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The Effects of Fibers on the Properties of Local Hot Asphalt Mixtures

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Keywords:
Fibers; Dry mix process; Fibers-asphalt mixtures; HMA; Marshall properties; Tensile strength ratio.

Highlights:

- *Three types of inorganic fiber were investigated: steel, glass, and basalt fiber.*
- *The dry mix process was used to add fibers to the asphalt mixture.*
- *The Marshall and indirect tensile strength tests of the asphalt mixtures with inorganic fibers were confirmed.*
- *Using 0.25% SF, 0.1% GF, and 0.15% Bf obtained the highest Marshall stability, TSR, and acceptable volumetric properties for HMA according to specifications for roads and bridges.*

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Abstract: Conventional flexible pavements are released to different types of failure in the initial phases of their service life due to high traffic density, high speeds, heavy loads, and harsh climates. To eliminate pavement damage and failure early, the present search investigates the impact of adding glass, steel, and basalt fibers in the asphalt mixtures. Also, the study evaluates these materials characteristics compared to the mixtures without fibers. The Marshall test and tensile strength ratio test (TSR) were utilized to evaluate the asphalt mixture's performance. A set of specimens were produced by incorporating glass fiber (GF), steel fiber (SF), and basalt fiber (BF) at (0.10%, 0.15%, 0.20%), (0.25%, 0.35%, 0.45%), and (0.15%, 0.35%, 0.50%), respectively. When using these fibers, the findings showed an improvement in Marshall stability, flow, volumetric properties, and TSR value. The highest improvement in Marshall stability and TSR value was obtained at 0.10% of GF by 14% and 11.5%, at 0.25% of SF by 16% and 10%, and at 0.15% BF by 8% and 14.1%, respectively, compared to the control mixture. Therefore, fibers can be used as a convenient modifier for asphalt mixtures to improve the performance of flexible pavement with an optimal addition of 0.1% GF, 0.25% SF, and 0.15% BF to the total mass of the mix.

دراسة تأثير الألياف على خواص الخلطات الإسفلتية الساخنة المحلية

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الخلاصة
تتعرض الخرسانة الاسفلتية المرنة التقليدية لأنواع مختلفة من اشكال الفشل التي تظهر في المراحل الأولى من عمرها التشغيلي نتيجة للكثافة المرورية العالية، والأحمال الثقيلة، والمناخ القاسي. للتخلص من الأضرار والفشل المبكر، يبحث هذا البحث في تأثير إضافة ألياف الزجاج والحديد، والبازلت في الخلطات الإسفلتية وتقييم خصائصها مقارنة بالخلطات الخالية من الألياف. تم استخدام اختبار مارشال واختبار نسبة قوة الشد لتقييم أداء الخلطات الإسفلتية. تم إنتاج مجموعة من العينات من خلال دمج الألياف الزجاجية، والألياف الفولاذية، والألياف البازلتية بنسبة (٠,١٠٪، ٠,١٥٪، ٠,٢٠٪)، (٠,٢٥٪، ٠,٣٥٪، ٠,٤٥٪)، و (٠,١٥٪، ٠,٣٥٪، ٠,٥٠٪)، على التوالي. أظهرت النتائج تحسنا في استقرار الخلطة، والتدفق، والخواص الحجمية، وقيمة، ونسبة قوة الشد عند استخدام هذه الأنواع من الألياف. تم الحصول على أعلى تحسن في استقرار مارشال ونسبة قوة الشد عند ٠,١٠٪ من الالياف الزجاجية بنسبة ١٤٪ و١١,٥٪، عند ٠,٢٥٪ من الالياف الفولاذية بنسبة ١٦٪ و١٠٪، وعند ٠,١٥٪ الالياف البازلتية بنسبة ٨٪ و١٤,١٪ على التوالي في مقارنة بخليط التحكم. لذلك، يمكن استخدام الألياف كمعدل مناسب للخلطات الإسفلتية لتحسين أداء الرصف المرن مع اضافة مثلى بمقدار ٠,١٠٪ للألياف الزجاجية، ٠,٢٥٪ للألياف الفولاذية و٠,١٥٪ للألياف البازلتية بالنسبة الى الكتلة الاجمالية للخلطة.

الكلمات الدالة: الألياف، عملية الخلط الجاف، مخاليط الألياف الأسفلتية، الخلطة الإسفلتية الساخنة، خصائص مارشال، نسبة مقاومة الشد.

1.INTRODUCTION

Hot mix asphalt (HMA) represents one of the fundamental components of flexible pavement systems [1,2]. Flexible pavements are characterized by driving comfort, low noise recyclability, and cost-effectiveness; therefore, they are widely utilized in constructing airports and roadways [3]. The HMA layer consists of asphalt binders and high-quality aggregates to withstand different distresses of the pavement, like cracking and rutting. Traffic and environmental conditions affecting flexible pavement performance include increased freeze-thaw cycles, tire pressures, and high traffic volumes [4,5]. HMA layers are influenced by various factors and can be divided into three categories: environment, traffic, and materials. Many studies looked for improved asphalt mixture materials that could decrease or even prevent the increase in flexible pavement deterioration and enhance the properties of HMA [6,7], especially when traditional HMA mixes are not designed according to pavement structure, environment, and traffic [8]. One method used in HMA design to improve the performance of flexible pavements is adding fibers [4] due to their excellent reinforcing effects and easy manufacturing processes [9]. Adding fibers raises the mixture's permanent deformation resistance and stiffness, decreases fatigue cracking, and increases the tensile resistance [10-12]. Furthermore, fibers reinforce the polymer mixtures in different manufacturing techniques [13,14]. Fibers improve the mixture's performance by enhancing the adhesion and reducing road maintenance costs [10]. Consequently, numerous researches have studied the effectiveness of adding fibers to HMA, such as carbon, glass, basalt, steel, polypropylene, aramid, and others [15–20]. Shukla et al. [21] studied the impact of glass fiber (GF) on asphalt mixture characteristics. The findings demonstrated that GF increased the stiffness and improved the permanent deformation resistance of asphalt mixes compared to conventional mixtures. Moreover, GF had a high tensile strength, increasing the asphalt mixture's indirect tensile strength (ITS). Al-Ridha et al. [22] assessed the impact of including steel fiber (SF) in the asphalt mixture. The Marshall test was conducted using different SF ratios (0.1%, 0.2%, 0.3%, and 0.4%). The findings showed that adding SF at 0.1% and 0.2% provided the highest increase in Marshall stability values compared to the control mixtures. However, increasing SF content decreased the Marshall stability, increasing voids in the mixture. Nevertheless, when the compaction increased, this percentage increment decreased. Among the new fibers applied in civil engineering are basalt fibers (BFs), one mineral fiber with a suitable temperature range for mixing, high elastic modulus, high tensile strength, environmental compatibility, and low water absorption. This fiber is more durable than ordinary GF and costs less than aramid and carbon fiber, which are more resistant [23]. Morova [24] examined the efficiency of incorporating BF into HMA mixtures. The results demonstrated that utilizing BF in HMA enhanced stability, and the optimal proportion of BF and asphalt binder content were 0.5% and 5%, respectively. Moreover, utilizing BF significantly improved the adhesion between aggregates to a certain extent. The main goal of this research is to use BF in asphalt mixtures for flexible pavements due to the limited use of BFs in local studies and then compare the performance of the BF-asphalt mixture with other types of mixtures, i.e., control asphalt mixture, SF-asphalt mixture, and GF-asphalt mixture. SF and GF are the most common fibers in the local mixture. The percentages used were 0.25%, 0.35%, and 0.45% for SF, 0.10%, 0.15%, and 0.20% for GF, and 0.15%, 0.35%, and 0.50% for BF. To evaluate the HMA performance and obtain the optimal content of each type of fiber, the asphalt mixture modified with fibers was tested and comprehensively analyzed using the Marshall and moisture susceptibility tests.

2.MATERIALS

2.1.Asphalt Cement

In this study, the asphalt cement was obtained with a grade of 40/50 from the Al-Daurah refinery in Baghdad. Table 1 provides asphalt's physical characteristics.

2.2.Coarse and Fine Aggregates

The coarse crushed aggregate and fine aggregate were brought from the Al-Nibaie quarry. According to the specification limit [25], the fine aggregate in this study ranged between passing sieve No. 4 and retaining sieve No. 200. The coarse aggregate sizes for the surface course Type IIIA varied between sieve No. ¾ in and sieve No. 4. Aggregate properties were determined through laboratory tests. Table 2 shows the results of these tests, while Table 3 shows the selected aggregate gradation, and Fig. 1 shows the gradation curve of the aggregate used for the wearing course.

Table 1 Asphalt Cement Properties.

Test	Unit	ASTM Designation	Asphalt Binder (40-50)	General specification for roads and bridges [25]
Penetration	1/10 mm	D-5	47	40-50
Flash Point	ºC	D-92	245	232 Min
Specific Gravity	-	D-70	1.02	--
Ductility	cm	D-113	150 >	>100
Softening Point	ºC	D-36	51.6	--

Table 2 Course and Fine Aggregates Properties.

Property	Specification	Fine Aggregate	Coarse Aggregate
Bulk Specific Gravity	C-128, C-127	2.632	2.612
Water Absorption, %	C-128, C-127,	0.98	0.24
Percent Wear (Los Angeles Abrasion), %	C-131	-	15

Table 3 Aggregate Gradation.

Sieve size	Sieve Opening (mm)	Selected Grade	Requirement Limits [25]
3/4"	19	100	100
1/2"	12.5	95	90-100
3/8"	9.5	83	76-90
No. 4	4.75	59	44-74
No. 8	2.36	43	28-58
No. 50	0.3	13	5-21
No. 200	0.075	7	4-10

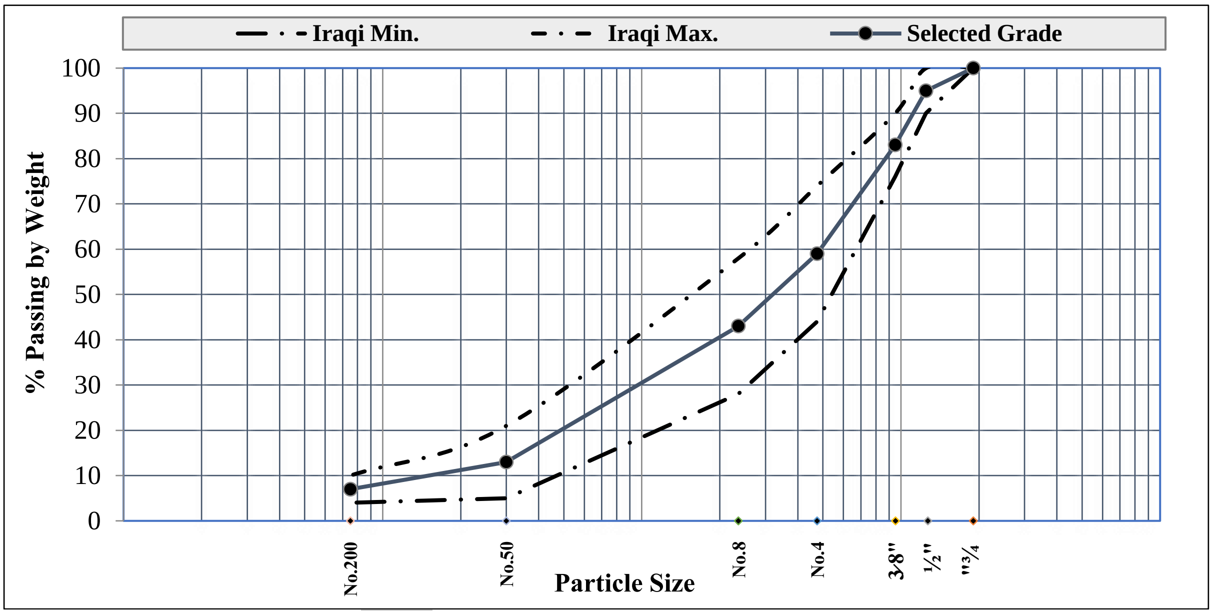

Fig. 1 Gradation Curve of Wearing Layer.

2.3.Mineral Filler

For this study, limestone dust was brought from Heet, Iraq. A filler is a non-plastic substance used to prepare an asphalt mixture and passes through sieve No. 200.

2.4.Fibers

Three inorganic fibers were utilized in different proportions: SF, GF, and BF bought from the Haining Anjie Composite Material Company in China. It was observed in the previous studies reported in the Introduction that the optimal content of SF, GF, and BF for asphalt mixtures were (0.2–1) %, (0.1-0.3) %, and (0.1-0.6) %, respectively. In this research, three contents for each fiber were used as follows: (0.25%, 0.35%, and 0.45%), (0.10%, 0.15%, and 0.20%), and (0.15%, 0.35%, and 0.50%) for SF, GF, and BF, respectively, by weight of the total mix. GF is an inorganic fiber that has a silica concentration of more than 50% [26]. It has high tensile strength, good resistance to high temperatures, fatigue performance, and water stability [27]. In addition, GF is low-cost and simple availability of the raw materials [28]. All these characteristics justify their use and make GF an efficacious material for reinforcing the asphalt mixture [29]. SF is the predominant type of metal fiber, made from steel wire [28, 30]. SF is characterized by its tensile strength and adhesive strength, making it a suitable option for enhancing asphalt mixtures [31]. Its good characteristics can have significant technical, environmental, economic, and social advantages [28]. BF is a high-performance inorganic fiber manufactured from natural basalt stone. Basalt is renowned for its thermal stability, strength, durability, and safety [32]. The production method of BF does not involve using chemical additives and requires a reduced quantity of energy [33]. Furthermore, there is an absence of any release of wastewater, gas, or slag. Therefore, BF is environmentally friendly [10]. BF and SF can be better dispersed in asphalt binders due to their composites with the help of carboxymethyl cellulose [28]. The fibers employed are depicted in Fig. 2, and Table 4 shows their properties. The properties of fibers, i.e., SF, GF, and BF, in Table 4 were tested by Haining Anjie Composite Material Company in China.

Table 4 Fibers Properties.

Steel Fiber Properties		
Property	**Unit**	**Detail**
Length	mm	13 + 1.2
Diameter	µm	20± 0.02
L/D (length-diameter ratio)	-	60 ± 6
Tensile strength	MPa	≥2850
Bending property	-	3mm /90°
Basalt Fiber Properties		
Property	**Unit**	**Detail**
Length	mm	16
Filament diameter	µm	13
Moisture content	-	≤ 0.2%
Tensile strength	MPa	≥ 1200
Elongation	-	≤ 3.1%
Tensile modulus	GPa	≥ 75
Glass Fiber Properties		
Property	**Unit**	**Detail**
Nature	-	Alkali Resistant Glass (AR-Class)
Appearance	-	Opaque
Specific gravity	g/cm³	2.68
Length	mm	12
Tensile strength	MPa	1700
Chemical resistance	-	Very High
Softening point	°C	860
Modulus of elasticity	GPa	72
Absorption	-	Nil


(a) (b) (c)

Fig. 2 Fibers: (a) Steel Fiber, (b) Basalt Fiber, and (c) Glass Fiber.

3.EXPERIMENTAL WORK

The testing program consists of the Marshall Test and the tensile strength ratio (TSR) test. The Marshall method was utilized to determine the optimum asphalt content, stability, and flow characteristics for controlling asphalt mixtures as well as for asphalt mixtures modified with fibers. The samples' susceptibility to moisture was assessed by employing the tensile strength ratio.

3.1.Mixing of Fibers and HMA

One of two mixing processes, dry or wet, is usually used to scatter the fibers in HMA mixtures [34–36]. The wet blending process depends on the addition type and nature. In wet blending, the additive and aggregates may be blended before the binder is added [11, 35–37] or after the binder and aggregates have been combined to create solids [11]. The fiber is mixed with the aggregate before adding the asphalt binder in a dry process, usually preferred over the wet process. Moreover, the dry blending method has been frequently used in field research on the production of fiber-modified asphalt mixtures, probably because fiber agglomeration in the dry method is the weakest, is relatively simple, and fibers mixed straight into the asphalt produce problems in fiber uniformity and that effect badly on mixture performance [11]. Furthermore, the fiber oil absorption in the wet method is more than that of the dry method, leading to errors in asphalt binder content calculations [35]. In the dry mix method, the fiber agglomeration must be avoided as much as possible to achieve the best uniform fiber distribution throughout the asphalt mixture. To solve this problem, the total mixing time of the fiber-asphalt mixture should be longer than the time required for mixing the conventional mix (without fiber).

3.2.Marshall Test

For preparing the control mix, Marshall test ASTM D6927-15 [38] was followed, compacting, and testing of specimens. The aggregate was sieved and mixed for each sample according to grading surface course type IIIA. Then, asphalt cement and aggregates were heated to 163°C and 155°C, respectively, for about 2 hours before mixing. Asphalt cement was added with different asphalt contents, i.e., 4, 4.5, 5, 5.5, and 6%, by the total weight of the mix in the required quantity for hot aggregates and mixed until the asphalt cement coated all the combined aggregate. The modified mixtures were prepared using the dry mixing method by adding fibers to the combined aggregate in different proportions and mixing. Finally, asphalt was added to the mix (fibers and aggregate) and blended until the asphalt binder covered all the particles of the aggregate and fibers. Then, the hot mixture was poured into the preheated to 130°C-heated molds, which measured 64 mm in height and 102 mm in diameter. Using a standard hammer, each side was compacted with 75 blows and left for 24 hours in the mold to cool. Figure 3 shows the Marshall testing method for the control and modified mixes.

3.3.Moisture Damage Test

Moisture damage in asphalt pavement is primarily attributed to two mechanisms: the reduction in adhesion between the asphalt and the aggregate, as well as the reduction in cohesion within the mixture [39, 40]. The tensile strength ratio (TSR) based on ASTM D-4867 was tested to evaluate the moisture damage resistance for compacted mixes. For this test, a set of Marshall samples was made for each type of fiber. In brief, the set was split into two groups: the unconditioned group was soaked in a water bath at a temperature of 25±1 °C for 20 minutes, while the conditioned group underwent a single cycle of freezing and thawing followed by being soaked in the water bath at a temperature of 25±1 °C for one-hour. Subsequently, the two groups were tested at a 50.8 mm/minute loading rate by the Versa tester apparatus until the maximal load was reached and the sample fractured, as depicted in Fig. 4. TSR must be a minimum of 80%. Utilizing the Eqs. (1) and (2) below, the TSR value may be determined:

$$ITS = \frac{2000\,P}{\pi\, t\, D} \quad (1)$$

$$TSR = \frac{TSR_{cond.}}{TSR_{uncond.}} * 100 \quad (2)$$

Fig. 3 Marshall Test.

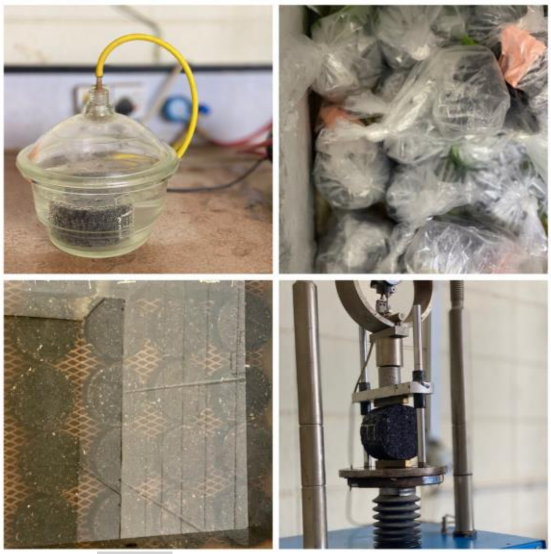

Fig. 4 Moisture Damage Test.

4.RESULTS AND DISCUSSION

In this study, two asphalt mixtures were created: the control mixture, which is a standard mixture without fibers, and the fiber-asphalt mixture, which is a standard mixture with adding fiber, i.e., steel, glass, or basalt, at different percentages.

4.1.Marshall Parameters

Five ratios for asphalt cement, between 4 and 6% by mass of the mixture with an increase of

0.5%, were employed to prepare the Marshall samples. Three Marshall samples were prepared for each asphalt ratio to find the optimum asphalt content (OAC). The OAC was 5% for the control mixture and used for the fiber-asphalt mixtures to test the effect of adding fibers to the control mix on the HMA's performance without adding any extra amount of asphalt, which increases the total cost of flexible pavement production. Then, the fiber-asphalt mixture samples were prepared by percentages of (0.25%, 0.35%, 0.45%), (0.10%, 0.15%, 0.20%), and (0.15%, 0.35%, 0.50%) for SF, GF, and BF, respectively. The results in Fig. 5 show that the fiber-asphalt mixture has higher Marshall stability than those without fiber. Adding 0.25%, SF increased Marshall stability by 16% more than the control HMA. This improvement is due to well-distributed SF in various directions in the asphalt mixture and linked the adjacent cracks through the bridging impact that delayed the development of the cracks [22]. However, hereafter, increasing the content of SF caused a deterioration in Marshall stability. Therefore, the Marshall stability of 0.45% SF decreased to about 8% less than the stability for the control HMA. Some fibers may clump with each other, which becomes more pronounced, especially when the fiber dosage increases in the asphalt mixture, which may decrease the Marshall stability, causing internal voids in the mix to increase, which causes a weak point in the specimen and decreases stability. Furthermore, the surface area of the fiber-asphalt mixture increased because high amounts of fibers absorb more asphalt, and the OAC reduced, causing a drop in stability. Compared to the control HMA, all GF-asphalt mixtures had higher Marshall Stability. The Marshall Stability increased by 14% with 0.10% GF. However, as can be observed, the increase in stability for the GF-asphalt mixture was lower than for those with SF. This difference in Marshall Stability values may be due to the material properties that constitute each type of fiber, as the impact of the chemical characteristics of fibers should be addressed. Finally, Marshall Stability results for GF-asphalt mixtures were analyzed, and the optimal GF content was 0.10%. These findings concurred with those of an earlier investigation [41]. Also, the present study came to similar conclusions to Mahreh and Karim [42], which showed that asphalt mixtures with more than 0.2% glass fiber had a lower performance. BF was the least effective fiber in the Marshall stability, as adding 0.15% of BF increased by 8% more than the control mixture. After that, the stability value decreased when adding a higher percentage of BFs (0.35 and 0.5%). This increase led to agglomeration of the BF within the mixture, causing a decrease in stability. According to Marshall stability's findings, BF's best content was 0.15% by mass of mix, which disagrees with the results of Morova [24], who found that the best BF ratio was 0.5%. The anti-crack resistance property is always better with asphalt mixtures with higher Marshall Stability [43]; therefore, asphalt mixtures modified with fibers are more effective in increasing service life and enhancing flexible pavement performance. Another reason is that the fiber in the asphalt mixture's structure plays a "bridge" role and prevents cracks from developing. Figure 6 illustrates the flow values for control and fiber-asphalt mixtures. Flow is the sample deformation rate at the moment of failure. The flow value for all asphalt mixtures modified with fiber (except for the BF addition at 0.15%) increased continuously with fiber content compared to the control mixture because fibers induce bonding and adhesion of different parts of the sample with each other and cause more deformation to appear at the time of failure. The flow value extended from 3.7 mm at 0.10% GF content to 4.1 mm at 0.2% GF content, which exceeds the maximum limitation of flow (4 mm).

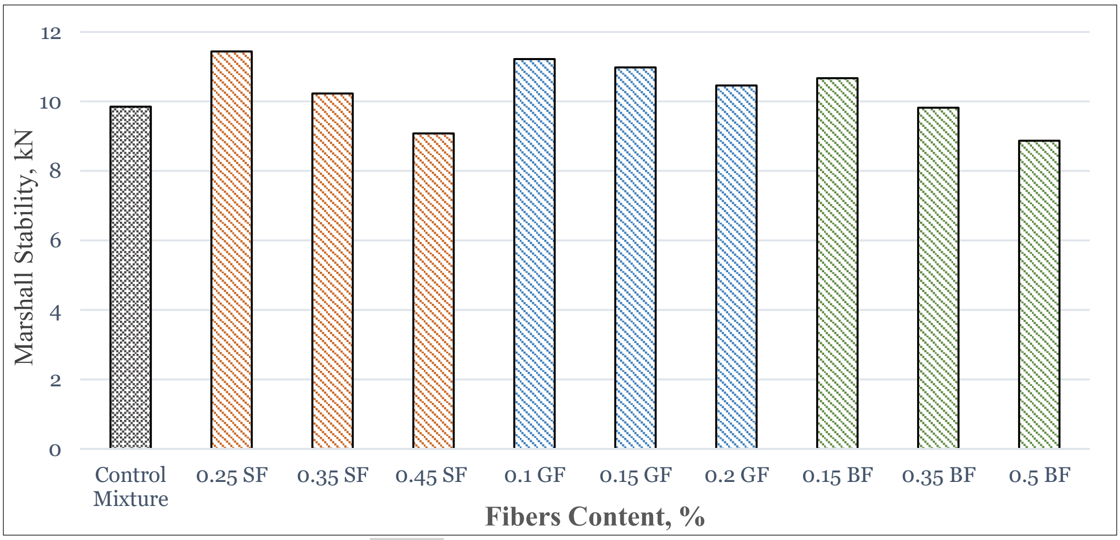

Fig. 5 Marshal Stability Results.

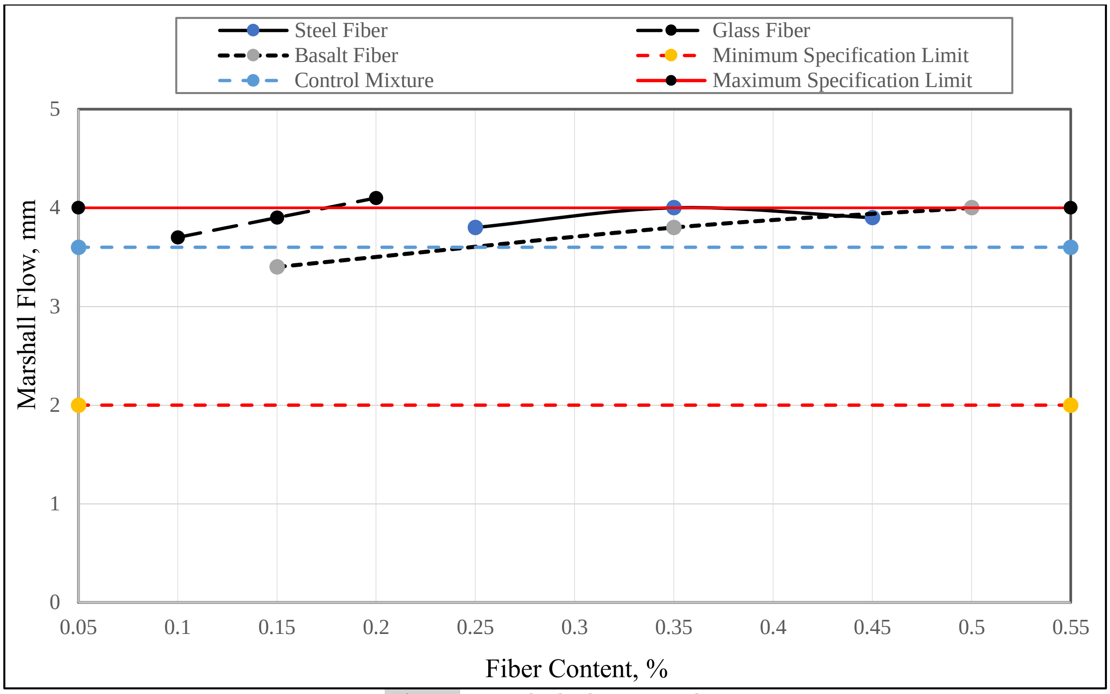

Fig. 6 Marshal Flow Results.

Table 5 shows that the bulk unit weight decreased slightly for all fiber-asphalt mixtures when the percentage of fibers increased. Fibers had a small density and occupied a certain space. For the same volume of Marshall specimens, the weight of the asphalt mixture reinforced by fiber was lower than that of the conventional asphalt mixture, decreasing the unit density of the fiber-asphalt mixture. Therefore, under the same compaction condition, the structure of the fiber-asphalt mixture was less dense than the control HMA. The values of voids in the mineral aggregate (VMA) increased with fiber contents, as illustrated graphically in Fig. 7. According to the specification limits, the VMA% value must be higher than 14% for the surface course to get stable mixtures and sufficient durability. This increase in VMA is due to the decrease in the bulk-specific gravity. As shown in Fig. 8, all the fiber-asphalt mixtures caused higher voids in the total mixture (VTM) than the control mixture (4.1%). When fiber content increased, the compressing of the mixtures became harder, and the fiber-asphalt mixtures required a higher asphalt binder content, i.e., more than 5%, due to the increase of the air void values. From this outcome, the SF-asphalt mixture was more difficult to compact than the Bf-asphalt mixture. As a result, the VTM for the SF-asphalt mixture was more than that of the Bf-asphalt mixture. In high temperatures, high VTM values increased the asphalt mixture's ability to prevent bleeding. Figure 9 displays the experimental results of voids filled with asphalt (VFA) for control and fiber-asphalt mixtures. The findings indicated that when fiber content was increased in the mixtures, voids filled with bitumen decreased because the asphalt content of the mixture decreased due to the fiber clusters increasing at high fibers' contents and absorbing more asphalt. Therefore, the asphalt became inadequate to cover all the voids.

Table 5 Unit Weight Results.

Mixture Type	Fiber Type	Fiber Content, %	Unit Weight, gm/cm3
Control	Without Fiber	0.00	2.343
Fiber-Asphalt	Steel Fiber	0.25	2.312
Fiber-Asphalt	Steel Fiber	0.35	2.306
Fiber-Asphalt	Steel Fiber	0.45	2.299
Fiber-Asphalt	Glass Fiber	0.10	2.305
Fiber-Asphalt	Glass Fiber	0.15	2.302
Fiber-Asphalt	Glass Fiber	0.20	2.297
Fiber-Asphalt	Basalt Fiber	0.15	2.314
Fiber-Asphalt	Basalt Fiber	0.35	2.31
Fiber-Asphalt	Basalt Fiber	0.50	2.304

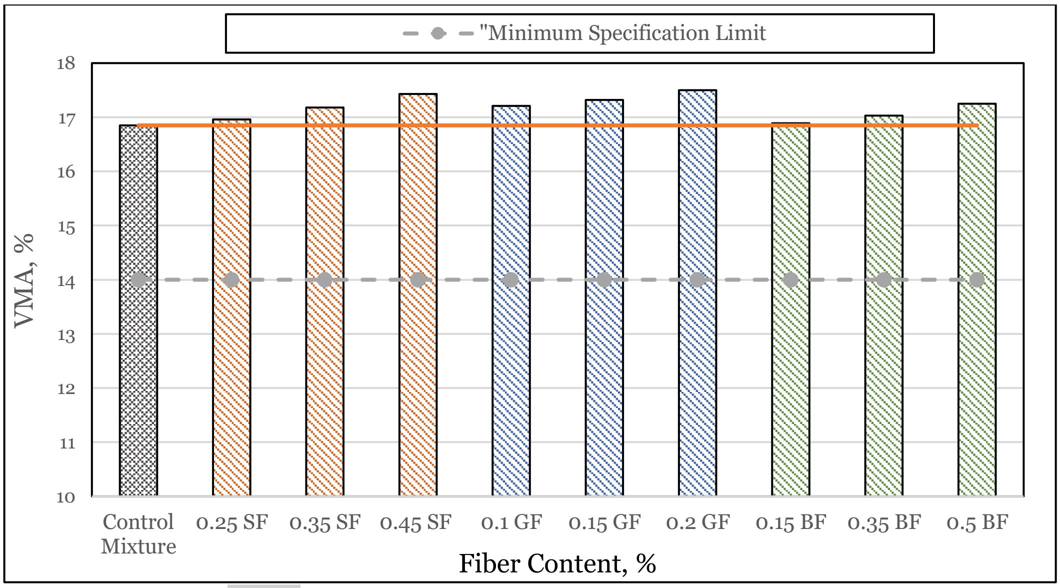

Fig. 7 VMA of Control and Fiber-Asphalt Mixtures.

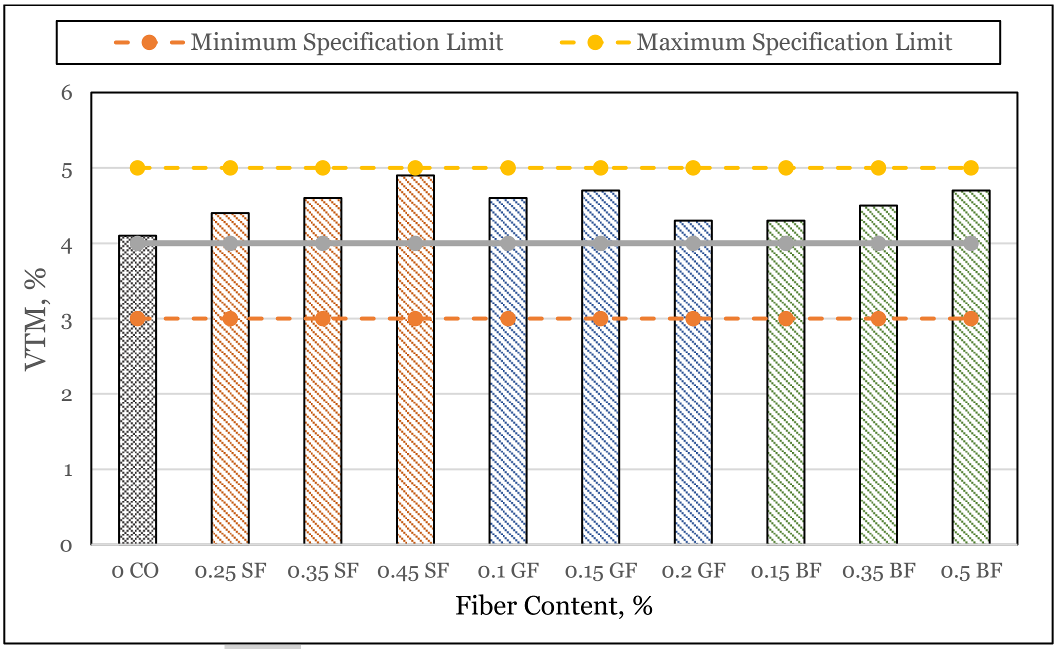

Fig. 8 VTM of Control and Fiber-Asphalt Mixtures.

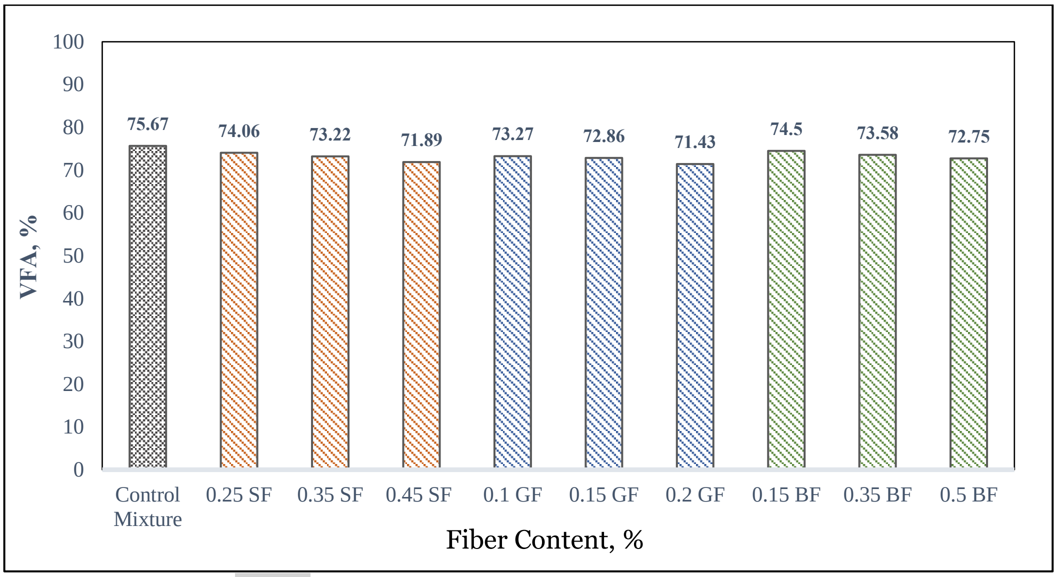

Fig. 9 VFA of Control and Fiber-Asphalt Mixture.

4.2.Moisture Damage Resistance

Fibers increase the tensile strength of HMA, and they are very effective during the fatigue and fracture stages of HMA because the strain is more absorbed in these stages. Figs. 10 and 11 show a rise in indirect tensile strength (ITS) for dry and wet specimens of SF and GF compared with the control mixture; however, a decrease appeared in the ITS value with adding BF (except for adding 0.15% in the wet condition). The ratio of the wet to dry value produced the indirect tensile value (TSR), as illustrated in Fig. 12. According to the TSR results for fiber-asphalt mixtures, BF (0.15% addition) produced the highest TSR with 92.5%, followed by GF (0.1% addition) at 90.4%, and finally SF (0.25% addition) at 89.2%. The TSR for the control mixture was 81.1%, which is less resistant to water damage than fiber-asphalt mixtures. The value of TSR significantly decreased as the fiber content increased because incorporating more fibers leads to uneven dispersion of the fibers and excessive porosity in the mixture, which lowers the moisture resistance of fiber-asphalt mixtures. According to ASTM D-4867 (2014), TSR must be at least 80%, indicating adequate moisture resistance [44]. The BF-asphalt mixture had the highest TSR. This phenomenon is primarily caused by the alkaline and acidic surfaces of asphalt and BF, respectively. Furthermore, BF has a large specific surface area. BF absorbed the light components in asphalt, thickened the asphalt film, and strengthened the bond between aggregate and asphalt, which are advantageous for preventing moisture from penetrating the asphalt-aggregate interface [45]. According to the experimental results, the TSR for the BF-asphalt mixture at 0.15% addition of BF was 14.1% higher than that of the control mixture. The previous results did not comply with the recommendation of Hui et al. [46], who stated that adding BF at a range of 0.2-0.4% achieved the best water resistance performance.

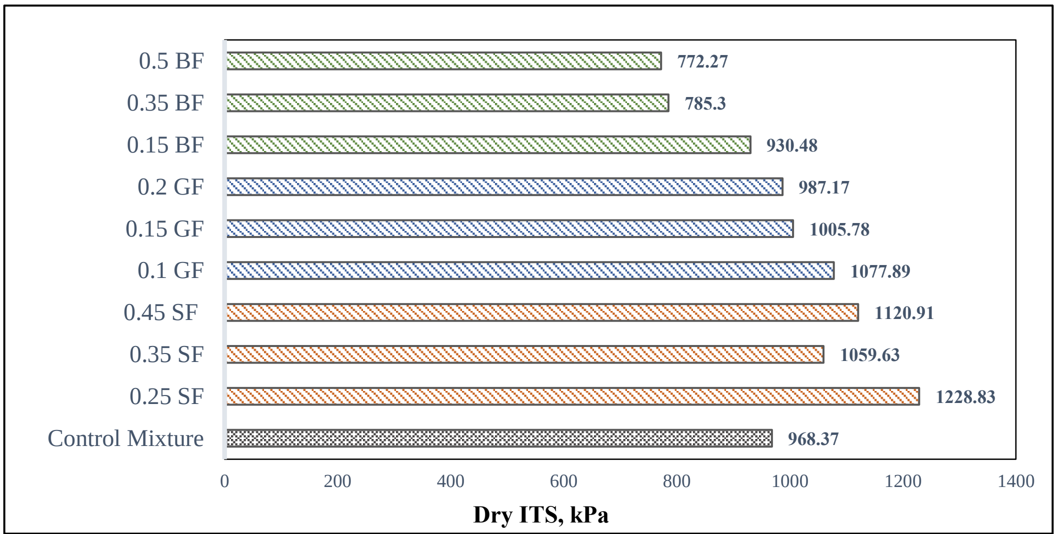

Fig. 10 ITS Results for Dry Condition.

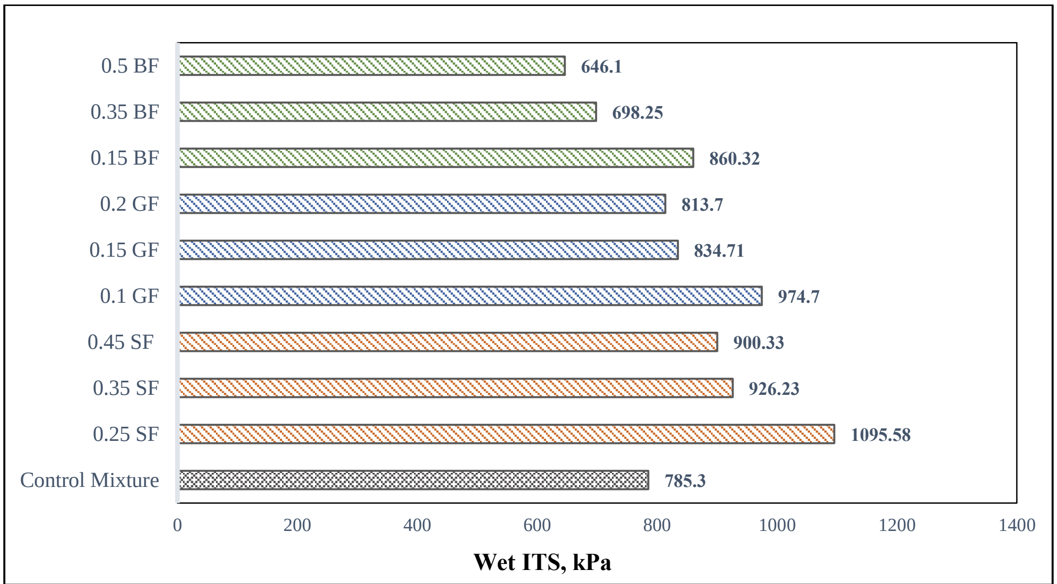

Fig. 11 ITS Strength Results for Wet Condition.

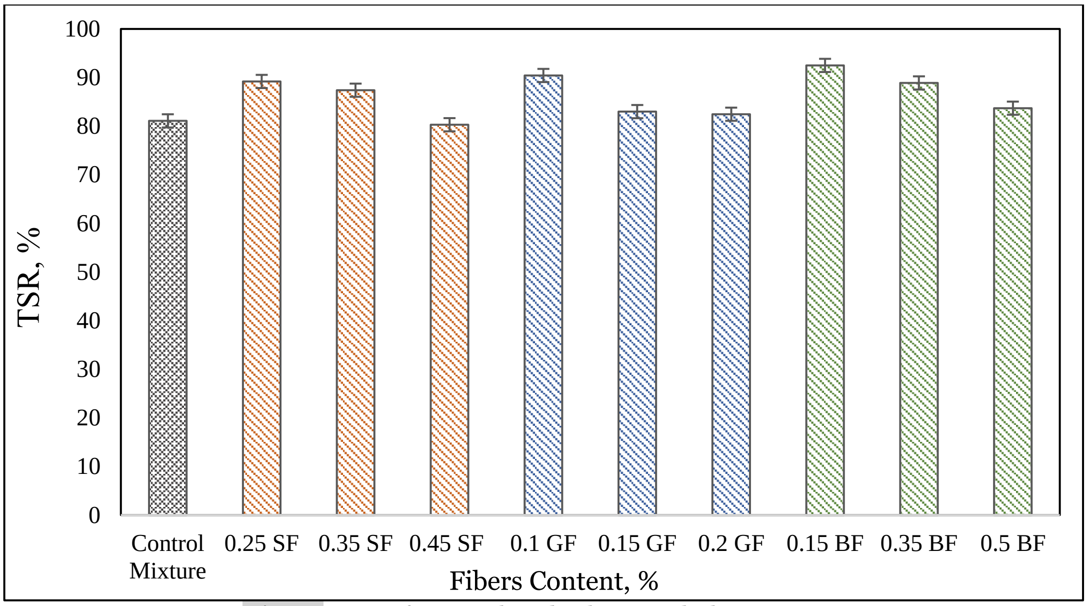

Fig.12 TSR of Control and Fiber-Asphalt Mixtures.

5.CONCLUSIONS

The present study evaluates the performance of asphalt mixtures modified with steel, glass, and basalt fibers. The following findings were found:

- Marshall stability increased when fiber was added to the asphalt mixtures (except the SF at 0.45%, and BF at 0.35%, 0.50% where stability dropped). The highest improvement was obtained by 16.14% when adding 0.25% of SF, while GF increased by 14% when included at a rate of 0.10%. On the other hand, BF recorded the lowest increase by 8.32% at a content of 0.15%.
- Fibers continuously increased the flow value for all asphalt mixtures (except Adding BF at 0.15%) as fiber content increased compared to the control mixture. The highest increase in flow was obtained at 0.20% of GF, reaching 4.1 mm, exceeding the maximum flow limitation, according to Iraqi road specifications.
- The TSR value increased with adding fibers (except for adding SF at 0.45%). The highest TSR value was achieved at rates of 80.3%, 90.4%, and 92.5% when adding SF, GF, and BF by 0.25%, 0.10%, and 0.15%, respectively.
- The findings indicated that 0.25% of SF, 0.10% of GF, and 0.15% of BF achieved the highest Marshall stability, TSR, and acceptable volumetric properties according to Iraqi specification roads. Despite additional costs, the significant advantages gained from reducing maintenance costs justify the value of utilizing such fibers.

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NOMENCLATURE

ITS	Indirect tensile strength, kPa
P	Failure load, N
D	Specimen diameter, mm
t	Specimen height, mm.
TSR	Tensile strength ratio, %
$TSR_{(cond.)}$	Average tensile strength of the conditioned sample, kPa
$TSR_{(uncond.)}$	Average tensile strength of the unconditioned sample, kPa.

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