted as CFRAMs) were produced using a dry mixing process, which promotes proper distribution and

minimizes clustering of the fibers. Aggregates and mineral fillers were heated to just over $160 \pm 5^\circ\text{C}$ and asphalt binders were heated separately to $150 \pm 5^\circ\text{C}$ so as to allow sufficient fluidity of the asphalt binder.

In the first step of preparing the two reinforced asphalt mixtures, a quantity of fibers was blended together with the heated aggregates in dry form using a mechanical mixer for approximately 90 to 120 sec. This was done to ensure uniform dispersion of the fiber throughout the aggregate skeleton and to minimize the risk of fiber clustering. Following this initial blend, the hot asphalt binder was slowly added to the aggregate/fiber blend and mixed for an additional 120 to 180 sec until a homogeneous coating of all aggregates and fibers was attained.

The total mixing temperature for both types of reinforced asphalt mixtures was maintained at $155\text{--}165^\circ\text{C}$ throughout the entire production process. After mixing, the loose asphalt mixtures were retrained for approximately two hours at the same compaction temperature ($150 \pm 5^\circ\text{C}$) before fabricating the specimens. The Marshall specimens were compacted with 75 blows per face in accordance with ASTM D6927. Care was taken throughout the entire mixing process so that complete dispersion of the fibers occurred so as not to create fiber balls, especially at higher fiber loadings.

Moisture Damage Performance Test

The Immersion Marshall Test

The Immersion Marshall test is performed to evaluate the ability of produced asphalt mixtures to resist moisture damage and examine some primary causes of failures in asphalt pavement. Therefore, it became necessary to compare the laboratory performance of conventional asphalt mixture and fiber-reinforced asphalt mixtures (micro carbon fiber and micro polyester fiber) against the potential for moisture damage. For each asphalt mixture type, six standard Marshall specimens are prepared and divided into two equal groups to conduct the immersion Marshall test. The first specimen group was submerged underwater for 30 min at 60°C . In contrast, the second group was stored underwater for 1 day, 2 days, and 3 days at a temperature of 60°C . Marshall stability was measured for all groups according to criteria (ASTM D-6927), and the residual Marshall stability (RMS) was calculated as a ratio of Marshall stability for specimens before and after being subjected to the water effect, as appears in Eq. (3). The higher value of MSR in the immersion Marshall test indicates a higher resistance against moisture damage.

$$\text{RMS} = \frac{\text{MS}_2}{\text{MS}_1} \times 100 \quad (3)$$

where RMS is residual Marshall Stability; MS₂ is the Marshall stability for specimens after being subjected to the water effect for (1 day, 2 days, and 3 days) at a temperature of (60°C); MS₁ Marshall stability for specimens before being subjected to the water effect for (30 min.) at a temperature of (60°C).

Freezing-Thaw Splitting Test

The modified Lottman test is one of the standard laboratory tests most widely used to measure the performance and durability of the asphalt mixtures under underwater influence. This test is conducted on conventional asphalt mixtures and fiber-reinforced asphalt mixtures (micro carbon fiber and micro polyester fiber) by measuring the loss of indirect tensile strength (ITS) before and after being subjected to freeze-thaw conditioning in water. According to the Marshall method, six specimens are prepared for each asphalt mixture type by using the Marshall compactor and splitting into two equal groups. The first group of specimens was submerged for two hours at a temperature of 25°C underwater to achieve unconditioned specimens. While, the second group specimens were subjected to vacuum pressure (10-26 in. Hg) for (20 min.) at a temperature of (25°C) and then kept for (16 hr.) at a temperature of ($-18 \pm 3^\circ\text{C}$) in a fridge, after that maintained for (24hr) at a temperature (60°C) underwater, and then removed and stored for (2 hr.) at a temperature (25°C) underwater to achieve conditioned specimens. Finally, the unconditioned and conditioned specimens were loaded until failure at a loading rate of 50 mm/min, and the indirect tensile strength (ITS) was calculated by applying Eq. (4).

$$(\text{ITS}_1) \text{ or } (\text{ITS}_2) = \quad (4)$$

Where ITS₁ and ITS₂ denote the indirect tensile strength (kPa) of unconditioned and conditioned specimens; P is the failure load (N); t is thickness (mm); and d is diameter (mm). Moisture damage in asphalt mixtures is evaluated by the Tensile Strength Ratio (TSR), calculated via Eq. (5). A TSR of at least 80% indicates adequate moisture resistance.

$$\text{TSR} = \frac{\text{ITS}_2}{\text{ITS}_1} \times 100 \quad (5)$$

High-Temperature Performance Test (Wheel Tracking Test)

The wheel tracking test evaluated asphalt mixture performance at high temperatures by measuring parameters such as Dynamic Stability (DS), Rutting Depth (RD), Rutting Behavior (RB), Wheel Tracking Slope (WTS), and Proportional Rut Depth (PRD). Four slab specimens (400×300×50 mm) were created—one conventional and three reinforced with micro carbon and polyester fibers—and were compacted with a steel roller as shown in Figure 4. The specimens were categorized into two groups and conditioned at 40°C and 60°C for 2 hours. A rubber tire exerted a 700 N load, oscillating along a 230 ±10 mm path at a rate of 27 passes/min for as many as 10,000 cycles. DS (times/mm) measures rutting resistance, whereas RD (mm) records the total rut depth after 10,000 cycles or 25 mm, depending on which is reached first. The RB is the rut depth measured at specific intervals using an LVDT.

Dynamic Stability (DS), expressed in times/mm, was used to evaluate the rutting resistance of the asphalt mixtures and was calculated using Eq. (6).

$$DS = \frac{(t_2 - t_1) \cdot N}{d_2 - d_1} \times C_1 \times C_2 = \frac{15N}{d_2 - d_1} \quad (6)$$

Where: DS is the Dynamic Stability (times/mm), d_1 and d_2 are the rut depths at times $t_1 = 45$ minutes and $t_2 = 60$ minutes, respectively (in mm), and C_1 and C_2 are equipment and specimen correction factors, both equal to 1. N is the constant loading frequency, set at 27 passes per minute. The Wheel Tracking Slope (WTS), expressed in mm/10³ cycles, represents the asphalt mixture's shear resistance to rutting deformation and is calculated over time using Eq.(7). Additionally, the Proportional Rut Depth (PRD) is used as a comparative parameter and is determined using Eq.(8).

$$WTS = \frac{(D_{10,000} - D_{5,000})}{5} \quad (7)$$

$$PRD = \frac{D_{10,000}}{50} \quad (8)$$

Where: $D_{5,000}$ and $D_{10,000}$ denote the rut depths at 5,000 and 10,000 loading cycles in (mm), respectively, with a specimen height of 50 mm. Table 7 shows the limits for wheel tracking parameters according to pavement layer position and traffic level.



Figure 4 Wheel tracking samples and testing.

Table 7 Wheel Tracking Parameters Limitations

Position in the pavement	Traffic level			
	T1	T2	T3	T4
Surface Layer	WTS ≤ 0.08 PRD ≤ 5%	WTS ≤ 0.10 PRD ≤ 8%	WTS ≤ 0.12 PRD ≤ 7%	WTS ≤ 0.15 PRD ≤ 10%
Base Layer	WTS ≤ 0.10 PRD ≤ 8%	WTS ≤ 0.12 PRD ≤ 10%	WTS ≤ 0.15 PRD ≤ 10%	WTS ≤ 0.15 PRD ≤ 10%

Results

Marshall Stability, Flow, and Volumetric Properties Results

Marshall stability, flow, and volumetric properties tests of asphalt mixtures were performed to estimate the OAC, as shown in Table 8. The conventional mixture's OAC was 4.8% to achieve durable maximum stability (kN), good flow (mm), a sufficient percentage of VTM, and satisfactory specific gravity.

Table 8 Results of the Asphalt Concrete Design

Properties	Asphalt content				
	3.75%	4.25%	4.75%	5.25%	5.75%
Marshall Stability (kN)	10.5	11.4	12.5	11.6	10.2
Marshall Flow (mm)	3.05	3.45	3.85	4.35	4.8
The bulk specific gravity (G_{mb})	2.301	2.319	2.325	2.320	2.309
VMA %	16.67%	16.46%	16.68%	17.29%	18.12%
VTM %	6.66%	5.26%	4.34%	3.88%	3.67%
VFA %	60.04%	68.03%	73.95%	77.56%	79.75%

Tables 9 and 10, respectively, illustrate the test results of Marshall stability, flow, and volumetric composition of control asphalt mixture (M0) and FRAM designed with different percentages of micro-polyester fiber (MPF) and micro carbon fiber (MCF). The results indicate that the OAC increases with an increase in MPF and MCF content; this phenomenon happens because the MPF and MCF absorb asphalt. The rise in the fiber content requires more asphalt to cover the surface area of the fiber, resulting in the increased need for the OAC of mixtures. However, the OAC of FRAM with MPF is relatively higher than that of fiber-reinforced asphalt mixtures with MCF. This may be attributed to the higher absorption capacity of MPF compared with MCF, as demonstrated by the WAT analysis.

Incorporating MPF and MCF significantly improved the Marshall stability of FRAM. The highest stability was noted at a fiber content of 0.75%—16.8 kN for MPF and 17.5 kN for MCF. However, when fiber content was too high, stability decreased due to increased asphalt absorption and poor fiber dispersion, which resulted in a non-homogeneous mixture. The stability gains for MPF were 2.3%, 18.8%, 31.3%, 22.7%, 11.7%, and 0.8%, whereas for MCF, they were 7.8%, 24.2%, 36.7%, 27.3%, 16.4%, and 2.3%, all of which complied with Iraqi standards. FRAM containing MCF exhibited superior stability over MPF and the control mix, likely attributable to improved fiber adhesion and network formation, suggesting enhanced resistance to rutting.

Marshall stability enhancement is associated with the microfibers' role as a reinforcer within the asphalt matrix. This means that they create an interlocking mechanism between the aggregate particles and asphalt mastic that helps transfer loads more efficiently and distribute the stresses experienced at the surface of the asphalt more evenly throughout the thickness of the pavement. Randomly distributed microfibers also create a three-dimensional reinforcing network that restricts local movements within the pavement and delays the initiation of microcracks. Due to having greater tensile strength (strength when pulled) and stiffness (resistance to deformation), the carbon fibers develop a more robust reinforcing structure than do the polyester fibers. Thus, increasing mixture stability and improving resistance to deformation.

The control asphalt mixture showed a flow of 3.85 mm. Overall, flow decreased with increasing fiber content and rose at higher levels. Thus, fiber addition generally improves flow resistance, but excessive MPF or MCF can have the opposite effect.

The increase in the MPF and MCF contents initially increases the bulk specific gravity of FRAM and then decreases; this phenomenon happens due to the lower bulk specific gravity of the MPF and MCF. In addition, the MPF and MCF are more elastic than asphalt, thereby it can impact the compaction effort and decreasing the bulk-specific gravity of mixtures. Increasing OAC requires more compaction to achieve the demanded bulk-specific gravity. Accordingly, the same compaction effort decreases the bulk specific gravity with excessive MPF and MCF content in mixtures. The FRAM with MCF has relatively higher bulk specific gravity than the FRAM with MPF and the control asphalt mixture (M0).

The durability of asphalt mixtures hinges on appropriate volumetric design, particularly VTM, VMA, and VFA. In FRAM, both VTM and VMA initially decline with the addition of MPF and MCF, subsequently rising due to enhanced interlock. However, at higher levels, issues with dispersion and compaction may occur. Fibers absorb asphalt, creating structured asphalt within VMA, which can lead to better durability. As MPF and MCF increase, VFA decreases due to this more structured asphalt. Nevertheless, excessive fiber content can elevate VTM, VMA, and VFA, leading to risks of cracking,

rutting, and bleeding. An optimal proportion of MPF/MCF enhances Marshall stability and aligns with Iraqi volumetric specifications. Consequently, FRAM with up to 0.75% MPF or MCF is advised for additional mechanical testing. Table 11 illustrates the volumetric properties of both control and FRAM mixtures at 0.75% fiber content.

Table 9 Properties of Micro Polyester Fiber Reinforced Asphalt Mixtures

Properties	Type of Asphalt Mixture						
	M0	M1-PF	M2-PF	M3-PF	M4-PF	M5-PF	M6-PF
OAC	4.8%	4.85%	5%	5.2%	5.3%	5.4%	5.5%
Marshall Stability (kN)	12.5	13.1	15.2	16.8	15.7	14.3	12.6
Marshall Flow (mm)	3.85	3.68	3.35	2.98	3.27	3.52	3.77
Marshall Stiffness (kN/mm)	3.25	3.56	4.54	5.64	4.80	4.06	3.34
Bulk specific gravity (G_{mb})	2.325	2.335	2.354	2.379	2.361	2.342	2.328
VMA %	16.90%	16.54%	15.87%	14.97%	15.62%	16.29%	16.79%
VTM %	4.01%	3.96%	3.91%	3.88%	3.94%	4.12%	4.30%
VFA %	76.28%	76.04%	75.35%	74.07%	74.78%	74.70%	74.42%

Table 10 Properties of Micro Carbon Fiber Reinforced Asphalt Mixtures

Properties	Type of Asphalt Mixture						
	M0	M1-CF	M2-CF	M3-CF	M4-CF	M5-CF	M6-CF
OAC	4.8%	4.8%	4.9%	5%	5.2%	5.3%	5.4%
Marshall Stability (kN)	12.5	13.8	15.9	17.5	16.3	14.9	12.8
Marshall Flow (mm)	3.85	3.60	3.22	2.83	3.03	3.41	3.72
Marshall Stiffness (kN/mm)	3.25	3.83	4.94	6.18	5.38	4.37	3.44
Bulk specific gravity (G_{mb})	2.325	2.339	2.365	2.385	2.377	2.349	2.332
VMA %	16.90%	16.40%	15.47%	14.76%	15.04%	16.04%	16.65%
VTM %	4.01%	3.94%	3.88%	3.82%	3.92%	4.09%	4.26%
VFA %	76.28%	75.99%	74.94%	74.15%	73.91%	74.50%	74.41%

Table 11 Properties of Fiber-Reinforced Asphalt Mixtures

Properties	Type of Asphalt Mixture		
	M0	PFRAM	CFRAM
Marshall Stability (kN)	12.5	16.8	17.5
Marshall Flow (mm)	3.85	2.98	2.83
Marshall Stiffness (kN/mm)	3.25	5.64	6.18
Bulk specific gravity (G_{mb})	2.325	2.379	2.385
VMA %	16.90%	14.97%	14.76%
VTM %	4.01%	3.88%	3.82%
VFA %	76.28%	74.07%	74.15%

The Immersion Marshall Results

Figure 5 shows the Marshall Stability of M0, PFRAM, and CFRAM over 1, 2, and 3 days of curing. On Day 1, M0 had the lowest stability (12.8 kN), while PFRAM and CFRAM reached 16.8 and 17.5 kN, respectively, indicating improved early strength with fibers, primarily carbon. Stability declined on Day 2, but CFRAM (16.2 kN) and PFRAM (15.1 kN) remained superior to M0 (10.6 kN). By Day 3, CFRAM led with 15.3 kN, followed by PFRAM (14.2 kN) and M0 (9.5 kN). These results confirm that fiber reinforcement, particularly with carbon, enhances mechanical performance and durability by improving bonding and load distribution, making CFRAM a promising option for resilient pavements (Hosseini et al., 2023).

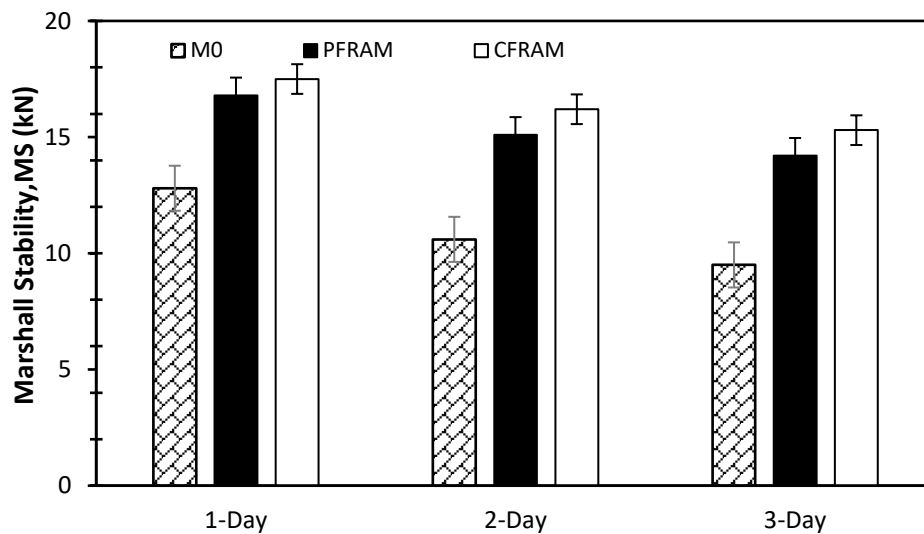


Figure 5 Marshall Stability after Immersion for (1, 2, 3 days).

Figure 6 shows the percentage loss in Marshall Stability over 3 days for three asphalt mixtures: M0, PFRAM, and CFRAM. All mixtures begin at 100%, but the M0 exhibits the most significant decline, dropping to approximately 83% on Day 1, 75% on Day 2, and 70% on Day 3. In contrast, PFRAM and CFRAM retain higher stability over time, with CFRAM consistently showing the least loss, followed closely by PFRAM. This indicates that fiber reinforcement, especially with carbon fibers, effectively reduces the degradation rate of asphalt mixtures, thereby improving their durability and resistance to moisture and aging effects compared to the unmodified control mix.

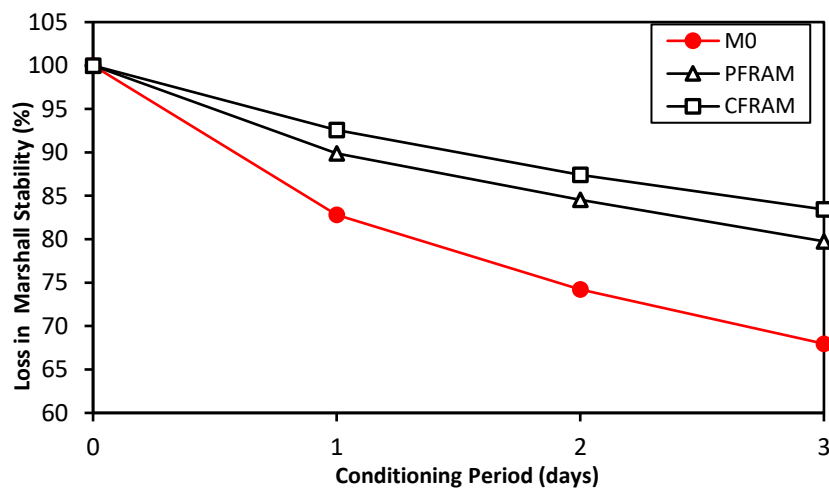


Figure 6 Immersion Residual Marshall Stability of Asphalt Mixtures.

Freezing-Thaw Splitting Results

The test results in Figures 7 and 8 illustrate the ITS and MD Resistance of three asphalt mixtures: M0, PFRAM, and CFRAM. The ITS results indicate that PFRAM and CFRAM exhibit higher tensile strength than the control mix under both unconditioned and conditioned states, suggesting enhanced resistance to moisture-induced weakening (Sodeyfi et al., 2021). This improvement is further supported by the TSR values, where PFRAM and CFRAM display higher moisture damage resistance, with TSR values above 85%, compared to approximately 80% for M0. Notably, CFRAM achieved the highest TSR, demonstrating superior moisture resistance, likely due to the synergistic effect of carbon and fiber reinforcement in improving the asphalt mixture's durability and bonding characteristics.

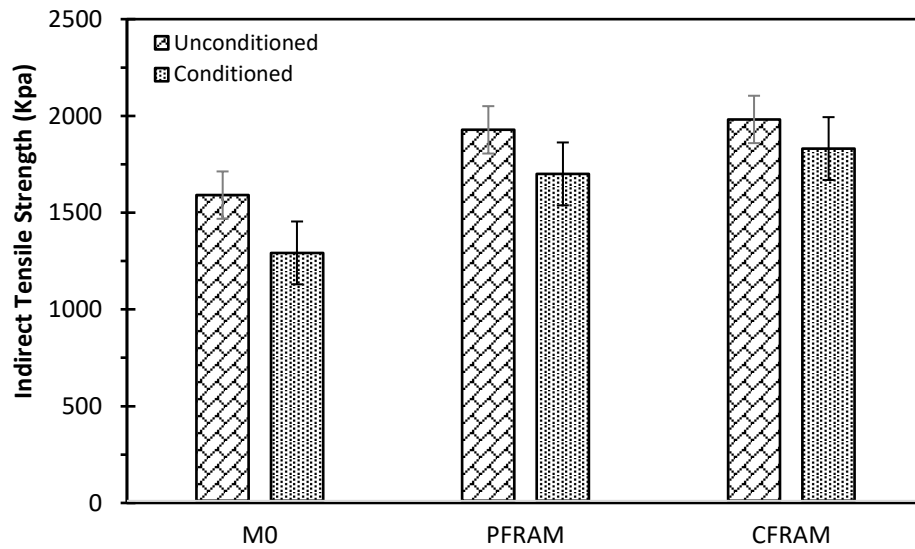


Figure 7 Indirect Tensile Strength (ITS) of Asphalt Mixtures.

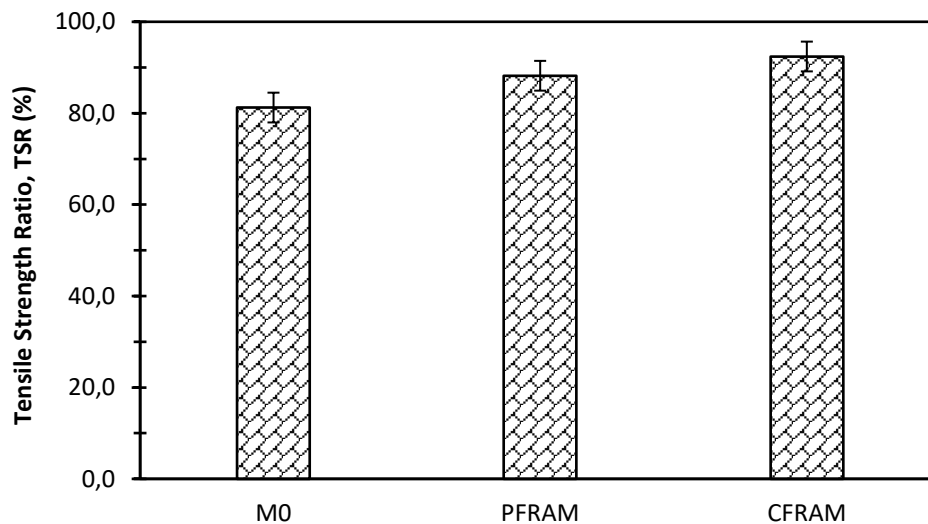


Figure 8 Tensile Strength Ratio (TSR) of Asphalt Mixtures.

Wheel Tracking Results

Based on the results provided in Figures 9 and 10, the test evaluated the performance of M0 against asphalt mortars reinforced with PFRAM and CFRAM under two key high-temperature performance indicators. The PD and the DS were assessed at 40°C and 60°C. The results consistently demonstrate that fiber reinforcement significantly improves performance compared to M0. CFRAM exhibits the highest resistance to permanent deformation and the most incredible dynamic stability, followed by PFRAM, and M0 performs the weakest. In addition, the performance of all combinations suffered from increased test temperature (60°C) as compared to lower test temperatures (40°C). However, one group of mixtures, namely the CFRAM group comprising fiber-reinforced mixtures, performed better than all other groups in regards to their resistance to damage at both test temperatures (60 and 40 °C).

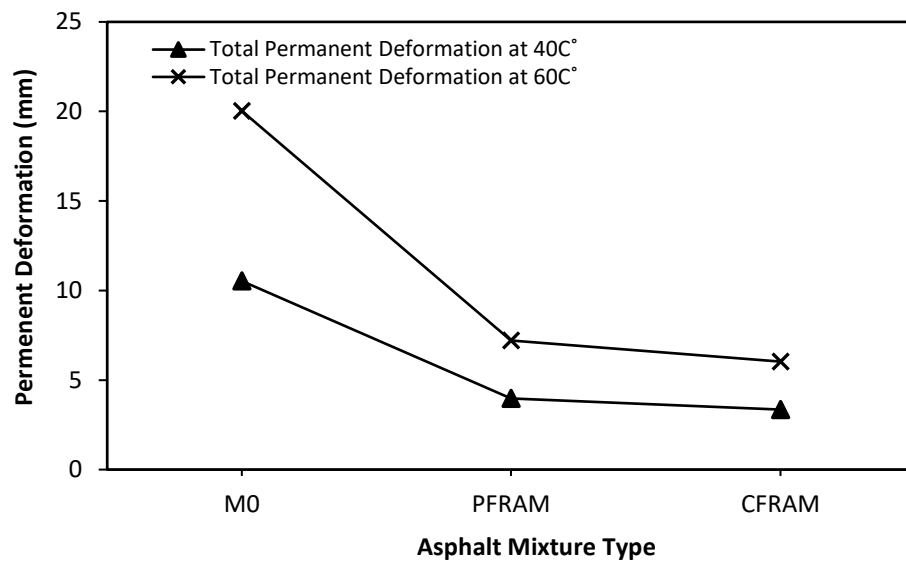


Figure 9 Permanent Deformation (RD) of Asphalt Mixtures.

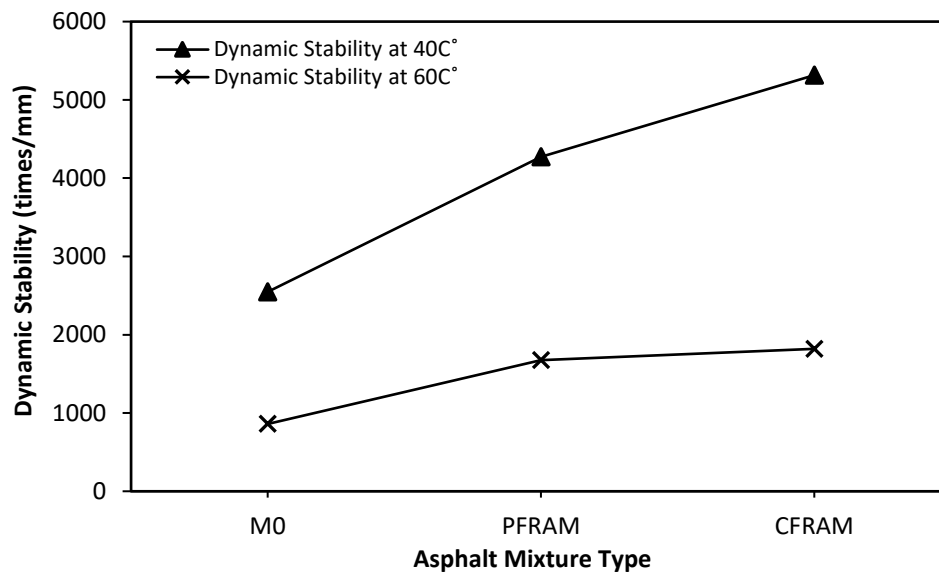


Figure 10 Dynamic Stability (DS) of Asphalt Mixtures.

The overall results in Table 12 show that fiber reinforcement, specifically the use of CFRAM, significantly enhances the high-temperature rutting resistance of asphalt. In addition, both PFRAM and carbon fiber provide lower levels of permanent deformation and improved dynamic stability with CFRAM providing the best overall performance. As the temperature is increased from 40 to 60 degrees Celsius, each of the mixtures loses its structural integrity, but the M0 mixture exhibits the greatest loss of integrity. Hence, the inclusion of fiber reinforcement is essential to support the structural integrity of pavements in hot climates.

Table 12 WTS and PRD Parameters of Asphalt Mixtures

Parameters	Type of Asphalt Mixture		
	M0	PFRAM	CFRAM
40° C	WTS	0.162	0.047
	PRD	0.211	0.080
	D _{10,000} (mm)	10.53	3.98
60° C	WTS	0.221	0.077
	PRD	0.401	0.144
	D _{10,000} (mm)	20.03	7.21

Discussions

Marshall Stability, Flow, and Volumetric Properties

Incorporating MPF and MCF significantly improved the Marshall stability of FRAM. The highest stability was noted at a fiber content of 0.75%—16.8 kN for MPF and 17.5 kN for MCF. However, when fiber content was too high, stability decreased due to increased asphalt absorption and poor fiber dispersion, which resulted in a non-homogeneous mixture. The stability gains for MPF were 2.3%, 18.8%, 31.3%, 22.7%, 11.7%, and 0.8%, whereas for MCF, they were 7.8%, 24.2%, 36.7%, 27.3%, 16.4%, and 2.3%, all of which complied with Iraqi standards. FRAM containing MCF exhibited superior stability over MPF and the control mix, likely attributable to improved fiber adhesion and network formation, suggesting enhanced resistance to rutting.

Marshall stability enhancement is associated with the microfibers' role as a reinforcer within the asphalt matrix. This means that they create an interlocking mechanism between the aggregate particles and asphalt mastic that helps transfer loads more efficiently and distribute the stresses experienced at the surface of the asphalt more evenly throughout the thickness of the pavement. Randomly distributed microfibers also create a three-dimensional reinforcing network that restricts local movements within the pavement and delays the initiation of microcracks. Due to having greater tensile strength (strength when pulled) and stiffness (resistance to deformation), the carbon fibers develop a more robust reinforcing structure than do the polyester fibers. Thus, increasing mixture stability and improving resistance to deformation.

The control asphalt mixture showed a flow of 3.85 mm. Overall, flow decreased with increasing fiber content and rose at higher levels. Thus, fiber addition generally improves flow resistance, but excessive MPF or MCF can have the opposite effect.

The increase in the MPF and MCF contents initially increases the bulk specific gravity of FRAM and then decreases; this phenomenon happens due to the lower bulk specific gravity of the MPF and MCF. In addition, the MPF and MCF are more elastic than asphalt, thereby it can impact the compaction effort and decreasing the bulk-specific gravity of mixtures. Increasing OAC requires more compaction to achieve the demanded bulk-specific gravity. Accordingly, the same compaction effort decreases the bulk specific gravity with excessive MPF and MCF content in mixtures. The FRAM with MCF has relatively higher bulk specific gravity than the FRAM with MPF and the control asphalt mixture (M0).

The changes recorded in the volumetric properties are viewed as indirect evidence of the effect of microfiber incorporation on the degree of homogeneity of the mixture. Conversely, the significant increase at the higher fiber contents may be suggestive of localized agglomeration of fibers and a decrease in compactability. No imaging analyses were done in this research; however, the volumetric results indicate that the fiber is uniformly distributed until the optimum dosage of 0.75% has been reached (Rassafi et al., 2021; Zarei, Mirbaha, et al., 2020). Future research will require advanced imaging techniques such as X-ray computed tomography (CT), digital imaging processing (DIP), or scanning electron microscopy (SEM) to quantify the distribution of air voids, fiber orientation and internal homogeneity.

The Immersion Marshall

Incorporating fiber reinforcement in the asphalt mixtures resulted in a higher stability and durability compared to that of the PFRAM and the control mixture. The higher performance of the CFRAM is attributed to better bonding and stress distribution within the asphalt matrix that minimize deformation and strength loss. The lower stability loss experienced by CFRAM is also indicative of the fact that the carbon microfibers can provide better resistance against deterioration, thus showing their capability of improving the long-term performance of pavement (Hosseini et al., 2023).

Freezing-Thaw Splitting

The increased resistance to moisture seen in fiber-reinforced mixtures can be attributed to fiber enhancement of the internal cohesion of the asphalt binder and increased bond strengths between the aggregate and asphalt binder. In addition, the fibers allow for redistribution of the tensile stresses generated due to moisture conditioning and the freeze/thaw cycling; therefore, there is less likelihood of cracking and adhesive failure. In conjunction with this, the network of fibers that forms through reinforcement will assist in preserving the structural integrity even when some degree of debonding has occurred within the mixture.

Wheel Tracking

The enhanced rut resistance of fiber reinforcement mixtures can be attributed to their ability to prevent permanent deformation during repetitive load cycles. Fibers function as micro-reinforcing agents during loads by transferring and redistributing stresses throughout the asphalt matrix, which minimizes strain localization. Additionally, the fiber matrix prevents the movement of fine aggregate particles while providing structural confinement to the entire mixture. This combination results in a reduction of shear deformation at elevated temperatures. As well as improving rutting resistance due to the above mechanism, the crack bridging capabilities offered by fiber delay the formation and propagation of microcracks under repetitive loading conditions. Carbon fibers provide superior rutting resistance when compared with polyester fibers as a result of their higher modulus of elasticity and tensile strength. These properties provide an advantage for stress transfer and structural reinforcement within the asphalt mixture.

The findings in the present research are analogous to previously published studies on the performance enhancements observed as a result of other types of asphalt modification technologies. For example, cellulose fibers are often utilized to improve the stability of asphalt mixtures and reduce the amount of binder drain down. Although cellulose fibers provide some degree of mechanical reinforcement, their mechanical performance is inferior to that of carbon fibers, which exhibit greater stiffness and tensile strength. Basalt fibers are also known to have good resistance to cracking and moisture-induced damage, but the relatively higher density and cost of basalt fibers may limit their widespread use. Nanoscale materials, such as nano silica, carbon nanotubes and nano clay, can significantly increase the binder's stiffness, as well as the rutting resistance of the asphalt; however, most of these materials require special non-collisional dispersion techniques and add to the production cost. Polymer-modified asphalt binders, especially those modified with SBS, have shown significant improvements in resistance to rutting and fatigue, but will require modification at the binder-level and require additional processing to produce. Of all the alternatives to polymer-modified asphalt binders, micro carbon fibers have a unique combination of high tensile strength, good thermal stability, and effective reinforcement at a comparatively low dosage, while polyester fibers provide improved flexibility and moisture-resistant properties. Micro carbon fiber and polyester fiber types should be viewed as viable options for reinforcing asphalt mixtures to improve overall performance, particularly in areas with high ambient temperatures and/or high levels of traffic loading

Conclusions

The main objective of this research was to investigate the mechanical and durability performance of hot asphalt mixtures enhanced with micro carbon and polyester fibers, aiming to identify optimal fiber types and contents for improving rutting resistance and moisture susceptibility. These findings open promising opportunities for integrating fiber-reinforced asphalt mixtures into full-scale pavement construction, particularly in regions exposed to high temperatures and moisture, by conducting pilot field trials and long-term performance monitoring.

This research was conducted under controlled laboratory conditions of controlled environment so as to assess the Marshall properties, moisture damage sensitivity, and high-temperature resistance to deformation of asphalt mixes with the usage of micrometrics of carbon fibers and polyester, which are essential type of performance properties of pavement in hot climate. The achieved results demonstrate that the best dosage for both types of fiber is 0.75% from weight that led to noticeable impact on the stiffness of asphalt, i.e., approximately 40% increase in asphalt mixes with carbon fibers, while asphalt mixes with polyester underwent approximately 34.4% improvement. In general, asphalt mixes with carbon fibers show better results in comparison with asphalt mixes with polyester and control asphalt mix (M0), especially, with reference to ability to withstand rutting, absorption of moisture, and thermal stability of asphalt mix, manifested by the reduction of rut depth at a temperature of 60 degrees Celsius in comparison with the depth of control mixture, M0. Both types of fibers emphasize the ability of asphalt to resist moisture-induced damages, as evidenced from the tensile strength ratio (TSR) of over 85% compared to approximately 80% for M0; moreover, the greatest retention of strength is noted with usage of carbon fibers. The obtained data indicate that the work of asphalt mix was seriously improved, since CFRAM showed the highest dynamic stability of temporary deformation and low level of wheel tracking slope (WTS), reflecting the appropriateness of asphalt mix for highways. Nevertheless, increasing fiber dosage of over 0.75% results in increase of asphalt voids. It's important to consider this fact when choosing fiber dosage to make sure that pavement is uniformly spread. The improvements of performance can be explained by several mechanisms of reinforcement, which explained the reason for application of carbon microfibers in order to improve the moisture resistance of pavement. It should be noted that this research doesn't focus on other important performance indicators like fatigue cracking resistance and low-temperature cracking resistance. Therefore, results of further research and field tests should provide more evidence regarding the effectiveness of using micrometrics of fibers in asphalt mix.

The findings from this research indicate that asphalt–micro-silica matrix mixes show potential for use in actual applications in the construction and/or maintenance of pavements. It appears that these types of mixes can provide increased durability to moisture related damage and permanent deformations, and could potentially extend the life of pavements; reduce maintenance schedules for high volume pavements, and help extend their "life" in hot weather; and, also, would likely provide a lower cost alternative to traditional methods of repairing damaged pavements due to moisture related issues in high volume locations, particularly if used on "hot" pavement materials subjected to heavy amounts of vehicle traffic. To verify laboratory results in actual service conditions, field trials and long-term performance monitoring of these asphalt-micro silica reinforced mixtures should be conducted.

Research Limitations

The researcher did not try to establish the long-term effects of the testing program used in this research project. While the experimental programs assessed the moisture and the high temperature rutting resistance of the asphalt by using a variety of fiber types to enhance the performance properties of the tested samples such as; Micro-Carbon Fiber and Micro-Polyester Fiber, did not investigate the potential effects of Ultraviolet Light exposure, thermal cycles, repeated wet/dry cycles, oxidative aging, or field aged asphalt pavements. Additional research is recommended to investigate the long-term performance characteristics and durability of Micro-Carbon Fiber Reinforced hot mix and Micro-Polyester Fiber Reinforced hot mix subjected to accelerated aging protocols and field conditions that will better replicate the service life of an asphalt pavement.

Moreover, the current research was concerned with studying asphalt mixtures rather than characterizing binders. The effect of fiber on the binder's viscosity and the uses of different types of fibers were not tested in this study. Future studies are encouraged to utilize sophisticated rheological testing techniques such as DSR, BBR, MSCR and frequency sweep testing methods to evaluate the impact of utilizing micro fibers in asphalt binder on the stiffness, elasticity, resistance to rutting, fatigue characteristics and viscoelastic properties of the binder across a broad spectrum of temperature and loading frequency.

One other limitation of this study was the lack of any direct microstructure characterization of the asphalt mixtures. Specifically, the lack of imaging methods (e.g. X-ray computed tomography (CT), digital image processing (DIP) and scanning electron microscopy (SEM)) used to evaluate fiber dispersion, air void distribution, and internal mixture homogeneity were notable. Future research should incorporate these imaging methods so that a quantitative relationship between microfiber distribution and volumetric properties (in terms of mechanical performance) can be established.

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Compliance with ethics guidelines

The authors declare they have no conflict of interest or financial conflicts to disclose.

This article contains no studies with human or animal subjects performed by the authors.

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