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ORIGINAL RESEARCH PAPER

The Performance of Modified Asphalt Mixtures with Different Lengths of Glass Fiber

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Abstract

One practical option for modifying an asphalt mixture's performance is to use additives. This will help the mixture perform better against the damaging effects of traffic, loads, and climatic variations. In this regard, glass fiber (GF) has drawn much interest because of its positive effect. Therefore, this paper attempts to study the effect of glass fiber length and content on the performance and strength of asphalt mixtures. It also aims to determine the optimum glass fiber content and the best glass fiber length of modified asphalt mixtures. An experimental program is carried out, which includes the Marshall test, volumetric properties, freeze-thaw splitting test, immersion Marshall test, and wheel tracking test to characterize related properties of glass fiber incorporated in asphalt mixtures. Seven different percentages (0, 0.25, 0.5, 0.75, 1, 1.25, and 1.5) of glass fiber by total weight of aggregates in three various lengths are used to design 19 asphalt mixtures. Based on the results obtained, the performance of the asphalt mixture was enhanced remarkably after adding glass fiber. The use of various lengths of glass fiber led to a better-quality asphalt mixture in terms of volumetric properties, moisture damage resistance, and permanent deformation resistance. Specifically, asphalt mixtures made with (0.5%) glass fiber illustrated the highest quality, and adding (20 mm) length of glass fiber was better than (10 mm and 30 mm) glass fiber lengths. The results also show that adding (10 mm and 30 mm) lengths of glass fiber can improve the resistance of asphalt mixtures to water damage and permanent deformation compared with the control mixture (M0). The findings indicate the applicability of 20 mm glass fiber length in asphalt mixtures to achieve better resistance against moisture and reduce the chance of irreparable permanent deformation under growing traffic loads and hot climate changes. Although the inclusion of glass fiber in asphalt mixtures led to a modest increase (6%) in overall cost, the effective improvement in performance and extension of the service life of the asphalt pavement constitute a convincing argument for this approach, making it an attractive option. Finally, it was concluded that a higher amount of glass fiber (i.e., > 0.5%) and a length greater than (20 mm) could diminish the positive effect of glass fiber to improve the properties of glass fiber asphalt mixtures.

Keywords Glass fiber (GF) · Permanent deformation (PD) · Dynamic stability (DS) · Moisture damage (MD) · Mechanical properties · ANOVA analysis · Cost analysis

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1 Introduction

Flexible pavement mixtures are widely used worldwide to pave roads due to adequate performance, good skid resistance, comfortable driving, low noise, and recyclability [1–5]. Generally, it consists of asphalt and aggregates considered sensitive materials when exposed to high traffic volumes, loads, and environmental effects that cause pavement deterioration during service life [6, 7]. Therefore, efforts are always made to prolong the service life and performance of pavements in different ways to avoid deterioration, including rutting deformation in summer and moisture damage in winter, which will seriously affect the travelling performance of vehicles [8–10]. Because of the significant issues with standard flexible pavements, the need for modified asphalt mixtures has significantly increased to improve the performance of asphalt pavements and minimize distress [11]. Due to its properties, such as in reinforcing asphalt mixtures, high stability, high durability, good resistance against water damage, and improved rutting resistance, which results in extending the service life and is considered to be an outstanding economic feature, glass fiber is regarded as the best method used in asphalt mixtures to enhance pavement performance [12]. Glass fiber is a type of inorganic fiber with high tensile strength and that it is non-flammable [13]. Therefore, previous researchers have reported that the (12 mm) glass fiber length effect in asphalt pavements can enhance the stability and resistance to deformability without increasing the asphalt content of mixtures, which will be useful to avoid rutting and bleeding at high temperatures during extremely hot weather [14]. It can be concluded that using glass fiber in mixtures becomes an adequate alternative for asphalt pavement construction [15]. Eisa et al. studied the effect of different percentages of glass fiber with (10 mm) length on the performance of asphalt mixtures. The results indicate an improvement in the pavement rutting behavior to a considerable extent, good resistance to moisture damage, and the loss of stability value increased [16]. This is due to the addition of glass fiber increasing the hardness of the asphalt mixtures with less binder drain down [17]. Another study showed that the addition of glass fiber with (12 mm) length in asphalt mixtures can improve fracture behavior and rutting performance due to a better bond mechanism between asphalt binder and aggregates [18]. Glass fiber length (3, 8, and 12 mm) played a significant role in asphalt mixtures to improve the fracture energy and crack intensity factor substantially [19]. Additionally, glass fiber with (4 mm to 22.5 mm) length can enhance the fracture behavior and resistance to cracks which is useful at low temperatures to avoid pavement cracks [20]. Likewise, the performance of modified asphalt mixtures with (12 mm) of glass fiber length was studied, and experimental results show that the rutting resistance, indirect tensile strength, and fatigue properties have been significantly improved and will have better applicability for hot regions [21]. The asphalt mixtures made with glass fiber showed significant improvement in terms of strength, fatigue properties, and ductility [22]. Wu et al. investigated to study the properties of an asphalt mixture made with glass fiber length (6 mm). The outcomes reveal that glass fiber does not influence bending strength [23]. However, the bending failure strain increased as the glass fiber volume increased in the mix. The results also showed that glass fiber could considerably enhance the resistance to permanent deformation. In this field, researchers have found that adding glass fiber to asphalt mixture improves resistance against rutting, cracking, and moisture damage. It should be noted that glass fiber inclusion can also increase construction costs while simultaneously lowering maintenance costs, indicating that its addition to the mix is cost-effective for pavement construction [24]. Another study in this field showed that adding glass fiber to asphalt mixtures substantially enhances rutting performance, indirect tensile strength, and dynamic modulus at low and high temperatures [25].

This paper aims to investigate the effect of glass fiber length and content on the strength, volumetric properties, moisture susceptibility, and rutting of modified asphalt mixtures. In the literature, some research has been carried out to investigate the impact of including glass fiber with lengths greater than 20 mm in asphalt mixtures. In addition, up to the authors' knowledge, no research had been carried out to evaluate the effects of GF with lengths greater than 20 mm on asphalt mixtures. Thus, seven different percentages (0, 0.25, 0.5, 0.7 5, 1, 1.25, 1.5) of glass fiber were adopted in three various lengths (10 mm, 20 mm, and 30 mm) to design 19 asphalt mixtures. During the first stage of this work, the most suitable percentage of glass fiber for each length is determined based on the outcomes of Marshall's tests. Then, a series of experiments such as Marshall tests, freeze-thaw splitting tests, immersion Marshall tests, and wheel tracking tests were carried out to investigate the effect of glass fiber lengths on the properties of glass fiber asphalt mixtures. The importance of this work is the utilization of three various lengths of glass fiber to strengthen the asphalt mixtures and compare between the effect of GF-length on asphalt mixtures performance. The laboratory experiments were used to identify the best-performing glass fiber content and the best-performing glass fiber length by having a closer look at the behavior of asphalt mixtures reinforced with glass fiber.

Table 1 Aggregates physical properties

Test	Unit	Standard [27]	Results
Bulk specific gravity of coarse aggregates	-	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
Bulk specific gravity of fine aggregates	-	ASTM C-128	2.651
Water absorption of fine aggregates	%	ASTM C-128	0.733
Bulk specific gravity of mineral filler	-	ASTM C-128	2.794
Mineral filler passing sieve No.200	%	----	95

Table 2 Asphalt binder physical properties

Property	Unit	Standard [28]	PG 70 – 16	
			Results	IQ-Specification [26]
Penetration at 25 °C	0.1 mm	ASTM D-5	46	40–50
Kinematics viscosity at 135 °C	Centistoke	ASTM D-2170	410	…….
Softening point	°C	ASTM D-36	51	……
Ductility at 25 °C	cm	ASTM D-113	130	> 100
Flash point	°C	ASTM D-92	272	> 232
Specific gravity	-	ASTM D-70	1.04	….
After Thin Film Oven Test (ASTM D1754)				
Retained penetration	%	ASTM D-5	60	> 55
Ductility at 25 °C	cm	ASTM D-113	80	> 25

2 Raw Materials

2.1 Aggregate

One type of aggregate (crush quartz) was chosen in this research. This type of aggregate is widely used in pavement construction in Iraq and is sourced from a local quarry. Ordinary Portland cement was used as mineral filler. The physical properties of coarse aggregates, fine aggregates, and mineral filler are given in Table 1. The aggregates gradation structure proposed in the Iraqi specification was used with the maximum size of aggregates (19 mm) [26]. According to the Iraqi specification, the mid-point of aggregate gradation is widely used in producing conventional mixtures for high-traffic intensity roads [26]. The aggregate gradation chosen with the lower and upper limits appears in Fig. 1.

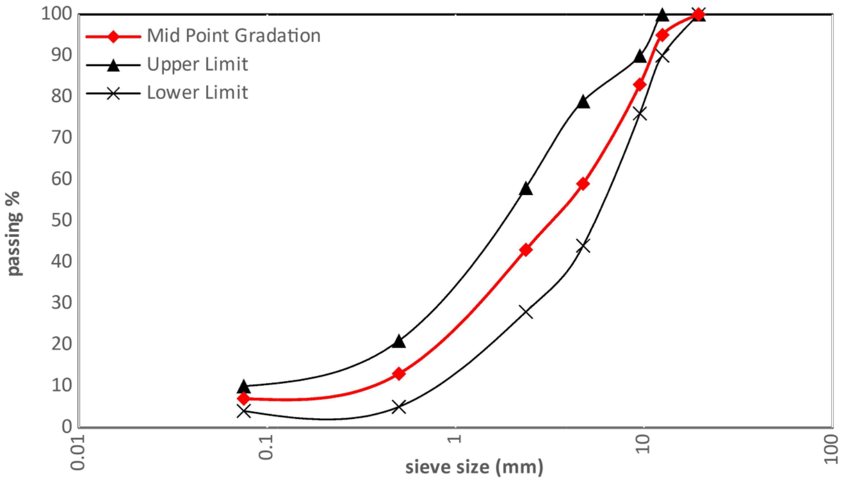
2.2 Asphalt Binder

The asphalt binder employed in this study had a penetration grade of (40–50). This type was sourced from the Daurah refinery and was traditionally colored black. Standard tests such as the ductility test, penetration test, viscosity test, and softening point test were used to describe the physical characteristics of the asphalt binder used. The results of the physical properties of the asphalt binder are given in Table 2.

2.3 Additive Materials

Glass fiber (GF) is an inorganic fiber with good tensile strength properties. Due to its high performance, it has been employed to successfully alter the asphalt mixture and enhance the interlocking effect between asphalt binder and aggregates. Its role mainly reinforces mixtures' adhesion, strength, and stability, which reduces the effect of moisture damage and deformation potential. Figure 2 shows the glass

Fig. 1 Gradation of aggregates [26]



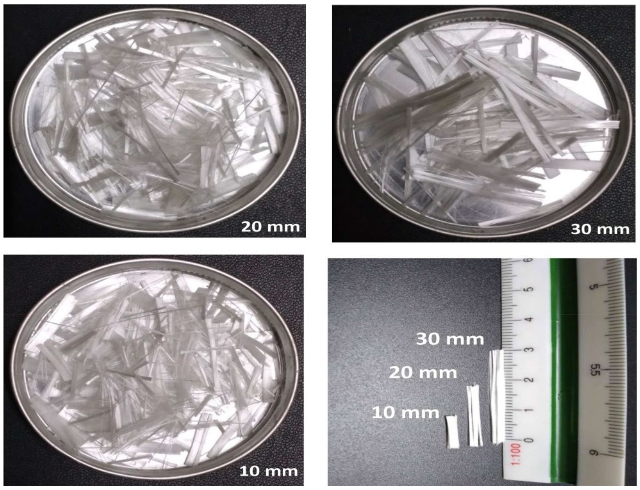


Fig. 2 Glass fiber

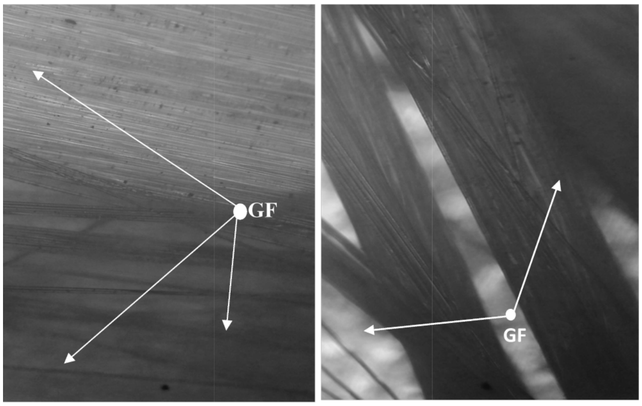


Fig. 3 Glass fiber under microscope (500x)

fiber lengths used in this work and Fig. 3 illustrates the glass fiber under microscopic. As mentioned earlier, glass fiber was included in different percentages (0.25, 0.5, 0.75, 1, 1.25, 1.5) by the weight of aggregates. The dimensions and physical properties of glass fiber are listed in Table 3.

3 Experimental Setup and Procedures

The following tests were conducted at least three times to ensure the accuracy and repeatability of the findings of the glass fiber and GF-asphalt mixtures.

3.1 Physical Properties of Glass Fiber

3.1.1 Water Absorption Test

The water absorption (WA) test was performed by preparing specimens (30 g) weight of fiber placed in dry beakers. Three glass fiber specimens were tested, and the mean value was reported. After that, the fiber's beakers were exposed for 5 days to air in a curing chamber at conditions of (90%) humidity and (20 ˚C) temperature. Then, the weight of the fiber's beakers was measured continuously for each (5 h.) period through these days to determine the weight change caused by absorbed water and computed by Eq. (1).

$$WaterAbsorption\,(\%) = \frac{W_1 - W_0}{W_0} * 100 \tag{1}$$

3.1.2 Loss in Heating Test

The thermostability of glass fiber was evaluated by using a short aging test. In this test, three specimens are prepared of glass fiber (50 g) kept in a beaker, and then stored in the oven at (163˚C) for (5 h) which is equivalent to the asphalt mixed temperature. The variations of fibers in weight were continuously observed, recorded, and computed by Eq. (2).

$$Mass\ Loss\,(\%) = \frac{W_0 - W_1}{W_0} * 100 \tag{2}$$

3.2 Preparation of Control Asphalt Mixture

The primary purpose of mix design is to investigate the behavior of mixtures that contain different percentages of asphalt to achieve a durable composition. This task is

Table 3 Glass fiber physical properties

Items	Unit	Standard [28]	Properties
Length	mm	ASTM D-204	10, 20, and 30
Width	mm	ASTM D-2130	1
Color	-	-	White
Shape (cross-section)	-	-	Rectangle
Specific gravity	-	ASTM D-792	2.69
Softening point	°C	ASTM D-7138	850
Tensile strength	MPa	ASTM D-5035	3100–3400
Modulus of elasticity	GPa	-	75

usually completed with the assessment of the asphalt mixtures' mechanical and volumetric properties using the Marshall method. Therefore, the Marshall method was selected to design the asphalt mixtures and determine the optimum asphalt content by taking the average of asphalt content for three parameters (maximum stability, maximum density, and (4%) voids in the total mixture). This method is used to produce specimens according to [28] with a diameter of (101.6 mm) and a height of (63.5 mm). The first step in this study is to establish the optimum asphalt content (O.A.C) by preparing specimens of conventional asphalt mixtures with various contents (4, 4.5%, 5.0%, 5.5%, and 6.0%) of asphalt binder with (1140 g) of aggregates. Type Aш aggregates gradation is used to design asphalt mixtures in this study. The gradation is selected so that the gradation curve falls on the midpoint between the upper and lower limits of the Iraqi standard. In Type Aш, the maximum aggregate size is (19 mm) and the nominal maximum size is (12.5 mm) with a mineral filler at a percentage of (7%). This type of asphalt mixture should exhibit a minimum Marshall stability of (8 kN). This type of mixture can be used in road construction projects subjected to high traffic volumes as required by Iraqi specifications [26].

3.3 Preparation of Modified Asphalt Mixtures

Generally, two approaches are adopted when using glass fiber in asphalt mixtures, by either following a wet or a dry method. The wet method included incorporating the glass fiber with asphalt at sufficient temperatures to produce the modified asphalt binder before adding the aggregate. The dry method included mixing the glass fiber with aggregates as a part of solid materials and then pouring the asphalt binder into the mixture. In this work, the dry method is used to modify the conventional mixtures by incorporating different percentages of GF (0.25, 0.5, 0.75, 1, 1.25, and 1.5) by weight of the aggregates. The aim behind the addition of these different percentages is to find the most suitable weight that can enhance the properties of asphalt mixtures. This phase was repeated by using three different lengths of glass fiber (10, 20, and 30 mm) to determine the most suitable percentage and length of glass fiber to be included in asphalt mixtures. Table 4 shows the full details of asphalt mixtures made in this work. This task is usually completed by assessing the mechanical and volumetric properties of the asphalt mixtures. Marshall's method is applied to determine the optimum glass fiber content by taking the average glass fiber content for three parameters (maximum stability, maximum density, and (4%) voids in the total mixture). The most suitable length of glass fiber was determined via the improvement of the performance of asphalt mixtures in different conditions.

Table 4 The asphalt mixtures prepared in this work

Code	Description	Function	Objective
M0	O.A.C	Used to compare with modified mixtures	Control mixture M0
M1-10 to M6-10	Mixtures prepared with O.A.C and different percentages of glass fiber at a length of (10 mm)	To determine the optimum GF content at a length of (10 mm)	M-10 GF
M1-20 to M6-20	Mixtures prepared with O.A.C and different percentages of glass fiber at a length of (20 mm)	To determine the optimum GF content at a length of (20 mm)	M-20 GF
M1-30 to M6-30	Mixtures prepared with O.A.C and different percentages of glass fiber at a length of (30 mm)	To determine the optimum GF content at a length of (30 mm)	M-30 GF

4 Moisture Damage Test

4.1 The Immersion Marshall Test

The Immersion Marshall test is used to measure the effect of water immersion on the stability of the asphalt mixtures by computing the immersion residual Marshall stability ratio (IRMS), described as the Marshall stability ratio for the wet-to-dry specimens and depends on this ratio as an indicator of mixture durability in different cases. The high value for immersion residual Marshall stability ratio (IRMS) means high retained stability and low sensitivity to moisture influences (good resistance against moisture damage) [1]. This test is performed by preparing the specimens with dimensions (101.6 mm) diameter and approximately (63.5 mm) height and dividing them into two groups, each group having three specimens for each length of Glass fiber [29]. In the first group, the specimens are immersed in water for (30 min) at a temperature of (60˚C), while in the second group, the specimens are immersed in water for (1-day, 2-days, and 3-days) at a temperature of (60˚C) to measure the residual stability. The test was following the specification [29]. Thereafter, the residual Marshall stability ratio (RMSR) is computed as follows [30, 31]:

$$\mathrm{RMSR}=\frac{\mathrm{MS2}}{\mathrm{MS1}}*100 \tag{3}$$

Where: RMSR is immersion residual Marshall Stability Ratio; MS2 is the Marshall stability after being immersed in water for (1-day, 2-days, and 3-days) at (60˚C); MS1 is Marshall stability after being immersed in water for (30 min) at (60˚C).

4.2 Freeze-Thaw Splitting Test

The common method used to evaluate the performance of the asphalt mixtures underwater is by measuring the loss in the indirect tensile strength (ITS) before and after freeze-thaw conditions in the water according to the specification [32]. Tests were performed on the specimens at (dry and freeze-thaw) conditions. Therefore, six specimens were prepared for each Glass fiber length with dimensions of (101.6 mm) diameter and (63.5 mm) height. The specimens were made according to specification [29] and split into two groups with three specimens per group. In the case of the dry conditions, half of the specimens were immersed under water for (2 h) at a temperature of (25˚C) to achieve dry conditions (ITS_{dry}). In the case of the freeze-thaw conditions, the other half of the specimens were cured in the vacuum for (20 min) and subjected to pressure (10–26 in.Hg). Then, the specimens were stored in the freezer for (16 h) at a temperature of (-18 ± 3˚C). After that, they were immersed under water for (24 h) at a temperature of (60˚C). Finally, the specimens were removed and placed under water for (1 h) at a temperature of (25˚C) (ITS_{wet}). The indirect tensile strength of (ITS_{dry}) and (ITS_{wet}) was calculated with (50 mm/min) loading rate by applying the following Equation:

$$(\mathrm{ITSdry})\ \mathrm{or}\ (\mathrm{ITSwet}) = 2F/\pi td \tag{4}$$

Where: ITS is the indirect tensile strength (kPa), F is the failure load (kN), t is the specimen thickness (m), and d is the specimen diameter (m). After calculating the indirect tensile strength (ITS) of specimens under dry and freeze-thaw conditions, then the tensile strength ratio (TSR) of asphalt mixtures is calculated by dividing the indirect tensile strength of wet specimens (ITS_{wet}) by the indirect tensile strength of dry specimens (ITS_{dry}), as presented in Eq. (5). The 80% is considered the minimum acceptable value for the tensile strength ratio (TSR) of asphalt mixtures according to [32]. Based on this limitation, any asphalt mixture with a TSR of less than 80% is susceptible to moisture damage.

$$TSR = (ITSwet/ITSdry) * 100 \tag{5}$$

5 High-Temperature Performance Test

5.1 Wheel Tracking Test

The wheel tracking test is used to assess the resistance of an asphalt mixture against rutting, which develops due to the buildup of tiny amounts of irreversible deformation and occurs outside. In this test, four square slab specimens of asphalt mixtures were prepared for each length of glass fiber with dimensions (400 mm) length, (300 mm) width, and (50 mm) thickness. The slab was compacted by using a smooth steel roller compactor according to [33]. This test is carried out to study the stability of asphalt mixtures at high temperatures by finding the dynamic stability (DS), rutting depth (RD), and rutting behavior (RB) in the laboratory. The slab specimens were divided into two groups. The first group was laid in a chamber under a temperature of (40˚C), while the second group was set in a chamber under a temperature of (60˚C). The storing time was (2 h) before testing. According to the European standard [34], a solid rubber tire applies a load (700 N) by moving forth and back on the slab surface for a distance (230 ± 10 mm) and a constant loading frequency (27 passes/min) up to (10,000 cycles). The dynamic stability (DS) was calculated by using Eq. (6). Figure 4 shows the wheel tracking test processes.

$$\mathrm{DS} = \frac{(\mathrm{t2}-\mathrm{t1})\,{*}\mathrm{N}}{\mathrm{d2}-\mathrm{d1}}{*}\mathrm{C1}{*}\mathrm{C2} = \frac{15\mathrm{N}}{\mathrm{D2}-\mathrm{D1}} \tag{6}$$

Where: (DS) is Dynamic stability (times/mm), d1 and d2 are the deformations (mm) at the time (t1 = 45 min and *t2* = 60 min) respectively, C1 and C2 are correction factors of equipment and specimen equal to (1), and N is the constant loading frequency equal to (27 passes/min). Wheel tracking slope (WTS) represents the shear resistance of asphalt mixtures against rutting and was calculated over a period of time by using Eq. (7) in units of (mm/10^3cycles). Proportional rut depth (PRD) was used as a compare parameter and calculated by using Eq. (8).

$$WTS = \frac{D_{10,000} - D_{5000}}{5} \tag{7}$$

$$PRD = \frac{D_{10,000}}{Specimen\ Height} \tag{8}$$

Where: D_{5000} and $D_{10,000}$ are the deformation at 5000 cycles and 10,000 cycles, respectively, and the height of each specimen is equal to (50 mm). Table 5 shows the wheel tracking parameters limits based on the pavement layer position and Traffic level according to [34].

6 Results and Discussion

6.1 Properties of Glass Fiber (GF)

The water absorption test result of glass fiber is shown in Table 6. The water absorption ratio for glass fiber is 0.03%.

Fig. 4 Wheel tracking test processes

Table 5 Wheel tracking parameters limitations [34]

Position in 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%

Table 6 Water absorption of glass fiber

Fiber type	Dry weight (g) W_0	Wet weight (g) W_1	Average water absorption (%)
Glass fiber	30	30.01	0.03

Table 7 Thermostability of glass fiber

Fiber Type	Before oven heating (g) W_0	After oven heating (g) W_1	Mass loss (%)
Glass fiber	50	49.73	0.54

Meanwhile, it was observed that the glass fiber adsorbed a very small amount of water after 5 days of exposure to moisture conditions at (90%) humidity and (20 ˚C) temperature, which can be detected with fingers. This indicator suggests that glass fiber is not sensitive to moist environments.

The results of mass loss due to heating appear in Table 7, as reported in the findings of the water absorption test. Glass fiber exhibited a minimal mass loss of 0.54% after heating at (163˚C) for (5 h). This negligible mass loss underscores the exceptional thermal stability possessed by glass fiber. In addition, the white color stability of the glass fiber remains conspicuously intact during the oven heating test.

6.2 Optimum Asphalt Content (O.A.C)

Marshall stability, flow, and volumetric properties tests of asphalt mixtures were conducted to calculate the optimum asphalt content (O.A.C) and the results of the laboratory experimentation are given in Table 8. The results infer that

Table 8 The results of the mixtures design

Properties	Asphalt content					IQ-Specification [26]
	4.0%	4.5%	5.0%	5.5%	6.0%	
Marshall Stability (kN)	10.5	11.4	12.5	11.6	10.2	8 kN min.
Marshall Flow (mm)	3.05	3.45	3.85	4.35	4.8	2–4 mm
The bulk specific gravity (G_{mb})	2.301	2.319	2.325	2.320	2.309	-
Maximum specific gravity (G_{mm})	2.4565	2.4392	2.4261	2.4053	2.3887	-
Percent voids in mineral aggregate (VMA)%	16.89%	16.67%	16.90%	17.51%	18.34%	14% min.
Percent voids in the total mix. (VTM)%	6.33%	4.93%	4.17%	3.55%	3.34%	3-5%
Percent voids filled with asphalt (VFA)%	62.52%	70.45%	75.34%	79.75%	81.81%	-

Table 9 Properties of asphalt mixtures with glass fiber length (10 mm)

Properties	Type of asphalt mixture						
	M0	M1-10	M2-10	M3-10	M4-10	M5-10	M6-10
Marshall Stability (kN)	12.5	14.6	16.2	15.1	14.5	12.7	11.5
Marshall Flow (mm)	3.85	3.62	3.23	3.48	3.65	3.79	4.21
Marshall Stiffness (kN/mm)	3.25	4.03	5.02	4.34	3.97	3.35	2.73
Bulk specific gravity (G_{mb})	2.325	2.344	2.374	2.349	2.339	2.328	2.304
Maximum specific gravity (G_{mm})	2.4261	2.4443	2.4735	2.4491	2.4411	2.4323	2.4121
voids in mineral aggregate (VMA)%	16.90%	16.22%	15.15%	16.04%	16.40%	16.79%	17.65%
voids in total mix (VTM)%	4.17%	4.10%	4.02%	4.09%	4.18%	4.29%	4.48%
Voids filled with asphalt (VFA)%	75.34%	74.71%	73.45%	74.52%	74.50%	74.47%	74.61%

Table 10 Properties of asphalt mixtures with glass fiber length (20 mm)

Properties	Type of asphalt mixture						
	M0	M1-20	M2-20	M3-20	M4-20	M5-20	M6-20
Marshall Stability (kN)	12.5	15.2	17.1	16.3	15.7	13.5	12.3
Marshall Flow (mm)	3.85	3.41	2.91	3.17	3.32	3.75	3.94
Marshall Stiffness (kN/mm)	3.25	4.46	5.88	5.14	4.73	3.60	3.12
Bulk specific gravity (G_{mb})	2.325	2.353	2.382	2.376	2.359	2.332	2.314
Maximum specific gravity (G_{mm})	2.4261	2.4532	2.4816	2.4768	2.4611	2.4361	2.4217
voids in mineral aggregate (VMA)%	16.90%	15.90%	14.86%	15.08%	15.69%	16.65%	17.29%
voids in total mix (VTM)%	4.17%	4.08%	4.01%	4.07%	4.15%	4.27%	4.45%
Voids filled with asphalt (VFA)%	75.34%	74.31%	73.00%	73.01%	73.55%	74.34%	74.29%

the Marshall stability and the bulk specific gravity increase with an increase in asphalt content until (5%) and start to decrease after this limit. This is because aggregates absorb a part of the asphalt binder, and another part covers the surface area of the aggregates. The increase in the asphalt content leads to improved stability, and bulk-specific gravity of asphalt mixtures until the optimum value is achieved. After this, and addition of asphalt binder is expected to cause a decrease in the stability and bulk-specific gravity of the asphalt mixture. The Marshall stability and the bulk specific gravity value increased, such that the maximum of (16.8 kN) and (2.325) was achieved at (5%). However, the excessive increase of asphalt content increased the Marshall flow values of mixtures until (4.8 mm).

However, the durability of any asphalt mixture is guaranteed via a suitable volumetric mixture design. The volumetric properties of major interest in asphalt mixtures are voids in the total mix (VTM), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA). The voids in the total mix (VTM) decrease with an increase in the asphalt content and voids in the mineral aggregate (VFA) increase with an increase in asphalt content, while the voids in the total mix (VMA) decrease with an increase in the asphalt content at (4.5%) then increase. It is worth mentioning, that the optimum asphalt content is calculated as the average of asphalt content corresponding to the maximum Marshall stability, maximum bulk specific gravity, and (4%) voids in the total mix. The results showed the optimum asphalt content was established to be (5%). This optimum asphalt content (O.A.C.) is adequate to supply maximum stability, proper flow, satisfactory air voids, maximum specific gravity, and acceptance (VMA% and VFA) [29, 35, 36].

6.3 Optimum Glass Fiber Content

Table 9 shows the outcomes summary of the Marshall stability, flow, and volumetric properties of asphalt mixtures made at different percentages (0.25, 0.5, 0.75, 1, 1.25, 1.5%) from the total weight of aggregates with 10 mm glass fiber length. The results indicate that all modified asphalt mixtures satisfy the minimum technical requirement of the Iraqi specification (SORB-R/9,2003) [26]. It can be seen that the Marshall stability, flow, and volumetric properties values gradually improve as glass fiber contents increase in the mixture. For example, the maximum Marshall stability of the M2-10 mixture at (0.5%) glass fiber content is (16.2 kN), the flow is (3.23 mm), and the VMA, VFA, and VTM are (15.15%), (73.45%), and (4.02%) respectively. Nevertheless, the addition of more glass fiber into the mixture resulted in a decrease in Marshall stability, flow, and the volumetric properties values for mixtures from (M3-10) to (M6-10). However, these mixtures still behaved better than the control mixture M0 except (M6-10) as shown in Table 9. These results are in line with those obtained by Abtahi et al. [37].

Table 10 presents the effect of different contents (0.25, 0.5, 0.75, 1, 1.25, 1.5%) from the total weight of aggregates with 20 mm glass fiber length on the Marshall stability, flow,

Table 11 Properties of asphalt mixtures with glass fiber length (30 mm)

Properties	Type of Asphalt Mixture						
	M0	M1-30	M2-30	M3-30	M4-30	M5-30	M6-30
Marshall Stability (kN)	12.5	14.2	15.8	14.3	12.4	11.8	11.2
Marshall Flow (mm)	3.85	3.73	3.31	3.69	3.88	4.11	4.35
Marshall Stiffness (kN/mm)	3.25	3.81	4.77	3.88	3.20	2.87	2.57
Bulk specific gravity (G_{mb})	2.325	2.336	2.363	2.337	2.319	2.307	2.302
Maximum specific gravity (G_{mm})	2.4261	2.4367	2.4625	2.4379	2.4211	2.4127	2.4112
voids in mineral aggregate (VMA)%	16.90%	16.51%	15.54%	16.47%	17.12%	17.55%	17.72%
voids in total mix (VTM)%	4.17%	4.13%	4.04%	4.14%	4.22%	4.38%	4.53%
Voids filled with asphalt (VFA)%	75.34%	74.97%	74.00%	74.88%	75.36%	75.03%	74.45%

and volumetric properties. The finding indicates that the use of glass fiber modifies the asphalt mixture's properties. It can be seen that the Marshall stability, Marshall Stiffness, and the bulk specific gravity of modified asphalt mixtures increase as the dosage of glass fiber increases until the peak is reached at 0.5% of GF. The Marshall stability, Marshall Stiffness, and the bulk specific gravity value increase to (17.1 kN), (5.88 kN/mm), and (2.382) at (0.5%) of GF. A different story can be seen with the flow and volumetric properties as they decreased as the dosage of GF increased. The flow and volumetric properties also peak at 0.5% GF as shown in Table 10. Therefore, the outcomes indicate that all the modified mixtures behaved better than the mixture with no GF. There was only one exception, the M6-20 mixture, which demonstrates less stability, Marshall stiffness, and bulk-specific gravity when compared with the control mixture (M0).

Table 11 illustrates the values of Marshall parameters and volumetric properties of asphalt mixtures made with different contents of 30 mm glass fiber length by (0.25, 0.5, 0.75, 1, 1.25, 1.5%) from the total weight of aggregates. The results indicate that the increase in the dosages of GF in the mixture can diminish its effect on the final product. As seen, the increase in the glass fiber contents led to improvements in intrinsic characteristics that significantly impacted the primary performance of modified asphalt mixtures. Based on experimental results, the glass fiber asphalt mixtures meet the requirement for the hot mix asphalt according to Iraqi specifications [26]. Consequently, the same trend in this finding was seen with previous results where the increase in glass fiber content leads to improvement in Marshall stability, flow, Marshall stiffness, bulk specific gravity, and volumetric properties. The values of the properties peaked at 0.5% GF as shown in Table 11. For instance, the Marshall stability of the M2-30 mixture enhanced in reaching up to 26.4%, VTM, VMA, and VFA up to (3%), (8%), and (2%) respectively when compared with the control mixture (M0).

According to the data obtained, it could be concluded that adding glass fiber to the asphalt mixture had a pronounced effect on the stability, flow, Marshall stiffness, and volumetric properties. The findings prove that the best-added percentage is (0.5%) of the total weight of aggregates in the mixture. Which was calculated based on taking the average glass fiber content for three parameters (maximum stability, maximum density, and (4%) voids in the total mixture). Table 12 shows the properties of modified asphalt mixtures prepared with optimum glass fiber content, i.e. (0.5%) of the total weight of aggregates in the mixture with different lengths. It can be seen that Marshall stability, Marshall stiffness, flow, and bulk specific gravity of modified asphalt mixtures were considerably enhanced as the GF-length increased from 10 mm in the (M2-10 GF) mixture to 20 mm in the (M2-20 GF) mixture, but they decreased when 30 mm GF-length is added in the (M2-30 GF) mixture. However, the (M2-30 GF) mixture still behaved better in terms of Marshall stability, Marshall stiffness, flow, and bulk specific gravity when compared with the control mixture (M0).

Table 12 Properties of asphalt mixtures with optimum glass fiber content

Properties	Type of Asphalt Mixture				IQ-Specification [26]
	M0	M2-10 GF	M2-20 GF	M2-30 GF	
Marshall Stability (kN)	12.5	16.2	17.1	15.8	8 kN min.
Marshall Flow (mm)	3.85	3.23	2.91	3.31	2–4 mm
Marshall Stiffness (kN/mm)	3.25	5.02	5.88	4.77	-
Bulk specific gravity (G_{mb})	2.325	2.374	2.382	2.363	-
Maximum specific gravity (G_{mm})	2.4261	2.4735	2.4816	2.4625	-
voids in mineral aggregate (VMA)%	16.90%	15.15%	14.86%	15.54%	14% min
voids in total mix (VTM)%	4.17%	4.02%	4.01%	4.04%	3-5%
Voids filled with asphalt (VFA)%	75.34%	73.45%	73.00%	74.00%	-

6.4 The Immersion Marshall Results

Figure 5 demonstrates the immersion residual Marshall stability of the control mixture (M0) and modified asphalt mixtures made with three different lengths of glass fiber. The test results show that the M0 mixture exhibited the lowest residual Marshall stability after immersion. On the other hand, the modified asphalt mixtures with various lengths of glass fiber showed different behaviors. Adding a 10 mm length of glass fiber improves the value of residual Marshall stability compared to that achieved by the M0 mixture. Furthermore, using a 20 mm length of glass fiber leads to the highest improvement in residual stability as shown in Fig. 5. However, the addition of a 30 mm length of glass fiber limited the improvement effect of GF as the (M2-30 GF) mixture demonstrated the lowest residual Marshall stability among the modified asphalt mixtures. It is well known that immersion in water for 1, 2, and 3 days can accelerate the loss of adhesion between aggregate and asphalt binder. However, based on the results of the immersion Marshall test, the use of GF has a remarkable effect on the mixture's resistance to water damage. In this regard, the immersion residual Marshall stability values of modified asphalt mixtures in 1, 2, and 3 days improved by 3.3%, 8%, and 10.9% (values of M2-10 GF mixtures), 7.6%, 13.1%, 16.8% (values of M2-20 GF mixtures), and by 1.5%, 6.6%, 7.3% (values of M2-30 GF mixtures) respectively. In addition, it has been found that when modified asphalt mixtures are submerged in water for two or three days, their resistance to water deterioration increases compared to that measured after one day of immersion in water. This is because glass fiber can strengthen the bond between the asphalt binder and aggregates, and lead to improve the ability of the two materials to resist stripping. However, excessive glass fiber length can result in uneven fiber distribution and raise the asphalt mixture porosity, negatively impacting the mixtures' water stability.

6.5 Freeze-Thaw Splitting Results

Figure 6 illustrates the ITS outcomes for asphalt mixtures in dry and wet situations. The experiment was carried out on specimens with the optimum amount of glass fiber (0.5%) of the mixture's aggregate weight and different glass fiber lengths. As expected, the ITS values of wet-condition specimens were drastically lower in comparison with the dry-condition specimens. This is due to water presence that initiates a decline in asphalt-aggregate adhesion, and consequently, the strength of specimens declines under loading. The most crucial point is that the resistance of dry and wet conditions specimens was less for the control mixture (M0) specimens compared to that measured for specimens made with 0.5% GF regardless of the length used in the mixture. According to the results, the ITS values of the (M2-10 GF) mixtures in wet and dry conditions increased by (19.3%) and (28.7%) when compared to that of the control mixture (M0). As for the (M2-20 GF) mixtures, the ITS values in wet and dry situations increased by (23.9%) and (37%) in comparison with the control mixture (M0). Finally, the values ITS measured for (M2-30 GF) mixtures in dry and wet conditions improved by (2.1%) and (8.8%) in comparison with asphalt mixtures made without GF. This scenario shows that the GF-asphalt mixtures have stronger cohesive properties than the control mixture (M0) exhibited.

The results demonstrated in Fig. 7 indicated the positive role of altered specimens by glass fiber (GF) against water sensitivity. According to these results, it can be observed that the control mixture (M0) had the lowest value of TSR (81.2%). The value of TSR increased with adding the GF of 10 mm length to (87.6%). The last value is further increased when GF of 20 mm length is added to the mix to reach a

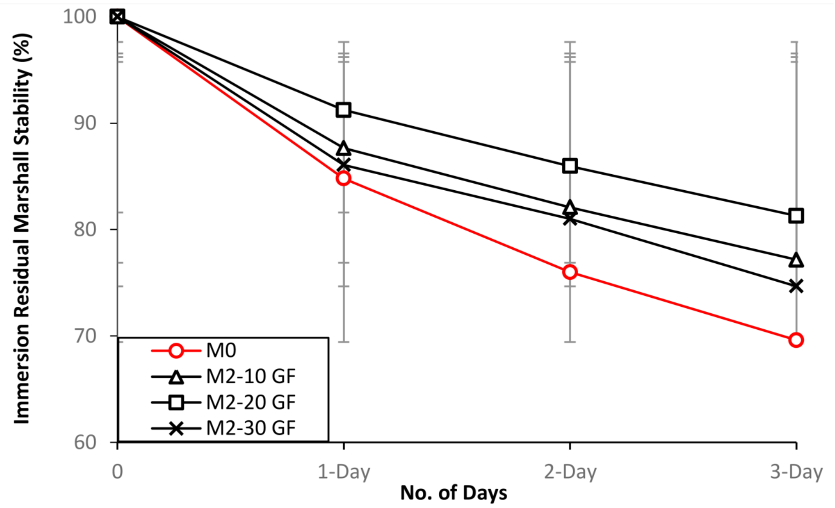


Fig. 5 Immersion residual marshall stability of asphalt mixtures

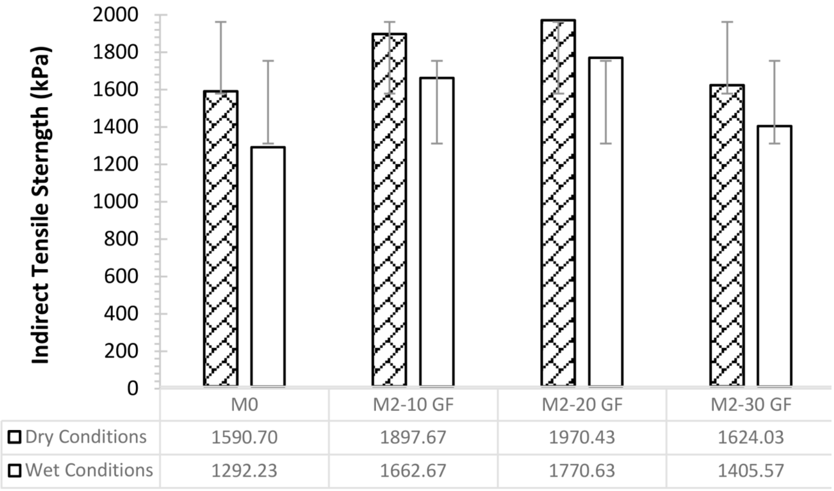


Fig. 6 Indirect tensile strength (ITS) of asphalt mixtures

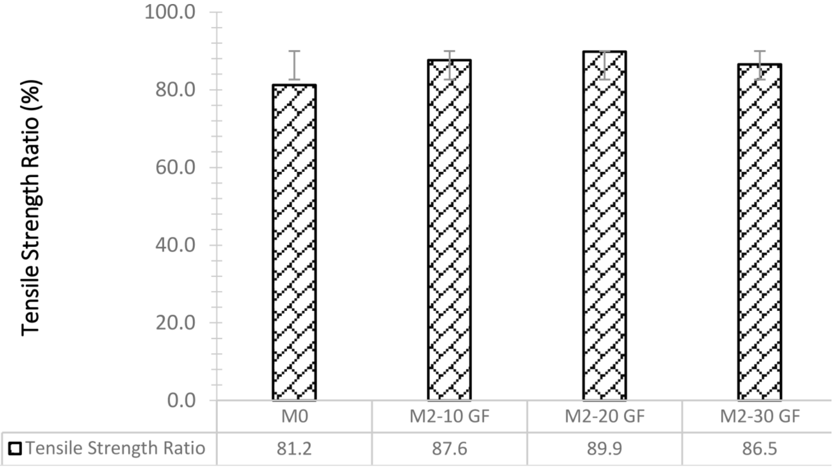


Fig. 7 Tensile strength ratio (TSR) of asphalt mixtures

peak of (89.9%). After that, the TSR decreased to (86.5%) for the asphalt mixture made with GF of 30 mm length. This outcome may be explained by the reduction in the mixture's workability due to the use of a length higher than 20 mm of GF (i.e. 30 mm). This Improvement in modified asphalt mixtures is represented in the (M2-10 GF) mixture about (7.9%) at a length of (10 mm), the (M2-20 GF) mixture about (10.6%) at a length of (20 mm), and the (M2-30 GF) mixture about (6.5%) at a length of (30 mm) compared with the control mixture (M0). Therefore, the suitable method to increase asphalt mixtures' resistance to moisture damage is to include glass fiber. To put it another way, adding a certain amount of glass fiber improves the mixtures' adherence and stability, prevents the asphalt binder from being removed easily from aggregate surfaces, and increases their moisture resistance relative to the control mixture (M0).

6.6 Wheel Tracking Results

To determine the values of dynamic stability (DS), permanent deformation (RD), wheel-tracking slope (WTS), and proportional rut depth (PRD), of asphalt mixtures made in this study, the wheel-tracking test was performed As shown in Fig. 8, the modified asphalt mixtures with glass fiber content had a lower permanent deformation at an equal number of cycles and sharply decreased with increasing glass fiber length as compared with the control mixture (M0). The findings reveal that the resistance to permanent deformation at (40˚C) and (60˚C) of the mixtures made with a GF length of 10 mm significantly increased by (62%) and (59.3%) respectively in comparison with that measured for the control mixture (M0). As for the mixtures made with a GF length of 20 mm, the rutting resistance at (40 ∘C) and (60 ∘C) increased by (66.8%) and (68.4%) as compared with that of the control mixture (M0). Keeping with this the mixtures made with a GF length of 30 mm exhibited higher rutting resistance than the control mixture (M0) but lower than that of mixtures prepared with 10 mm and 20 mm GF length as shown in Fig. 8. The improvement in permanent deformation of the mixtures made with a GF length of 30 mm at (40˚C) and (60˚C) were (48.1%) and (42.4%) respectively, as compared with the control mixture (M0).

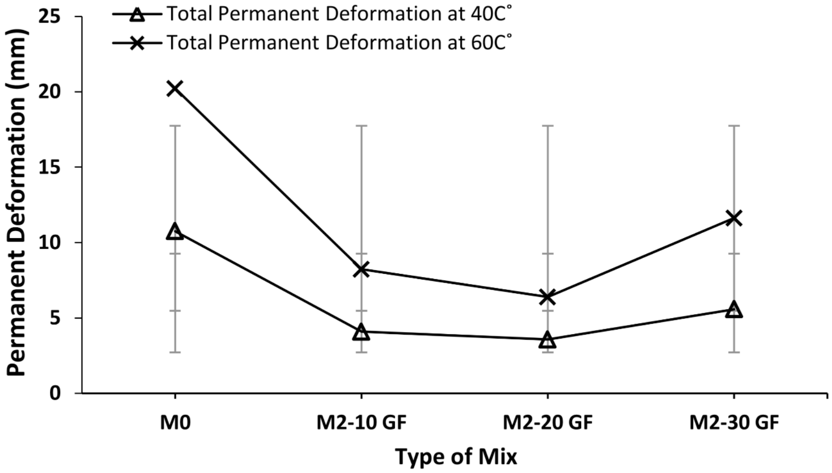


Fig. 8 Permanent deformation (RD) of asphalt mixtures

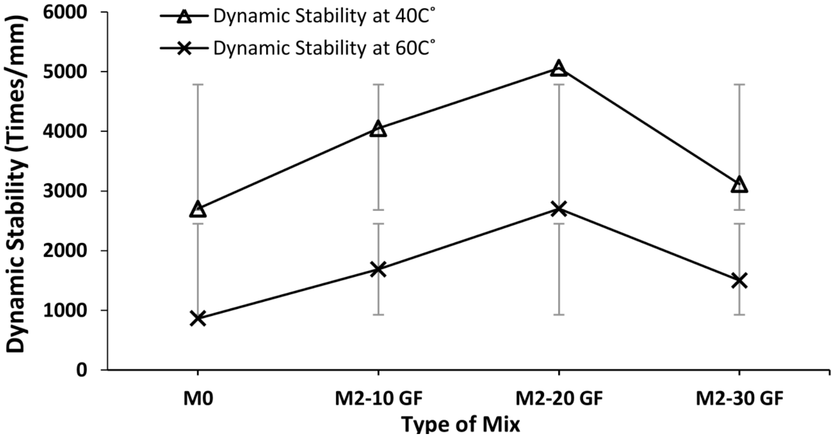


Fig. 9 Dynamic stability (DS) of asphalt mixtures

The findings suggest that glass fiber could boost mixtures' capacity to withstand persistent deformation. The temperature can considerably impact the permanent deformation of asphalt mixtures, indicating that temperature rises deteriorate the resistance to permanent deformation. To keep the asphalt binder from flowing at high temperatures and loads, glass fiber can hold the binder, prevent its movement, and increase the resistance to permanent deformation. As a result, the asphalt develops a three-dimensional (3D) network that decreases fluidity while strengthening the skeleton structure to withstand shear pressure [38]. According to the findings, the temperature had the least impact on the performance of the mixtures at high temperatures in the (M2-20 GF) mixture.

Figure 9 shows that modified asphalt mixtures' dynamic stability (DS) increases as the length of added GF increases. It can be seen that the dynamic stability decreases with increases in the temperature test. Firstly, the dynamic stability (DS) at (40˚C) and (60˚C) of mixtures made with 10 mm GF increased by (50%) and (95.7%) compared to that measured for the control mixture (M0). Additionally, the dynamic stability is further improved when a 20 mm length of GF is added. The mixtures made with a 20 mm length of GF obtained dynamic stability higher than that of the control mixture by (78.5%) and (213%) respectively. The aforementioned values of DS were the highest among all mixtures in this research. While the dynamic stability of the asphalt mixture made with a 30 mm length of GF represented (15.4%) and (73.9%) higher than that reported for the control mixture (M0) at (40˚C) and (60˚C) respectively. According to the findings, the addition of glass fiber increases the dynamic stability (DS) of the modified asphalt mixture (GF), and the highest improvement rate was achieved when a 20 mm length of GF is added to asphalt mixtures. It is possible to conclude that the addition of GF could boost the dynamic stability (DS) value and improve rutting resistance. While including GF with lengths higher than 20 mm can diminish the effect of using GF against rutting, these results confirmrevious findings [21, 39].

Table 13 presented the WTS and PRD parameters that were calculated for the control mixture (M0) and the modified asphalt mixture with glass fiber in different lengths and two temperatures. When comparing these results with the limits displayed in Table 5, It can be seen that all modified asphalt mixtures (M2-10 GF, M2-20 GF, and M2-30 GF) made with (0.5%) glass fiber content and tested at (40

Table 13 WTS and PRD parameters of asphalt mixtures

Parameters		Type of asphalt mixture			
		M0	M2-10 GF	M2-20 GF	M2-30 GF
40˚C	WTS	0.166	0.048	0.045	0.068
	PRD	0.22	0.08	0.07	0.11
	$D_{10,000\ (mm)}$	10.75	4.09	3.57	5.58
60˚C	WTS	0.225	0.094	0.072	0.142
	PRD	0.40	0.16	0.13	0.23
	$D_{10,000\ (mm)}$	20.22	8.23	6.39	11.62

∘C) fulfill the specification of surface pavement subjected to T1 traffic (the highest requirement). While the control mixture (M0) failed to achieve this criterion. Nevertheless, when comparing WST for all modified asphalt mixtures at (60˚C) only one mixture fulfilled the specification of surface pavement subjected to high traffic T1, i.e., the (M2-20 GF) mixture. In addition, the (M2 -10 GF and M2-30 GF) mixtures satisfied the requirement of the traffic levels T2 to T4 mean from medium to low level, respectively, while the control mixture (M0) was out of limitations. However, it noted that the PRD parameter of all asphalt mixtures satisfied the standard requirements of all traffic levels at testing temperatures, as shown in Table 5. These results conform with the previous investigation as documented by [18].

7 ANOVA Analysis

Based on the aforementioned findings, it is evident that glass fiber dosage and lengths enhance the Marshall stability (MS), volumetric properties, indirect tensile strength (ITS), moisture damage (MD), immersion residual Marshall stability (IRMS), permanent deformation (RD), dynamic stability (DS), wheel-tracking slope (WTS), and proportional rut depth (PRD) of the asphalt mixture. Nonetheless, the primary objective of this paper was to assess how glass fiber lengths (GF lengths) impact the pavement characteristics of asphalt mixtures. To achieve this goal and acquire more profound insights, the statistical analysis of variance (ANOVA) technique to assess the effects of the addition of different glass fiber lengths. The analysis of variance (ANOVA) technique is applied by using Microsoft Office 365 (Excel)to assess the percent contribution of each factor to the responses [40, 41]. In this research, a one-way and two-way analysis of variance was performed with replication to assess the effect of glass fiber lengths on asphalt mixture properties. In the ANOVA test, a significance level (α) of (0.05) was selected to evaluate the statistical significance, i.e., confidence level of (95%). If the reported probability value is less than 0.05, the null hypothesis is rejected, and the outcomes are statistically significant. The results of the analysis are presented in Tables 14 and 15 respectively.

As shown in Table 14, a one-way ANOVA was carried out to test the significance of GF lengths on moisture damage (MD) and volumetric properties of asphalt mixtures. The ANOVA revealed that the addition of GF with different lengths can significantly affect the results of MD (p-value = 6.27E-11), VTM (p-value = 0.005148), and VFA (p-value = 4.63E-11). On the other hand, the one-way ANOVA showed that the addition of 10 mm, 20 mm, and 30 mm GF did not affect the results of VMA at (95%) confidence level as the p-value = 0.862471 are far than (0.05) in this case. While the primary objective of the two-way ANOVA is to examine the effects of two or more independent variables (i.e., GF lengths, temperature, duration of immersion, and state condition) on dependent variables (i.e., permanent deformation (RD), dynamic stability (DS), proportional rut depth (PRD), wheel-tracking slope (WTS), immersion residual Marshall stability (IRMS), Marshall stability (MS), and indirect tensile strength (ITS)). It also can test the interaction effect of the independent variables on a dependent variable. This study performed a two-way ANOVA to examine the effects of two independent variables (i.e., GF lengths and testing temperature) on RD, DS, PRD, and WTS. The results of the two-way ANOVA are presented in Table 15. It can be seen that the value of F is bigger than that of F-crit, and the p-values are far smaller than (0.05) in all cases. ANOVA proves that GF lengths and testing temperature can significantly affect the performance of GF-asphalt mixtures at elevated temperatures. Also, the ANOVA revealed that the interaction effect of both GF length and testing temperature on RD, DS, PRD, and WTS is significant from a statistical point of view, where p-values are 9.95E-09, 5.4E-11, 9.95475E-09, and 2.06E-06 respectively. ANOVA results may be explained as follows. First, glass fibers can adhere to the viscous asphalt binder, impeding its flow at elevated temperatures. Secondly, they establish a three-dimensional network within the asphalt matrix, fortifying the structural integrity and augmenting its resistance to shear forces while simultaneously diminishing fluidity [38]. In addition, two-way ANOVA was carried out to test the effects of two independent variables (i.e., GF lengths and duration of immersion) on IRMS and MS.

Table 14 One-way ANOVA results of asphalt mixtures made with different lengths of GF

Item	Source of variance	F^a	*P*-value	F-crit	Significant
MD	GF lengths	307.986	6.27E-11	4.600	YES
VTM	GF lengths	10.963	0.005148	4.600	YES
VMA	GF lengths	0.0311	0.862471	4.600	NO
VFA	GF lengths	322.281	4.63E-11	4.600	YES

Table 15 Two-way ANOVA results of asphalt mixtures made with different lengths of GF

Item	Source of variance	F[a]	*P*-value	F-crit	Significant
RD	GF lengths	598.962	1.22E-16	3.239	YES
	Temperature	854.947	2.57E-15	4.494	YES
	GF lengths, Temperature	56.399	9.95E-09	3.239	YES
DS	GF lengths	2561.815	1.16E-21	3.238	YES
	Temperature	13259.170	8.75E-25	4.494	YES
	GF lengths, Temperature	113.451	5.4E-11	3.239	YES
PRD	GF lengths	598.962	1.22415E-16	3.239	YES
	Temperature	854.947	2.56863E-15	4.494	YES
	GF lengths, Temperature	56.399	9.95475E-09	3.239	YES
WTS	GF lengths	1027.114	1.69E-18	3.239	YES
	Temperature	715.829	1.04E-14	4.494	YES
	GF lengths, Temperature	26.195	2.06E-06	3.239	YES
IRMS	GF lengths	122.038	1.35E-17	2.901	YES
	Duration of Immersion	1560.817	9.35E-35	2.901	YES
	GF lengths, Duration of Immersion	17.378	5.8E-10	2.189	YES
MS	GF lengths	417.473	1.01E-25	2.901	YES
	duration of immersion	229.726	1.02E-21	2.901	YES
	GF lengths, Duration of Immersion	0.577	0.805	2.189	No
ITS	GF lengths	81.522	6.56E-10	3.239	YES
	State Condition	108.736	1.53E-08	4.494	YES
	GF lengths, State Condition	0.881	0.472	3.239	No

ANOVA reveals that the effect of both mentioned independent variables is statistically significant. It can be seen that the F values of GF lengths and immersion duration are bigger than those of F-crit values. Also, the p-values are far smaller than (0.05). The ANOVA shows an interaction effect in the IRMS results (p-value = 5.8E-10) but not in the case of MS results (p-value = 0.805). Another two-way ANOVA was conducted to evaluate the effects of two independent variables (i.e., GF lengths and state conditions (dry or wet)) on the ITS results. The results presented in Table 15 show that GF lengths and state conditions significantly affect the ITS, where p-values were far smaller than (0.05). While the interaction effect was not significant at a 95% confidence (p-value = 0.472).

8 Cost Analysis

The analysis of economic benefits is an essential part of a feasibility study when constructing pavements, and it is a significant basis for the economic rationality of construction projects and government approval to construct these projects [42]. This manuscript analyses the raw material cost of the surface layer, to improve the field utilization of glass fiber incorporated in asphalt mixtures. To achieve this, a comprehensive cost analysis of the control asphalt mixture (M0) and modified asphalt mixtures made with three different lengths of glass fiber (M2-10 GF, M2-20 GF, M2-30 GF) has been conducted. The production cost of asphalt pavement is comprised of two essential parts: the raw materials cost and manufacturing cost which involves various stages, such as preparation (heating and mixing), transportation, and laying [43]. In the present study, the cost of raw materials, specifically asphalt, natural aggregates, and mineral filler (Portland cement) are taken from local companies with expertise in asphalt pavements in Iraq. The cost of glass fiber is obtained from the Sika company. The required percentage of raw materials to produce asphalt mixtures is shown in Table 16, while Table 17 displays the cost of raw materials per 1-Ton.

Table 16 The required percentages of raw materials to produce asphalt mixtures

Materials	M0	M2-10 GF	M2-20 GF	M2-30 GF
Asphalt binder	0.05	0.05	0.05	0.05
Coarse aggregates	0.57	0.57	0.57	0.57
Fine aggregates	0.36	0.36	0.36	0.36
Mineral Filler	0.07	0.07	0.07	0.07
Glass Fiber	0	0.005	0.005	0.005

Meanwhile, Table 18 shows the quantities of raw materials required to produce (1-km) length of asphalt pavement

Table 17 The cost of raw materials for 1-ton in ($-USA)

Materials	Asphalt weight (Ton)	Coarse aggregates weight (Ton)	Fine aggregates weight (Ton)	Mineral Filler weight (Ton)	Glass Fiber (Ton)
M0	200	30	35	100	0
M2-10 GF	200	30	35	100	500
M2-20 GF	200	30	35	100	500
M2-30 GF	200	30	35	100	500

Table 18 The quantities of raw materials demanded to produce 1-km of asphalt mixtures

Materials	Volume (m^3)	Specific gravity	Asphalt mixture weight (Ton)	Asphalt weight (Ton)	Coarse aggregates weight (Ton)	Fine aggregates weight (Ton)	Mineral Filler weight (Ton)	Glass Fiber (Ton)
M0	775	2.325	1801.9	90.09	1027.07	648.68	126.13	0.00
M2-10 GF	775	2.374	1839.9	91.99	1048.71	662.35	128.79	9.20
M2-20 GF	775	2.382	1846.1	92.30	1052.25	664.58	129.22	9.23
M2-30 GF	775	2.363	1831.3	91.57	1043.86	659.28	128.19	9.16

with dimensions of (15.5 m) width and (0.05 m) thickness. The cost of raw materials of the asphalt mixtures was determined by multiplying the demanded quantity, which appeared in Table 18, with adopted prices for one ton in Table 17, and adding the manufacturing cost to the raw materials cost to obtain the total cost associated with creating (1-Km) of asphalt pavement. The collective cost of raw materials and manufacturing of each asphalt pavement type for covering (1-km) is shown in Table 19. The results show that the cost of asphalt mixtures incorporating different lengths of glass fiber was slightly higher than the control mixture (M0). This cost increase is solely attributed to the inclusion of glass fiber. In this regard, the addition of glass fiber at a dosage of (0.5%) of the weight of the aggregates in the asphalt mixture yielded notable improvement in many properties, such as dynamic stability (DS), permanent deformation (RD), wheel-tracking slope (WTS), proportional rut depth (PRD), Marshall stability, freeze-thaw, and volumetric properties. It's essential to highlight that the cost of additional glass fibers amounted to a modestly constituted (6%) of the total cost of constructing (1-km) of asphalt pavement. The improvement in asphalt mixture properties may compensate for this increase in cost. For instance, glass fiber has a positive influence in reinforcing the asphalt mixtures by creating a three-dimensional network leading to an in turn, reduction in fluidity, and increased resistance, which reduces the chance of irreparable rutting deformation [38]. Thereby, the pavement can withstand damage for the duration of its service life while simultaneously lowering maintenance costs.

9 Conclusions

This study investigated the effect of GF dosage and lengths on the properties of the resultant mixtures. In the first stage, the most suitable percentage of GF was determined through Marshall testing. While in the second stage, the effect of GF lengths on moisture susceptibility and stability at high temperatures was assessed by immersion Marshall stability test, freeze-thaw splitting test, and wheel tracking test. The work aimed to investigate the effect of the addition of GF with lengths higher than 10 mm as the research in this area was limited. Based on the results and analysis, the following findings can be summarized:

1. The results of Marshall parameters confirm that the best glass fiber content is 0.5% for asphalt mixtures made with different GF lengths.
2. The Marshall stability, flow, and volumetric properties of the modified asphalt mixtures notably improve and then subsequently reduce with increasing glass fiber content. With the addition (0.5%) of the glass fiber to the asphalt mixture in different lengths, the properties improved at the maximum in the (M2-GF20) mixture with 20 mm GF length by (36.8%) Marshall stability, (24.4%) flow, (12.1%) VMA, (2%) VFA, and (17.5%) VTM compared with the control mixture (M0).
3. The resistance to moisture damage is measured by either tensile strength ratio (TSR) or immersion residual Marshall stability ratio (IRMS)) increased as the length of GF increased. The increase in TSR and immersion Marshall stability values peaked at the addition of 20 mm GF length, but it decreased when 30 mm GF length was added to the mixture.

Table 19 The cost of raw materials and manufacturing for 1-km of asphalt pavement

Materials	Cost of Raw Materials for 1-Km ($-USA)					Manufacturing Cost ($-USA)			Total cost ($-USA)
	Asphalt	Coarse aggregates	Fine aggregates	Mineral Filler	Glass Fiber	Preparation	Transportation	Laying	
M0	18,019	30,812	22,704	12,613	0	3000	1200	800	89,148
M2-10 GF	18,399	31,461	23,182	12,879	4600	3000	1200	800	95,521
M2-20 GF	18,461	31,567	23,260	12,922	4615	3000	1200	800	95,826
M2-30 GF	18,313	31,316	23,075	12,819	4578	3000	1200	800	95,101

4. Based on the wheel tracking test results, the modified asphalt mixtures with GF performed better than the control mixture (M0) in terms of final rut depth, DS, WTS, and PRD. The mixtures made with 20 mm GF length showed the smallest rut depth, the highest DS, and the lowest WTS and PRD at different testing temperatures (40˚C) and (60˚C).
5. According to the results and analysis, the addition of 0.5% of 20 mm GF length can lead to a remarkable improvement in strength, water stability, and high-temperature performance. This research recommends using GF with lengths higher than 10 mm to boost the resistance of asphaltic pavement against moisture damage and rutting. Therefore, further laboratory and field investigations are needed to support and generalize the findings achieved in this study.
6. In the context of economic evaluation, it is noted that using (0.5%) glass fiber in the modification of asphalt mixtures led to a small nonsignificant increase in the overall costs compared to the control mixture (M0). This cost increase may be compensated by the improvement in the performance of GF asphalt mixtures, specifically in terms of the extending service life of the asphalt pavement layer.

With a high softening point of 850˚C and a high tensile strength of roughly 3100–3400 MPa, glass fiber is a reinforcing material. It is frequently utilized as a reinforcing ingredient in asphalt mixtures because of its capacity to endure high temperatures and stress. The adhesive bond, also known as stripping, increases due to the fiber overlaps between the aggregates and asphalt binder in the mixture. Using GF in asphalt pavement may support traffic loads in hot climates. The pavement can withstand damage for the duration of its service life, reducing the chance of irreversible deformation like rutting. GF, therefore, satisfies the performance standards for asphalt pavement.

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Declarations

Ethics approval and consent to participate The authors state that the research was conducted according to ethical standards.

Conflict of interest None declared.

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