

Research Article

Sozan S. Rasheed*, Maha H. Nsaif and Ahmed S. Abduljabbar

Experimental study of improving hot mix asphalt reinforced with carbon fibers

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Abstract: Using hot asphalt mixtures (HMAs) is very common in flexible pavement construction due to its mechanical properties of durability, water resistance, and riding comfort. It proved to substantially reduce the applied stresses from vehicular traffic to subgrade. However, these types of pavements can undergo different types of distress such as cracks and rutting, which could be the result of weak mixing of the asphalt mixture and/or increasing traffic volumes. Therefore, the need to improve the mechanical properties of hot mix asphalt mixtures using different additives and modifiers was raised. Different materials have been recently used to reinforce asphalt concrete. For the construction of road pavements, using fibers in a HMA has emerged as a significantly more appealing option due to their strengthening properties. The alteration of asphalt binder is expected to benefit from carbon fibers (CFs) more than other types of fiber. In this study, an experimental study is carried out to investigate the effects of adding CFs to the asphalt mixtures with grades of (40–50) which comply with the Iraqi specifications. Twelve Marshall specimens were tested for stability and flow, 24 specimens for moisture failure testing, and two specimens for the rutting resistance of the asphalt mixture. The optimum bitumen content of 5.0% was used to prepare all the specimens. Different percentages of CFs by weight of asphalt (0, 0.2, 0.4, and 0.6%) were implemented to study the performance of paving mixtures. The way to mix the disperse the CFs homogeneously is by dry state (after separating the fibers manually) for 10 min, and then the asphalt was added; the mixture was heated to 165°C and mixed for at least 20 min. The results

showed that the optimum properties of the HMA were reached by adding 0.4% CF to the HMA. Marshall stability was increased by 48%, the flow was decreased by 23%, and in addition, rut depth was reduced by 50%. The unit weight and the percentage of air voids in the mix were maintained and, along with other mix properties, are preserved within acceptable limits. Moreover, the indirect tensile strength has increased by 88.6%. Furthermore, moisture susceptibility reached 88%. Therefore, the addition of 0.4% CFs improved the performance of HMA at a high temperature of 60°C, which is close to the paving temperature in Iraq, by reducing the rutting of the asphalt mixture, which is considered the most dangerous tiling problem in Iraq. By improving the performance characteristics of asphalt mixture, the durability of the pavement will increase, and the riding will be more comfortable.

Keywords: carbon fiber, reinforcing, durability, moisture resistance, rutting resistance

1 Introduction

Road pavement cannot consistently maintain acceptable quality standards, especially when subjected to intense environmental influences, for example, load deformation and the impact of seasonal temperature variations. As a result, the lifespan of the pavement is reduced [1,2]. The major factors of asphalt pavement failure – cracks, rutting, and fatigue – are a lack of mixing characteristics and/or heavy traffic loads [3,4]. Numerous researchers investigated the enhancement of bitumen performance using different additives, such as asphalt rubber, fly ash, red mud, carbon black, polymers, sulfur, and bottom ash [5]. Some studies investigated the effect of adding fiber reinforcement to asphalt concrete to enhance its mechanical characteristics [6]. Four different types of fibers have recently been added to asphalt–concrete mixtures to determine the ideal type and the optimum amount of fiber to be used to improve the mechanical properties of the mixture. [7]. Another study showed that, by adding polypropylene and polyester fibers and carbon fibers (CFs), the properties of

* **Corresponding author: Sozan S. Rasheed**, Civil Engineering Department, College of Engineering, University of Technology, Baghdad, Iraq, e-mail: bce.20.23@grad.uotechnology.edu.iq

Maha H. Nsaif: Civil Engineering Department, College of Engineering, University of Technology, Baghdad, Iraq, e-mail: 40273@uotechnology.edu.iq

Ahmed S. Abduljabbar: Civil Engineering Department, College of Engineering, University of Technology, Baghdad, Iraq, e-mail: 40095@uotechnology.edu.iq

the asphalt mixture can be improved. However, CFs introduced the best enhancement by increasing flexural strength, strain capacity, and toughness. These conclusions were consistent with those made by the research done by Yoo *et al.* [8]. Fibers have given this material less deformation and more durability, leading to more ductile behavior [9]. These fibers provide more strength and rigidity to the composites, enabling the matrix to distribute loads across the fibers. Additionally, fibers were included to improve the quality of asphalt mixtures, increase sustainability by extending the service life, and reduce the frequency of road maintenance. To solve the main issues with flexible pavement, such as rutting, fatigue cracking, thermal cracking, and raveling, numerous fiber-modified asphalt binders and fiber-modified asphalt mixtures have been developed [10].

Several contents of carbon nanofibers were used by the weight of the asphalt mixture and obtained the optimum asphalt content (OAC) for each one. In this case, the wet procedure was used; a fiber content greater than 0.3% by weight of the mixture increases the stability, reduces the flow number, and increases the void content; likewise, nanofibers absorb part of the binder, thus leading to an increase in the content of voids in the mixture [11].

Furthermore, adding 0.4% nanofiber by weight of the mixture results in higher resistance to permanent deformation, resilient modulus, and fatigue life. Moreover, moisture susceptibility can be improved by adding 1% microfibers by weight of bitumen, which also minimizes the deterioration caused by non-chloride [12]. The optimal type and concentration of fibers to reinforce and enhance the mechanical properties of the asphalt mix were investigated by another study [7].

CFs of a length of 12 mm were used. A dry method was adopted to mix them with asphalt concrete. The authors reported that adding 1% fibers increases the flexural strength and the toughness value of the asphalt concrete by 12.1 and 65.5%, respectively, when compared to a mixture without fibers.

From previous studies, it can be concluded that the CFs can offer more advantages than other fiber types for the modification of asphalt mixture. Since the fibers are composed of carbon and asphalt is a hydrocarbon, they are thought to be inherently compatible. On the other hand, CFs are produced from either polyacrylonitrile or pitch precursors; it was observed that adding fiber does affect the properties of asphalt mixtures, i.e. an increase in its stability and a decrease in the flow value with an increase in voids in the mixture. The results indicated that fibers have the potential to resist structural distress in pavement, in an increase of traffic loads, and thus improve fatigue by increasing resistance to cracks or permanent deformation.

All the above studies aim to improve the properties of the asphalt mixture, and the results of these studies indicate that low percentages of CF can improve some mechanical properties and improve the performance properties of the mixture and that increasing the percentage of CF is critical to moisture failure.

Despite the availability of these previous studies, it is rare to find research that investigates CF reinforcement using the rutting test, which reflects the real performance characteristic of asphalt mixture.

In Iraq, due to a considerable increase in traffic volume and hard environmental conditions, especially in summer with high temperatures, the roadway pavements are currently suffering from a variety of pavement distresses. Hence, the big challenge is how to extend the life cycle of flexible pavements. From this point, the importance of this study was introduced.

This research is considered one of the first studies to include using CF for improving the performance characteristics of the asphalt mixture at a high temperature of 60°C, which is close enough to the paving temperature in Iraq, by examining the rutting of the asphalt mixture.

2 Materials and methods

2.1 Asphalt binder

To prepare the hot mix asphalt, a bitumen with a penetration grade of 40–50 or a performance grade of 70–16 is brought from the Al Durah refinery in Baghdad. The specific gravity of this substance is 1.032, and its physical characteristics are listed in Table 1.

2.2 Aggregates

Hot asphalt mixture (HMA) samples were prepared using coarse and fine aggregates, as shown in Figure 1. The filler material used is limestone. Table 2 displays the characteristics of aggregates used in research.

2.3 CF

CF or graphite fiber are fibers of 7.5 μm in diameter and composed mostly of carbon atoms. CFs have several advantages, including high stiffness, high tensile strength, low

Table 1: Asphalt binder physical properties of a 40–50 grade of penetration

Test	Test conditions	Criteria	Results	Specification limits as (SCR/B/R9, 2003)
Penetration	100/–25°C, 5 s (0.1 mm)	(ASTM D5) [13]	48	40–50
Ductility	25°C – 5 cm/min	(ASTM D113) [14]	127	>100
Flash and fire point	—	(ASTM D92) [15]	Flashpoint 298°C Fire point 310°C	>232°C —
Rotational Viscosity	Pa s	(ASTM D4402) [16]	@135°C 0.398 @165°C 0.187	—
Softening point	—	(ASTM D36) [17]	53	—

**Figure 1:** Sieve Shaker device and sieving sample.**Table 2:** Physical properties of coarse and fine aggregate

Property	Standard	Results	Specification
Coarse aggregates > 4.75 mm			
Wear% (Los Angeles abrasion)	ASTM C535 [18]	21.2%	30 max.
Soundness (loss by Na ₂ SO ₄) (%)	ASTM C88 [19]	3.3%	10–20 max.
Angularity (%)	ASTM D5821 [20]	98%	95 min.
Flat and elongated particles (%)	ASTM D4791 [21]	0.91%	10 max.
Fine aggregate properties (crushed sand < 4.75 mm)			
Bulk specific gravity	C 128-4 [22]	2.625	—
Apparent spec. gravity	C 128-4 [22]	2.618	—
Water absorption (%)	C 128-4 [22]	0.19	—
Equivalent sand (clay content %)	ASTM D2419 [23]	89.7%	45 min
Deleterious material, (%)	ASTM C142 [24]	1.11	3 (max.)

weight, high chemical resistance, high-temperature tolerance, and low thermal expansion. These properties have made CF very popular in aerospace and civil engineering.

Additionally, CFs are combined with other substances like graphite to create reinforced carbon–carbon composites, which have a very high heat tolerance [7]. CF has a tube

Table 3: Physical properties of CF

Number of filaments	12,001
Yield texture (g/1,000 m)	730
Tensile strength (ksi)	581
Tensile modulus (msi)	37
Elongations (%)	1.7
Density (g/cm ²)	1.9

shape with a consistent distribution. Scanning electron microscope images of HMA containing CF reflect the intricate structure and create a spatial network, enhancing the mechanical characteristics of the asphalt mixture. The integral strength of the asphalt matrix is increased by aggregate sliding at the interface, dispersing and reducing stress concentration.

Table 3 shows the components of CF, while Figure 2 shows its shape.

3 Preparation of specimens

After several attempts to mix the fibers with the asphalt mixture to produce a homogenous mixture, it was found that the proper method is to disperse the CFs by hand first to avoid the clumps between them. Then, raw materials were mixed in a dry state with CF for 10 min, and then the asphalt was added; the mixture was heated to 165°C and mixed for at least 20 min. The CF levels in the earlier investigations were set to vary from 0.3 to 0.8% by weight of bitumen [25,26]. In this study, the CF contents were chosen to be (0, 0.2, 0.4, and 0.6%) as a percent of bitumen weight, with lengths of 12.5 mm. The primary issues of fibers clumping or balling in HMA were reduced by using the dry technique. Bitumen and aggregate were heated to

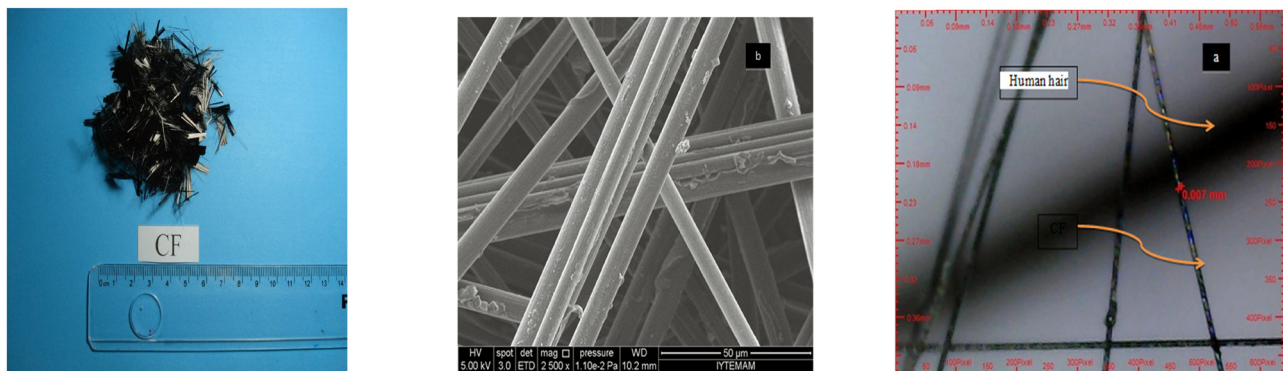
165°C in an oven. Initially, bitumen was added to the CF-aggregate mixture, after which the CF was well-blended with the hot aggregate. Using a Marshall device to compress the produced mixture samples, three triplicate samples of asphalt. Figure 3 shows the preparation of samples.

4 Characterization of the modified asphalt mixtures

The Marshall test is used to identify the characteristics of hot mix asphalt (HMA) of the control and modified mixes. This study employs the Marshall test method to calculate the OAC, and three HMA sample sets were prepared at 4.0, 4.50, 5.0, and 5.50% of asphalt content. Samples are compacted with 75 blows using the standard hammer. The first group of samples is created to evaluate the parameters of the control mix, including the optimal asphalt content, mix stability, flow, unit weight, air voids, voids in mineral aggregates, and voids filled with bitumen. Three more specimens were produced using modified asphalt and various CF percentages to attain the desired mix properties, according to ASTM D6927-15 [27]. Similar sets of modified test specimens were also created using the modified asphalt with the determined OAC and varied CF percentages.

5 Indirect tensile strength samples preparation

The tensile strength test aims to determine the tensile strength or resistance to fracture of samples of asphalt mixture. ASTM D6931-12 [28] method is used to conduct

**Figure 2:** CFs used in the work.

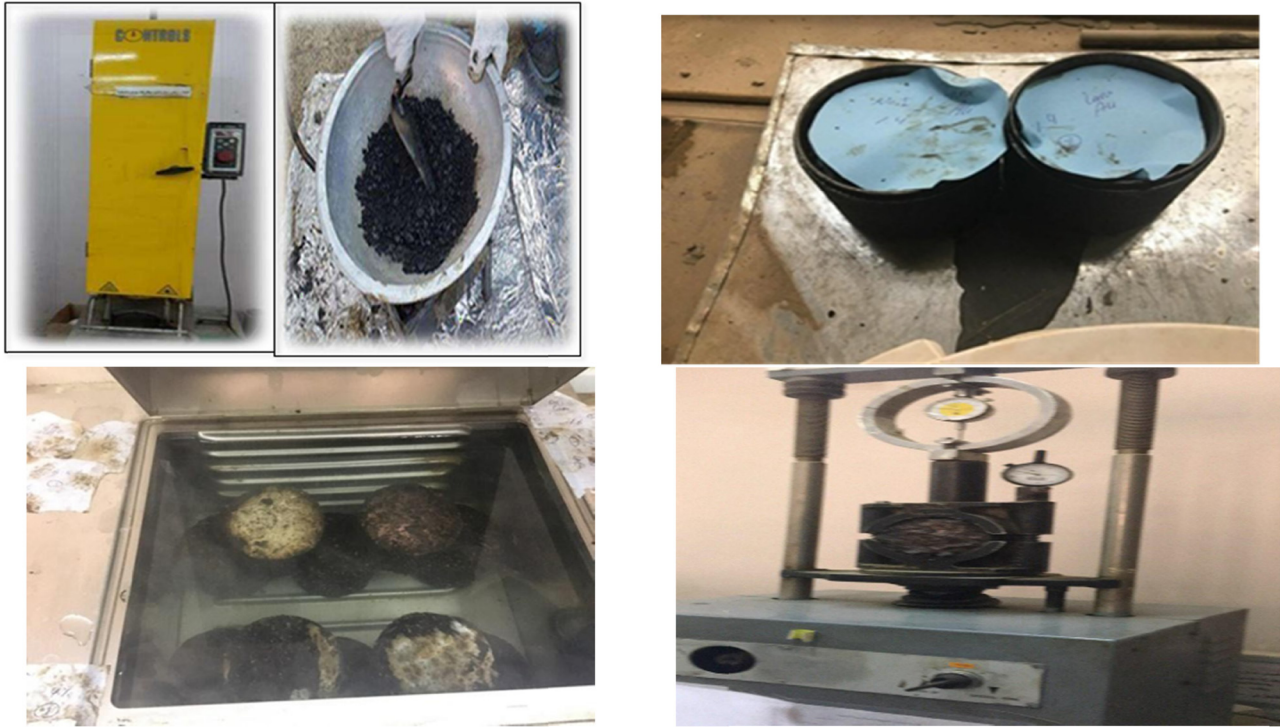


Figure 3: Preparation of Marshall samples.

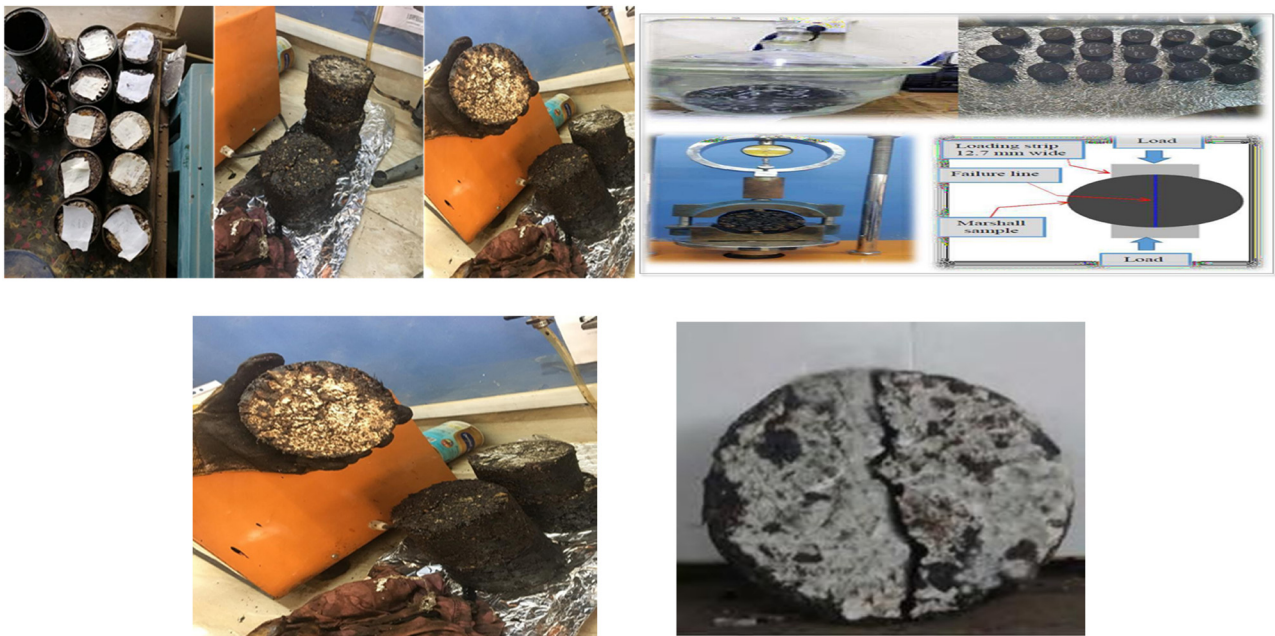


Figure 4: Procedures of the indirect tensile strength test.

the test. The same steps as for the Marshall specimen were used to prepare the samples of asphalt mixture; however, they were immersed in a 25°C water bath for 30 min before being tested for tensile strength. The specimen was then

positioned on the vertical diametrical level (12.7 mm wide) between the two parallel loading bands. For the ITS test, the samples were subjected to a load rate of 50.8 mm/min until they fractured as shown in Figure 4. The maximum

load value is noted when the fracture occurs. The equation below was used to compute ITS value:

$$ITS = 2,000 \times P/(\pi \times D \times T),$$

where St is the tensile strength (kPa), P is the maximum load (N), T is the height of the specimen immediately before test (mm), D is the diameter of the specimen (mm).

6 Moisture susceptibility evaluation

This method indicates that a loss of serviceability has been brought on by moisture. Moisture sensitivity refers to the severity of moisture damage. This test is used to evaluate the mixes' resistance to moisture damage, and the procedure followed ASTM D4867 [29], 2018, and AASHTO T283 [30], 2016. An average value of (ITS) for three specimens was indicated by S_{dry} (ITS for un-conditioned specimens) after placing them at 25°C for 30 min in a water bath. The final three specimens were made by placing them in a 4,000 ml volumetric container filled with water at room temperature (25°C) and applying a vacuum of 3.74 kPa for 5–10 min to achieve a saturation level of 55–80%. Three specimens were indicated by S_{wet} (ITS for conditioned specimens). The samples were first placed at 60°C for 24 h in a water bath, and then they were moved to a water bath at 25°C for 1–2 h S_{wet} . Their indirect tensile strength was then evaluated. The six specimens for each asphalt kind were prepared in a Marshall mold with air gaps ranging from 6 to 8%. A minimum tensile strength ratio of 80% should be included in the combination. The equation below was used to determine the TSR:

$$\%TSR = S_{wet}/S_{dry} \times 100,$$

where % TSR is the indirect tensile strength ratio, S_{wet} is the average ITS for moisture-conditioned samples (kPa), and S_{dry} is the average ITS for un-conditioned samples (kPa).

7 Permanent deformation testing

Rutting is one of the main problems with flexible pavements because of increased pressure, heavy axle loads, and high summer temperatures. In this study, the HMA plates are compacted using roller compacting equipment. According to BS EN 12697-33 [31], at a temperature of 60°C, compacted plates of 300 × 400 × 50 mm were created for each type of mixture with an optimum binder content and (18–22%) air content. The surface of the asphalt mixture specimen is rolled over by a steel wheel (with the required size) bearing an additional force of 705 N (158 pounds). The test temperature is 60°C for all slab specimens to simulate the climatic conditions and the high temperature, especially in Iraq, to which the pavement is subjected during service. The test specimen can be pushed back and forth in a horizontal position under the loaded steel wheel using the wheel-tracking apparatus. When the required number of cycles or the rut depth exceeded the maximum permissible depth, the testing apparatus automatically stopped, if the maximum permitted rutting depth (20 mm) is achieved before reaching 10,000 cycles (20,000 passes). All test details are shown in Figure 5.

8 Results and discussion

8.1 Effect of CF on Marshall stability

According to Marshal's test results, 4.9% bitumen was found to be the optimum percentage for the control mix.



Figure 5: Slab specimens preparation by a roller compactor device.

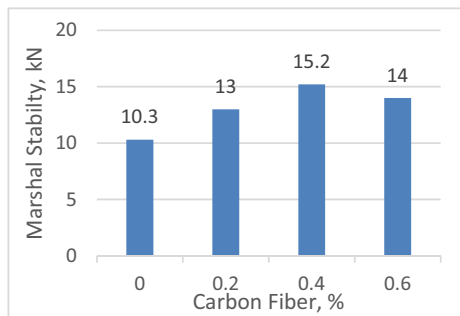


Figure 6: Impact of the addition on stability.

At this percentage, a different content of CF was added to the mixture. Figure 6 shows the effect of adding CF on Marshall stability. It can be seen that the stability increased with the increase in CF until 0.4% of CF. Adding 0.4% boosts the stability by 48% from 10.3 to 15.2 kN. This enhancement in stability can be attributed to the fact that the fibers could create an adhesion network between the mixture components. It is expected that this improvement will lead to a decrease in the rutting susceptibility and plastic deformation of the pavement. However, the mixture of 0.6% CF showed a slight decrease in stability. This could be the result of decreasing the contact area between the aggregate when there is a significant amount of CF. Therefore, adding 0.4% of CF to the mixes can be considered an ideal CF content to achieve higher stability.

8.2 Effect of CF on Marshall flow

It is clear from Figure 7 that Marshall flow significantly decreases by 23% by utilizing CF with the mixes. The decrease in flow values is a reflection of how proper asphalt mixtures can tolerate settlements and changes in subgrade without causing cracking. Also, the flow value reflects the rutting parameter. It may also be deduced

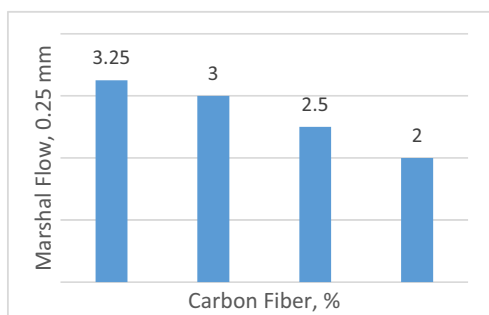


Figure 7: Impact of the addition on flow.

that these mixtures sustain pavement for more extended periods without deforming because of traffic load. The presence of fibers helps to restrain the movement of the asphalt binder and aggregates, resulting in a more rigid and less flow-prone mixture. The decrease in flow due to the addition of CF is often accompanied by an increase in Marshall stability. This means that the mixture becomes more resistant to deformation and rutting, providing better structural integrity and longevity to the pavement. However, although the stability decreased at 0.6%, the flow continued to decrease. High percentages of CFs in the mixture can displace the asphalt binder, reducing the overall asphalt content. A decrease in the asphalt binder content can negatively affect the workability and compaction of the mixture, leading to a decrease in both flow and stability.

8.3 Effect of CF on the density of the mixture

Test results shown in Figure 8 indicate that an increase in CFs resulted in a reduction in the value of bulk density. This can be attributed to the decrease in the contact points between the aggregates when adding a large amount of CF to the mixture. The geometry and length of the CFs can affect AV%. Longer fibers may create larger voids. During the compaction process, CF can influence the distribution of particles and air within the mixture. Improper compaction may result in air voids being trapped within the composite and a reduction in unit weight. It is important to carefully balance the amount to achieve the intended benefits without compromising other crucial mix properties, such as workability and compatibility.

8.4 Effect of adding CF on air voids (AV%)

Figure 9 illustrates that the increase in CF content causes a significant increase in AV% by 13%. The rise in CF

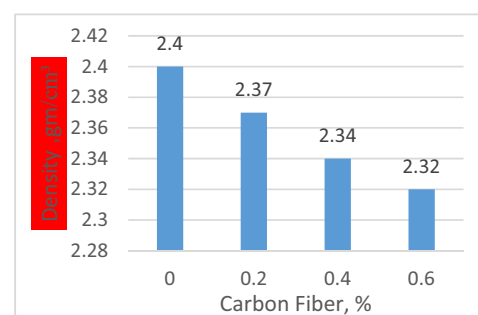


Figure 8: Impact of the addition on unit weight.

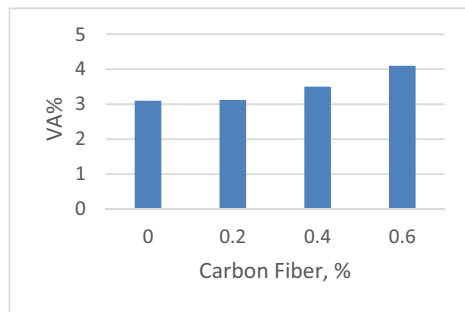


Figure 9: Impact of the addition on air void.

percentage may cause an increase in air voids since higher temperatures increase the viscosity of the asphalt binder, which prevents it from filling the voids and compacting the particles of the asphalt mixture. The AV% obtained for various CF content levels is within the acceptable limit for asphalt mixtures.

8.5 Effect of adding CF on Marshall stiffness (stability/flow)

Marshall quotient (MQ) evaluates the ability of the material to withstand shear forces and permanent deformations. The ratio of stability to flow, which describes the ability of the asphalt mixture to resist deformation under the given load, is known as mixture stiffness. This investigation also computed MQ values to assess each mixture's resistance to deformation. Figure 10 indicates that when CF increases, stiffness increases until it reaches its maximum value of 0.4% CF. The stiffness of modified mixtures is greater than that of the original. Finally, CF improves the rigidity of the combination by roughly 92.4% by adding 0.4% of CF to the mixture. CFs have several advantages, including high stiffness and high tensile strength. The presence of CF in the asphalt mixture provides additional

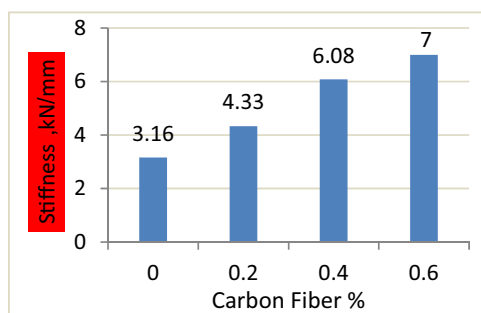


Figure 10: Impact of the addition on stiffness.

structural reinforcement. It can enhance the overall strength and stability of the road surface.

8.6 Effect of adding CF on ITS

ITS results are shown in Table 4 and Figures 11 and 12. It can be seen that ITS exhibits an increase in an increase from 731 to 1,379 kPa, representing an 89% improvement. By adding 0.6% CF to an asphalt mixture, the resistance of the mixes to the tensile stresses was increased. Therefore, the bonding characteristics between the bitumen and aggregate can be significantly improved by including CF as a reinforcement. In other words, CF-prepared mixtures offer more cohesive strength than control mixtures.

Table 4: The improvement obtained with modifications in the ITS test

Modifications	ITS dry (kPa)	ITS wet (kPa)	TSR (%)
Conventional	731	621	84.9
0.2% CF	809	701	86.6
0.4% CF	967	851	88
0.6% CF	1,379	1,331	96.5

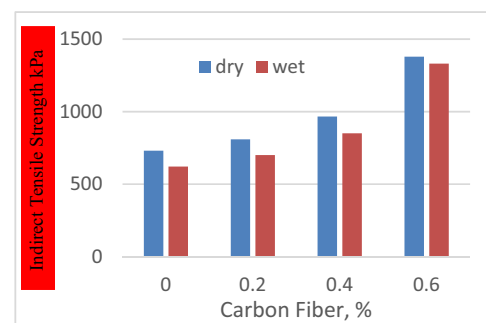


Figure 11: ITS values for conditioned and unconditioned.

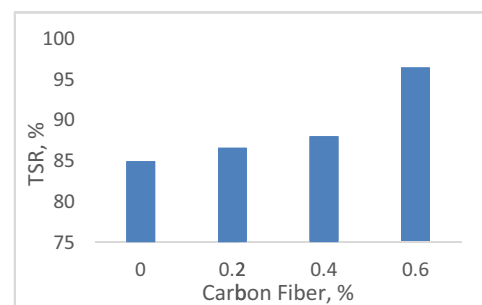


Figure 12: Impact of the addition on moisture damage.

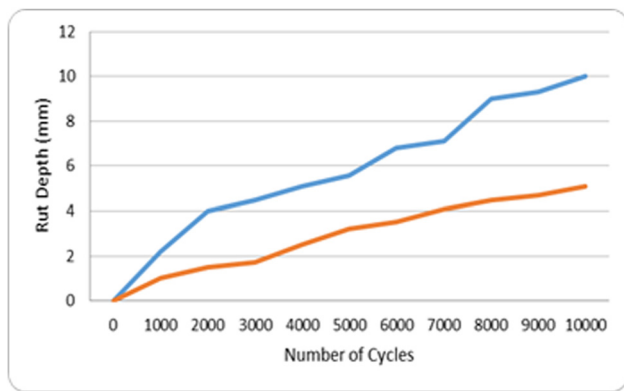


Figure 13: Impact of the addition on rut depth.

“Figure 8” illustrates the relationship between TSR and various mixture types. Because of the rise in CF content, the asphalt mixtures’ Indirect Tensile Strength Ratio values have been rising steadily. The TSR percentage for the 0.6% CF mixture is 96.5. CFs act as reinforcement within the asphalt binder, providing additional strength and resistance to cracking when subjected to tensile stresses.

8.7 Effect of adding CF on permanent deformations of asphalt mixtures

The rut depth value for modified asphalt mixes has been reduced, as observed in “Figure 13”. The particles absorb the lighter portions of the asphalt binder, resulting in viscous gels that allow asphalt to coat the aggregate particles efficiently. The inclusion of CF in reinforcing asphalt mixtures greatly enhanced rutting performance. The addition of CF can increase the modulus or stiffness of the asphalt mixture. This improved stiffness can help distribute load more effectively and reduce the tendency for rutting. The fibers act as a reinforcement, limiting the permanent deformation by restraining the movement of aggregate particles and maintaining better overall stability.

In summary, the addition of CF to a mixture can result in a stronger, and stiffer composite material with improved mechanical properties. However, it is essential to consider the trade-offs, such as the higher cost of CF, when determining its suitability for specific applications.

9 Conclusions

This study looked into how CF additions affected the performance characteristics of HMA. The main conclusions are listed below:

1. According to the findings of the Marshall stability and flow experiments, adding CF to asphalt mixtures increases their stability by 48% while lowering their flow values by 23%. As a result, mixes with CF had high MQ values of 92.4% by adding 0.4% of CF to the mixture.
2. The use of CF additive considerably improved the durability and cohesiveness ability of asphalt mixtures. The indirect tensile strength ratios of the specimens indicated that mixes had a high moisture resistance to water damage. As a reinforcement addition, CF has improved the adhesion between the aggregate and asphalt in the mixture, as evidenced by the high moisture resistance. The TSR percentage for the 0.4% CF mixture is 88%.
3. According to the results of this study, adding CF improves the performance characteristics of asphalt pavement; CF can be used in practical implications for designing a better performance and safety pavement.
4. The inclusion of CF in reinforcing asphalt mixtures by 0.4% greatly enhanced rutting performance as the rut depth decreased by 50%.
5. For future work, it is recommended to consider the amount of CF carefully. It should be determined based on the specific needs of the project and the required technical specifications. It is recommended to start with a low percentage and increase it gradually based on the results obtained. Moreover, it is also recommended to use adjuvants to help achieve a homogeneous CF distribution within the mixture.

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Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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