

Laboratory Evaluation of the Fracture Resistance of Asphalt Mixtures Containing Carbon Fibers

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Abstract

The most common distresses of asphalt pavements are fatigue and cracking, which can lead to stripping and structural failure. The fracture mechanic concepts can be used to evaluate pavement material's resistance to crack initiation and propagation. The cracking behavior of asphalt mixtures can be improved by fiber reinforcement. The addition of carbon fibers can strengthen asphalt binders or mixtures. The optimum length and content of carbon fibers in asphalt binders and mixtures need to be investigated to improve their cracking behavior. In this paper, carbon fibers with different contents and lengths were added to asphalt binders and mixtures, and their fracture, fatigue, resilient modulus, tensile strength, and flexural bending strength were investigated. The results showed that adding up to 1.5% of fibers leads to an increase in the fracture and fatigue performance of the mixtures. The mixtures containing fibers with lengths between 15 mm to 20 mm indicated the best performance in terms of fatigue, fracture, and tensile strength. The results of the mixed-mode SCB fracture and the RSCB tests of the mixtures reinforced with the optimum fiber length and content show that the highest fatigue and fracture resistance happens in the pure mode II condition. The effective fracture toughness and fatigue life decline by approaching the mode I condition. Asphalt binder test results showed that fiber reinforcement was significantly effective in improving the flexural strength of the asphalt binders and mastics.

Keywords: Carbon fibers, Fiber length, Asphalt mixtures, repeated loading test, Asphalt binder bending test

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1. Introduction

Fatigue and cracking are of the most prevalent distresses of asphalt pavements, which can lead to premature failure of the pavements and impose high costs on pavement maintenance for transportations agencies [1-3]. It is reported that the unmodified asphalt mixtures are sensitive to fatigue and cracking when subjected to heavy traffic loading or harsh environmental weather respectively [4, 5]. Investigations also have shown that a fall in temperature and increase in traffic loading can cause fatigue and cracking problems to asphalt pavements [6- 8]. Therefore, it is important to find a reliable and effective method to enhance the fatigue and cracking performance of asphalt mixtures from which, asphalt modification and fiber reinforcing are of the most effective methods.

The presence of cracks in an object can make it sensitive to applied stresses, which subsequently leads to premature failure [3]. As a result, the service life of the pavement will be significantly reduced. The crack initiation and crack propagation resistance of different materials can be evaluated using the fracture mechanic theories [7, 9], and many researchers have used the fracture mechanics to estimate the cracking performance of asphalt mixtures [1, 2, 10]. Different test configurations have been introduced to conduct the fracture tests, from which the Semi-Circular Circular Bending (SCB) specimen has received much attention due to its simplicity [11].

Different additives and modifiers are introduced to improve the fatigue and cracking behavior of asphalt binders and mixtures such as polymers, fibers, crumb rubber, etc [12, 13]. Kim et al. in 2013 indicated that using SBS as a modifier in asphalt mixtures can improve the fatigue performance to a great extent [14]. Although the polymers have a great effect on the fatigue and cracking behavior of asphalt mixtures, using polymer modified asphalt binders requires special facilities such as high

shear mixer, additional asphalt tanks, strong pumping facilities and also an accurate schedule to prevent settlement [5]. Therefore, using additives such as fibers can be a more viable method to improve the fatigue and cracking resistance of asphalt binders and mixtures.

Different types of fibers such as Basalt, jute, glass, poly-aramid, polypropylene, ceramic and etc. have been introduced for reinforcing the asphalt mixtures [15-20]. Carbon fibers, which are produced from either polyacrylonitrile (PAN) or pitch precursors [21], are of the fibers that are expected to have an excellent influence on the performance of asphalt mixtures owing to their inherent compatibility with asphalt binders and desirable mechanical properties [22].

The main specification of carbon fibers is their high tensile strength, which can affect the tensile properties of the mixtures and extend the fatigue life of asphalt mixtures [23]. In addition, the high melting temperature of the carbon fibers is another parameter that allows these fibers to be mixed with bitumen at high temperatures without changing the fibers' properties and shape [24].

Therefore, carbon fibers are expected to have a positive effect on the fatigue and cracking resistance of asphalt mixtures [21]. Cleven et al. in 2000 stated that carbon fibers increase the stiffness and subsequently the tensile strength of asphalt mixtures [22]. Kim et al. in 2018 used 0.5% and 1% of the carbon fiber as an additive in asphalt mixtures and investigated the Marshall Stability, rutting, tensile strength, flexural strength, and fracture toughness of asphalt mixtures [25]. They showed that using carbon fibers does not have any significant effect on the Marshall Stability, rutting resistance, and tensile strength of the mixtures, however, it improves the fracture toughness and the flexural strength to some extent. Moghaddas Nejad et al. in 2014 added the carbon fibers as a modifier in asphalt binder [26]. They indicated that using carbon

fiber modified binder in asphalt mixtures can improve the tensile strength and also the fatigue resistance of asphalt mixtures.

The length of the fibers also affects their function and can play an important role in their performance [27-29]. Different lengths of Parafiber were used in asphalt mixtures by Aboutalebi Esfahani and Namavar Jahromi in 2020. They showed that the fiber length affects the performance properties of asphalt mixtures such as Marshall Strength, indirect tensile strength, and resilient modulus as the fibers should bridge the aggregates and resist cracking [17]. Geo et al. in 2020 investigated the durability, rutting, cracking, and moisture resistance of asphalt mixtures containing different lengths and percentages of basalt, polyester, and lignin fibers [30]. They demonstrated that the fiber type, content, and length are the key parameters that substantially influence the performance properties of the fiber-reinforced asphalt mixtures.

1.1. Significance and Innovation

It can be seen in the previous researches that some investigations have been conducted on the effect of carbon fibers on asphalt mixtures. However, limited literature exists about the effect of the length of carbon fiber on the fatigue and cracking performance of the mixtures. Moreover, the fracture resistance of the carbon fiber-modified asphalt binders has not yet been investigated. Therefore, in this research study, different percentages of carbon fibers with different lengths were added to asphalt mixtures, and the fracture toughness, fatigue life, resilient modulus, and tensile strength of the mixtures were evaluated. Afterward, the optimum length of the carbon fiber was used as an additive in the asphalt

binder and the flexural bending resistance of the fiber-modified binders was evaluated.

2. Materials

2.1. Asphalt Binder and Aggregates

The materials used in this study include asphalt binder, aggregate, and carbon fibers. The asphalt binder was an AC 60-70 grade provided by the Isfahan Jay Oil Company. The specifications of the asphalt binder used in this research are listed in Table 1.

The limestone aggregate materials were provided from the quarries around the Haraz road in the northeast of Tehran province. The limestone powder passing through sieve no 200 was also used as filler material. The gradation was chosen based on the AASHTO M323 limitations for aggregates with a maximum nominal size of 12.5 mm, which are depicted in Fig 1. The physical properties of the aggregates are also presented in Table 2.

2.2. Carbon Fibers

Carbon fiber is one of the most widely used fibers in the industry, which is utilized in the production of various composites. The coefficient of thermal expansion of these types of fibers at different temperatures is very low, which makes the size of carbon fibers being constant at different temperatures. High tensile strength, low unit weight, and low thermal expansion are also the most prominent properties of these fibers. The characteristics of the carbon fibers used in this study are summarized in Table 3. Figure 2 also shows the typical shape of the carbon fiber. In this research fibers with different lengths of 10, 15, 20, 25, and 30 mm were used as a modifier in asphalt mixtures.

Table 1. Properties of the asphalt binder used in this research

Experiment	Standard of the testing method	Test results	Allowable limits	
			Upper limit	Lower limit
Specific weight (gr/cm ³)	ASTM D3289	1.013	1.06	1.01
Penetration rate (0.1/mm)	ASTM D5	68	70	60
Softness point (°C)	ASTM D36	49.4	56	49

Experiment	Standard of the testing method	Test results	Allowable limits	
			Upper limit	Lower limit
Elasticity (cm)	ASTM D113	+100	-	100
Flash point (°C)	ASTM D92	334	-	232
Solubility (wt%)	ASTM D2042	99.97	-	99
Weight loss due to temperature (wt%)	ASTM D6	0.003	0.2	-
Decrease in the penetration rate after TFOT loss due to temperature (%)	ASTM D6 & D5	7.8	20	-
bitumen spot test	AASHTO T102	Neg.	Negative	

Table 2. Properties of the aggregates used in this research

Test	Standard	Unit	Result
Specific gravity (coarse agg)	ASTM C127	g/cm ³	2.57
Specific gravity (fine agg)	ASTM C128	g/cm ³	2.54
Los Angeles abrasion loss	ASTM C131	%	22.2
soundness (Sodium sulfate)	ASTM C88	%	2.7
Sand equivalent	ASTM T176	%	65
Flat and elongated particles	BS-812	%	0.3

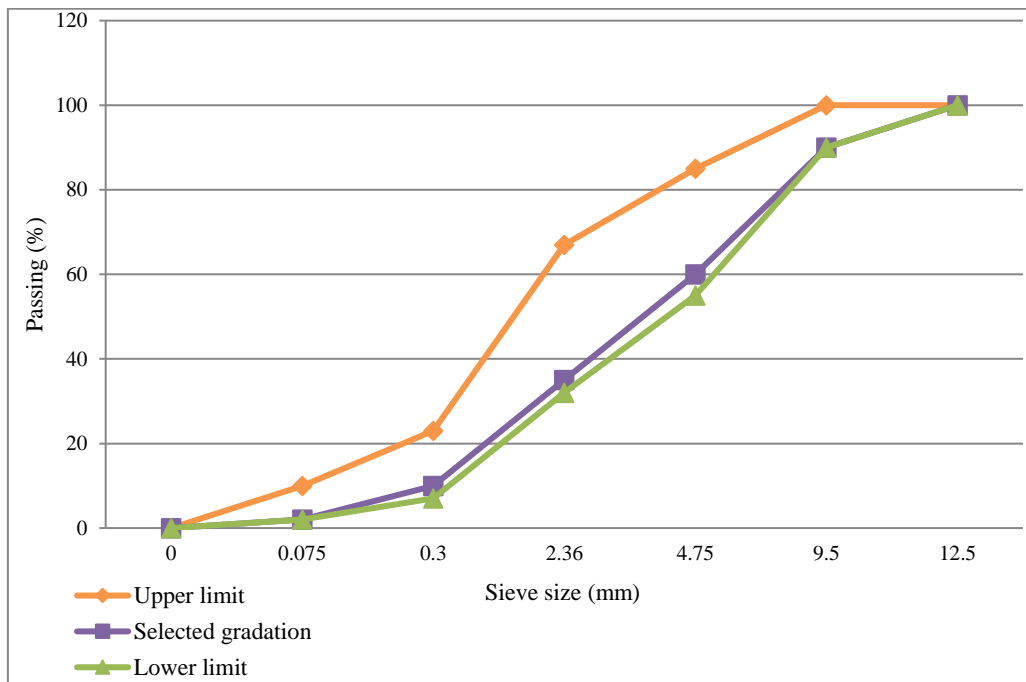


Figure 1. Aggregate gradation of asphalt mixtures used in this research

Table 3. Specifications of carbon fibers

Tensile modulus <i>GPa</i>	Water absorption %	Tensile strength <i>MPa</i>	Special Weight $\frac{gr}{cm^3}$	Diameter μm
230	0-1	3800	1.78	8-150



Figure 2. The carbon fibers used in this research

2.3. Mix Design

The Superpave mixing design was used to determine the optimum asphalt binder content according to AASHTO R35 and AASHTO M323. The optimum asphalt content was chosen as the asphalt content corresponding to air voids of 4%, which was determined as 4.4% of the total mixture. The ratio of filler to effective bitumen was also calculated as 1.11, which meets the limitations of AASHTO M323 for asphalt mixture with continuous granulation.

2.4. Sample Preparation

2.4.1. Asphalt Mixtures

The Superpave gyratory compactor (SGC) was then used to compact the mixtures until reaching the required unit weight. The

cylindrical specimens with a diameter of 150 mm were prepared and cut into SCB specimens using a saw cut. The thickness of the specimens was 5 cm and a notch with a length of 15 mm was also made in the center of all SCB specimens. The sample preparation steps are depicted in Fig 3. The IDT specimens were also fabricated using the SGC with a 100 mm mold diameter. In this research, the fiber content of the specimens was 0.5, 1, 1.5, 2, 2.5, and 3.5 wt% of the total asphalt binder. The fibers were added directly to the aggregates before adding the asphalt binder. The lengths of the fibers were also chosen as 10, 15, 20, 25, and 30 mm.



Figure 3. Steps for preparing SCB samples

2.4.2. Asphalt Binder and Mastics

In order to determine the effect of the fibers on asphalt binder and mastics, four different mastic types were fabricated as shown in Table 4. The filler content in samples b and d was the same as the filler content used in asphalt

mixtures indicated in Fig 1. The fiber-modified specimens were fabricated using 1.5% fiber with 15 mm length as the optimum fiber length and content obtained from the mixture test results.

Table 4. Details of the asphalt binder specimens.

Sample A	Sample B	Sample C	Sample D
Pure bitumen	Bitumen and filler	Bitumen and carbon fibers	Bitumen, filler, and carbon fibers

To prepare the asphalt binder specimens, a mold with a size of 25 x 25 x 150 mm was provided as shown in Fig 4. The specimen dimensions were chosen based on the fiber

size. As the optimum length of the fibers in the mixture was 15 mm, the specimen dimensions were considered more than the optimum length.



Figure 4. Molds made for preparing the binder specimens

3. Testing Program

3.1. SCB Fracture Test

The mode I SCB fracture test was carried out by placing the SCB specimens under a monotonic compression load with a rate of 2.5 mm/min at a temperature of -5 °C according to AASHTO TP124. The linear elastic fracture mechanic (LEFM) principles are used to analyze the test results, as the performance of asphalt mixtures in this temperature is brittle elastic [11, 31]. The critical value of the stress intensity factor of fracture toughness (K_{Ic}), which is known as one of the most popular criteria for the fracture resistance of asphalt mixtures at minus temperatures is selected in this study to describe the fracture resistance of the mixtures. The fracture toughness is calculated using equation 2. The fracture energy until failure of the stored fracture

energy, a parameter for describing the resistance of asphalt mixtures against crack initiation, was also calculated and compared to other parameters [32]. The stored fracture energy is calculated as the area under the load-displacement curve of the SCB fracture test.

$$K_i = \frac{F_{cr}}{Dt} Y_i \sqrt{\pi a} \tag{1}$$

Where F_{cr} is the peak load, Y is the shape factor obtained from the finite element analysis performed by Ayatollahii et al. (2011) [33], D and t are the diameter and thickness of the SCB sample respectively.

As the performance of the fibers may change by changing the mode of failure, the tests were repeated at mode I, mode II and a mixed-mode I and II on the specimens containing the optimum fiber content and length. The mixity parameter, which shows the contribution of modes I and II is defined as M^c , which is

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calculated using equation 2. The M^e parameter is 1 for the pure mode I and 0 for the pure mode II conditions. This parameter is a number between 0 and 1 for the mixed-mode condition. The shape factors and the crack intensity factors of the SCB specimens were obtained from Ayatollahi et al. (2009) [33], and are summarized in Table 5. For the mixed-mode condition, the effective mixed-mode I/II

fracture toughness (K_{eff}) is calculated using equation 3. Different loading modes were adjusted by changing the support conditions as shown in Fig 5.

$$M^e = \frac{2}{\pi} \tan^{-1} \left(\frac{K_I}{K_{II}} \right) \quad (2)$$

$$K_{eff} = \sqrt{K_I^2 + K_{II}^2} \quad (3)$$

Table 5. Computational numerical parameters for different loading of the SCB specimen

loading mode	M^e	Y_{II}	Y_I	K_{II}	K_I
I	1	0	3.734	0	0.195
II&I	0	1.130	1.191	-0.0590	0.0622
II	0.5	2.298	0	-0.120	0

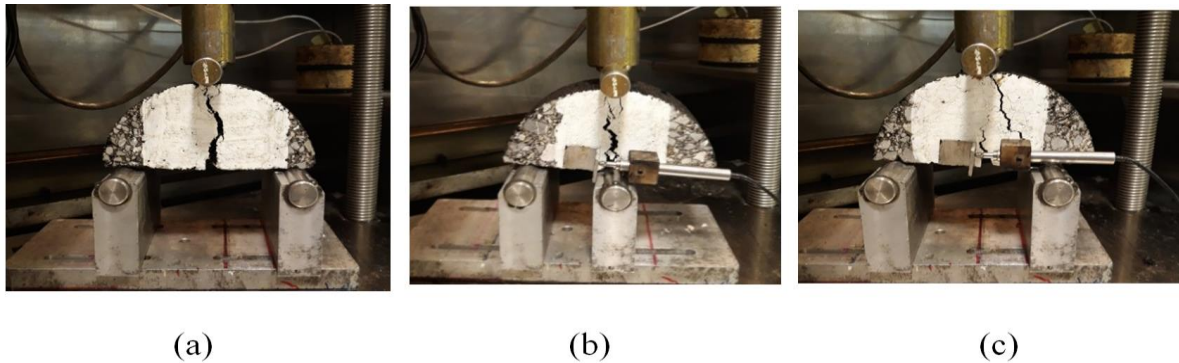


Figure 5. Supporting conditions for different failure modes (a) mode I with 24 cm support distance, (b) mode II with 6 cm support distance, (c) mixed-mode I and II with 9 cm support distance

3.2. Repeated Loading SCB Test

The repeated loading SCB test (R-SCB) was conducted at the temperature of 20 °C to evaluate the fatigue performance of the mixtures. The sample size and geometry of this test were identical to the samples of the SCB fracture test. In this test, a three-point bending fixture was employed, and dynamic compressive loading at a frequency of 10 Hz with no resting time was applied in the center point of the specimens. The test was conducted in a stress controlled mode. For determining

the stress level, at first, a monotonic fracture test was conducted on all mixtures at the same temperature. A typical result of the monotonic fracture test is presented in Fig 6 (a). Then, 40%, 60%, and 100% of the average peak stresses of the tests were chosen as the stress levels of the cyclic repeated loading SCB tests. The cycle number at which the specimen failure occurs and the deformation starts to increase dramatically is reported as the fatigue parameter as shown in Fig 6 (b).

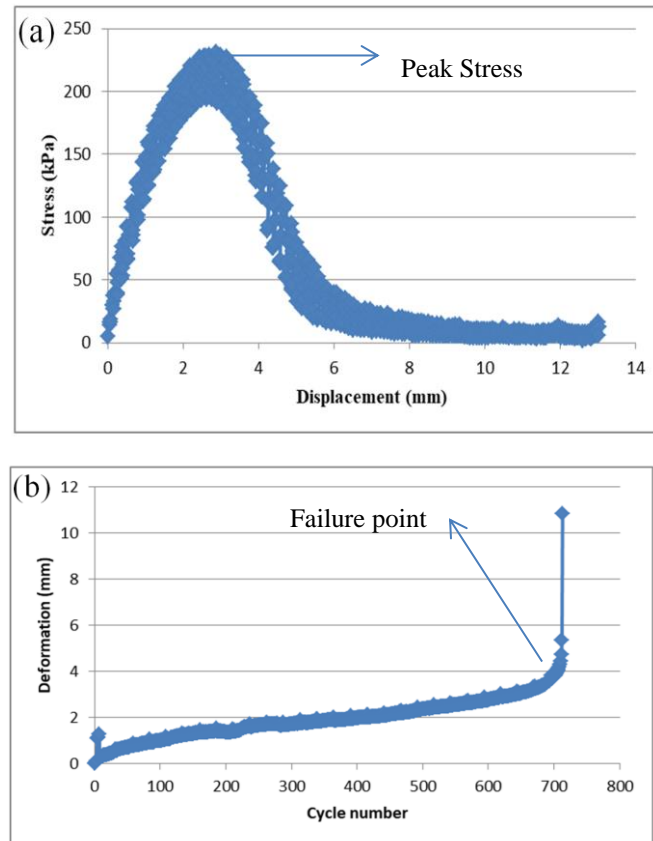


Figure 6. The typical results of a monotonic fracture test (a) and a cyclic fracture test (b) at 20 °C

3.3. Indirect Tensile Strength (IDT) Test

Indirect tensile testing was performed according to the AASHTO T322 standard. For this purpose, gyratory compacted cylindrical specimens were divided into two sections with a diameter of 150 mm and a thickness of 40 mm. In the IDT test, compression stress is applied in the direction of the diameter of the sample, which results in a perpendicular tensile deformation and a tensile failure in the specimen. The fixture of the test is shown in Fig 2. The test was conducted at -10°C, and the tensile strength of the mixture was calculated using equation 3.

$$S_t = \frac{2 \times P_f}{\pi \times t \times D} \quad (4)$$

Where, S_t is the tensile strength, P_f is the peak load and t and D are the specimen thickness and diameter respectively.

3.4. Resilient modulus test

Resilient modulus is another important parameter of asphalt mixtures, which is used as an input for designing of flexible pavements [34]. This parameter is calculated as the ratio of the applied stress to the recoverable axial strain [35]. This test was conducted on the cylindrical specimens containing different percentages of carbon fibers with varied lengths. The test was conducted at the temperature of 20 °C according to ASTM D 4123.

3.5. Asphalt binder bending test

In the asphalt binder bending test, the resistance of the asphalt binders against bending is measured, which can estimate the fatigue or cracking resistance of the materials. This test is usually performed by a universal tension machine with either a three-point or four-point bending fixture. In this test, a monotonic force is applied on the top of the specimens by a piston at a constant rate between 0.1 to 5 mm/min. When it collides

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with the specimen, the applied load is increased, and the specimen is moved downward at a contact rate. The bending tester software draws the force-deformation curves in a two-dimensional diagram. During the bending test, compressive and tensile stresses were formed at the upper and lower surfaces of the specimen until the failure happens.

In this research, three loading rates of 0.5, 2 and 5 mm/min were considered for the binder bending test at the temperature of $-5\text{ }^{\circ}\text{C}$. The peak load and the maximum deformation were chosen as the tensile resistance criterion of the asphalt binders. The fixture of the asphalt binder bending test is shown in Fig 7.

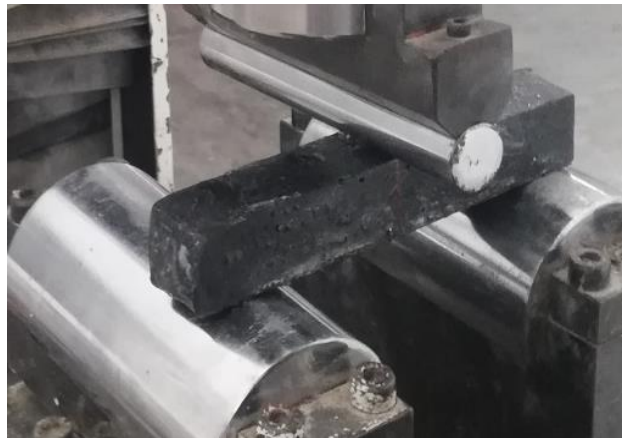


Figure 7. The fixture of the asphalt binder bending test

4. Results and Discussions

4.1. SCB Fracture Test

The results of the SCB fracture tests are presented in the bar charts of Fig 8. It can be seen that increasing the fiber content to about 1.5% results in an increase in the fracture toughness of the mixtures compared to the control specimen. The increase is mainly due to the three-dimensional distribution of the fibers in the mixtures, which bridge the aggregates and prevent the crack initiation in the mixture. In other words, when the cracks are forming, they want to separate the aggregates and propagate through the spaces between the aggregates. Fibers prevent the aggregates from separating and thus improve the fracture resistance of asphalt mixtures.

Increasing the fiber content to more than 1.5% results in a decline in the fracture toughness of the mixtures, and when the fiber content increases to 2.5%, the fracture toughness falls dramatically by about 25%. This behavior may be owing to the agglomeration of the fibers when high contents of the fiber are added to

the mixture. The fiber agglomeration is caused when excessive fiber length or content is used. Fiber agglomeration leads to a non-uniform distribution of the fibers in the mixtures and prevents them from reinforcing the mixture properly. A picture of fiber agglomeration is shown in Fig 9. It is also observed that the error bars of the 3% fiber modified mixtures are larger than the mixtures containing lower amounts of fiber, which can be because of the high data scatter due to the agglomeration.

Comparing the results of the mixtures with different fiber lengths shows that increasing the length of the fibers to about 20 mm also leads to an almost 50% increase in the fracture resistance of the mixtures. However, a sharp decline happens when the fiber length increases from 25 mm to 30 mm. the reason is that when the fiber length increases, the chance of agglomeration also increases. Moreover, as the weight of the fiber is constant, using longer fibers results in a reduction in fiber numbers in the mixture. Subsequently, the uniformity of the fiber dispersion in the mixture declines, which can result in an adverse effect on the

performance properties of the fiber-reinforced mixtures.

In brief, it is inferred from the results that fiber reinforcement delivers a positive effect on the fracture toughness of asphalt mixtures and all

fiber-reinforced mixtures have better fracture performance than the control mixture. Moreover, using 1.5% of carbon fibers with 20 mm length leads to a 70% improvement in the fracture toughness of the mixtures.

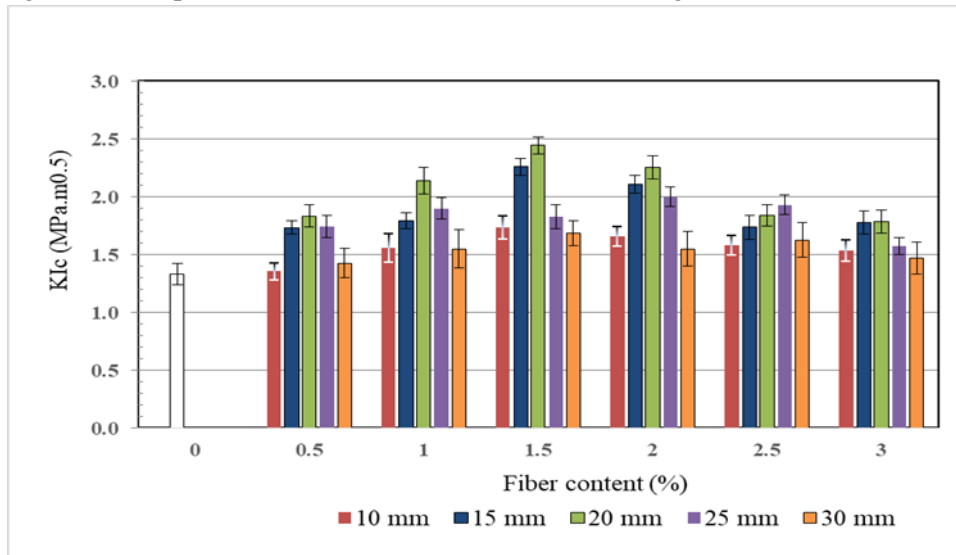


Figure 8. The mode I SCB fracture test results



Figure 9. A picture of fiber agglomeration when excessive fiber length or content is used

The results of the mixed-mode fracture tests on the mixtures containing the optimum fiber content and length are presented in Fig 10. It can be observed that the higher the value of M° results in the lower K_{eff} value. In other words, the fracture resistance decreases when the loading mode becomes closer to the mode II condition. The reason is mainly because of the positive T stress in the SCB specimens [36]. It is also seen from the results of Fig 10 that the ratio of K_{IIc}/K_{Ic} is about 0.83 which is lower

than its typical value in the previous researches [31]. The reason is that the fibers perform better when the specimens are subjected to bending loading in mode I condition. However, the fiber reinforcement is not effective against the pure shear stresses of the mode II condition. Therefore, the mode I fracture results become greater and the K_{IIc}/K_{Ic} ratio decreases when the mixtures are reinforced with fiber.

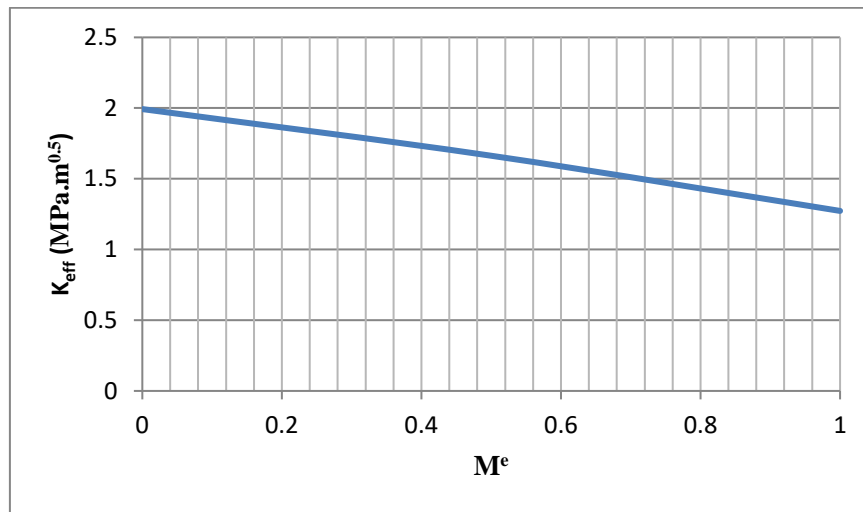


Figure 10. The effect of fiber reinforcement on different modes of fracture failure

4.2. Repeated Loading SCB Test

The R-SCB test results are shown in Figs 11 to 13. As indicated, using up to 1.5% of fibers can increase the cycle numbers to failure and enhance the fatigue performance of the mixtures, and the fatigue life of the asphalt mixtures containing 1.5% of carbon fibers is 65% higher than that of the control mixture. This enhancement can be because of the three-dimensional reinforcement of the fibers in the mixture, which prevents the formation of the micro-cracks and postpones the fatigue failure. In other words, when the fibers are added to the mixtures, the fibers will bridge the aggregates and prevent them from separating. Therefore, when cracks are forming, the fibers prevent them from opening and propagation, causing the cracks to remain in very dimensions, named micro-cracks [37].

On the other hand, adding more than 1.5% of the fibers can result in a substantial decline in fatigue life. However, the fatigue life of the mixtures containing 3% carbon fiber is still more than that of the control mixture. This behavior can be the result of the fiber agglomeration in the mixture as described in section 4.1.

The fiber length also has a significant effect on the fatigue life of the fiber-modified mixtures. The fibers with 10 mm length do not have any significant effect on the fatigue life of the

mixtures. The reason is that the short fibers cannot bond the aggregates together and reinforce the mixtures against tensile stresses and as a result, the fibers with extremely short lengths are not effective in enhancing the fatigue performance of the asphalt mixtures.

The best fiber performance occurs when fibers with about 20 mm lengths are used. It is seen in the results of the mixtures modified with 1.5% of carbon fiber that increasing the fiber length to 20 mm can double the fatigue life of the mixtures. Using 30 mm length fibers also does not significantly affect the fatigue life of the mixtures compared to the control mix. The reason is that using too long fibers causes them to agglomerate, which prevents the uniform distribution of the fibers in the mixtures and makes them less effective in reinforcing the asphalt mixtures.

Therefore, it can be concluded that the best fiber performance occurs when fiber with 20 mm length and maximum content of 1.5 % is added to the asphalt mixtures.

The results at different stress levels show that the mixture's fatigue performance follows the same trend when tested at different stress levels. However, the number of load cycles to failure declines by increasing the stress level. Moreover, the error bars also become larger when the stress level increases, which shows that using higher stress levels does not provide

significant results and is not statistically recommended.

The R-SCB tests were conducted on the optimum mixture, which contained 1.5 % fiber with a length of 20 mm, at different stress levels and different loading conditions. The results are plotted in Fig 14. As it can be seen, the fatigue life is higher when the loading condition approaches mode II of failure. In

other words, the asphalt mixtures subjected under the mode I condition are more sensitive to fatigue compared to those subjected under the mixed-mode or mode II condition. This is because the tensile stresses in the bottom of the specimens are higher when the mixtures are subjected to flexural loadings in mode I condition that causes fatigue cracks to form more quickly.

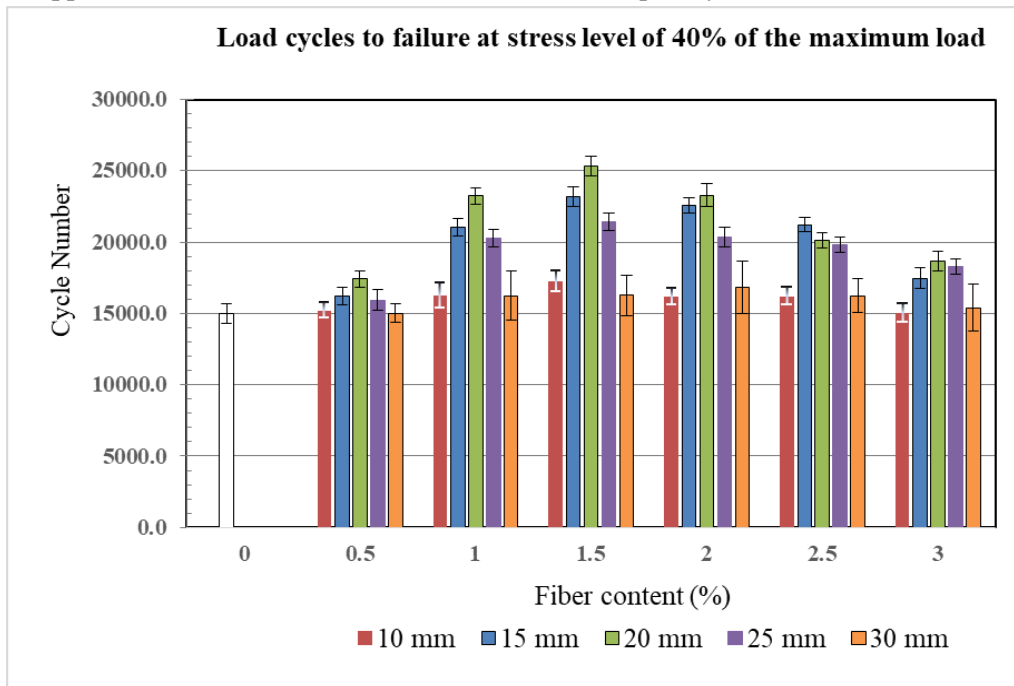


Figure 11. The R-SCB test results for different fiber contents, fiber lengths at a stress level of 40% of the maximum load

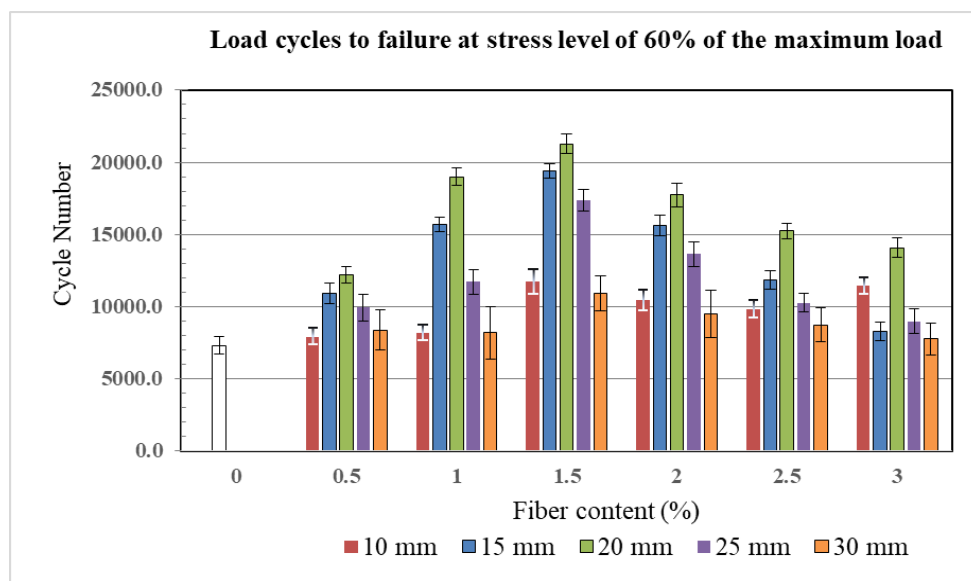


Figure 12. The R-SCB test results for different fiber contents, fiber lengths at a stress level of 60% of the maximum load

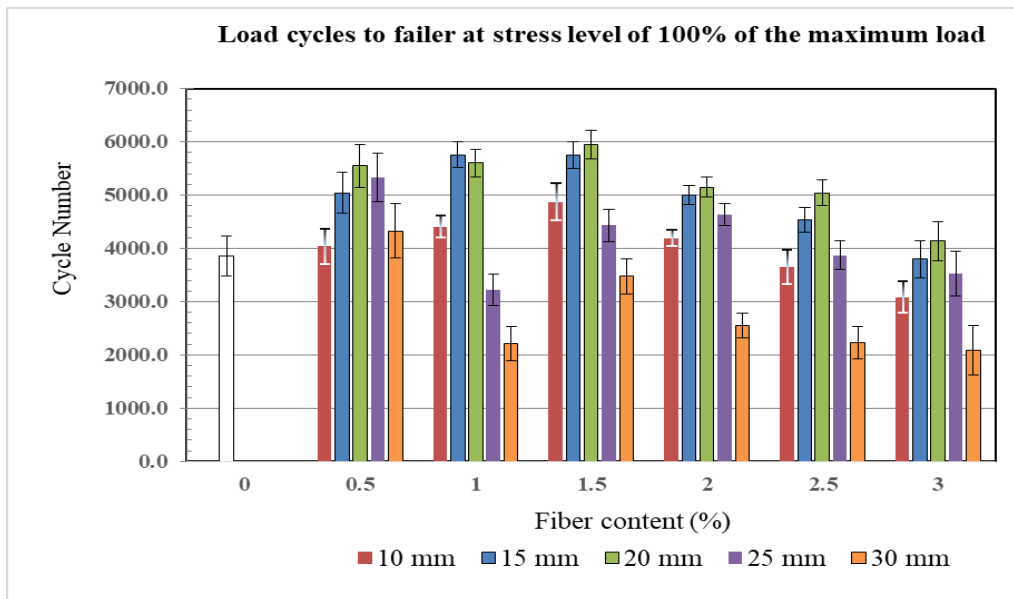


Figure 13. The R-SCB test results for different fiber contents, fiber lengths at a stress level of 100% of the maximum load

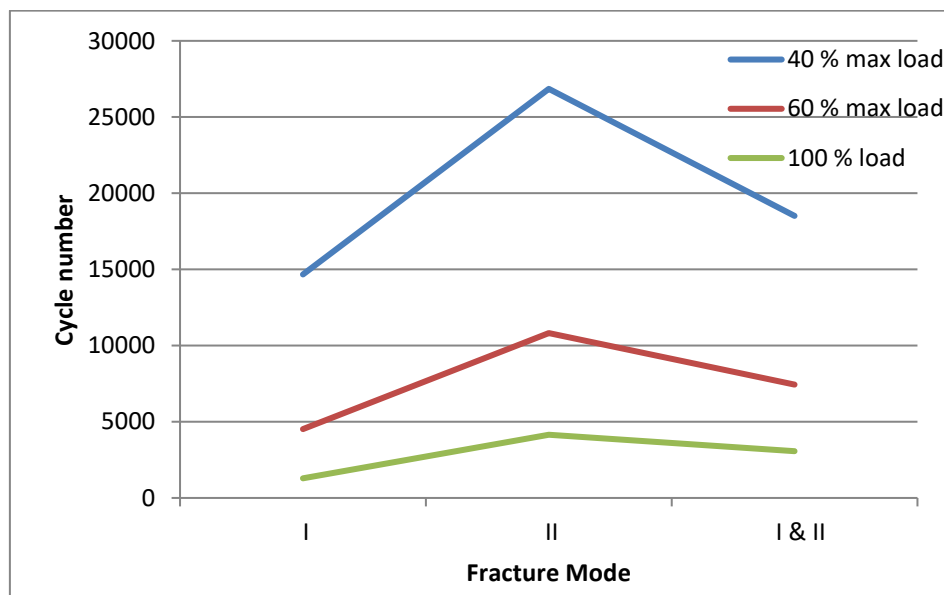


Figure 14. The R-SCB test results of the optimum mixture for different stress levels and loading conditions

4.3. Indirect Tensile Strength

The effect of fiber content on the indirect tensile strength of the mixtures is shown in Fig 15. The optimum fiber content is 1.5%, and the tensile strength of the mixtures containing 1.5% of carbon fiber is more than twice of the control mix. The increase in the tensile strength of the fiber-modified mixtures is mainly due to the reinforcement of the high strength fibers which bind the aggregates

together and prevent the mixtures from breaking due to tensile stresses. Increasing the fiber content from 1.5% to 2.5% results in a slight decrease in the tensile strength, and it is shown that the indirect tensile strength of the asphalt mixtures modified with 2.5% of carbon fibers is about twice the control mixture. However, A sharp reduction is observed when the fiber content increases to 3%. However, it still performs better than the control mixture,

and the indirect tensile strength of the mixtures with 3% of carbon fibers is 20% higher than that of the control mixture. The reduction of the tensile strength due to the excessive fiber content is mainly because of the fiber agglomeration. The fiber agglomeration led to a non-uniform distribution of fibers in the mixture, which caused the fibers not to reinforce the mixtures properly.

The effect of fiber length on the tensile strength of the fiber-modified mixtures is shown in Fig 16. The tensile strength does not change significantly when the length of the fibers increases from 10 mm to 15 mm. A dramatic rise in the tensile strength occurs when to fiber length increases to 20 mm. It can

be observed that the indirect tensile strength of the asphalt mixtures containing 20 mm length carbon fibers is more than twice of the control mixture. Therefore, it can be inferred that short fibers cannot bridge between the aggregates and play their reinforcing role properly.

Using fibers with lengths of more than 20 mm results in a sharp reduction in the tensile strength parameter. The reason is that the fibers tend to agglomerate when their length is increased. The agglomeration impairs the ability of the fibers to reinforce the mixtures properly, which subsequently leads to a reduction in the tensile strength of asphalt mixtures.

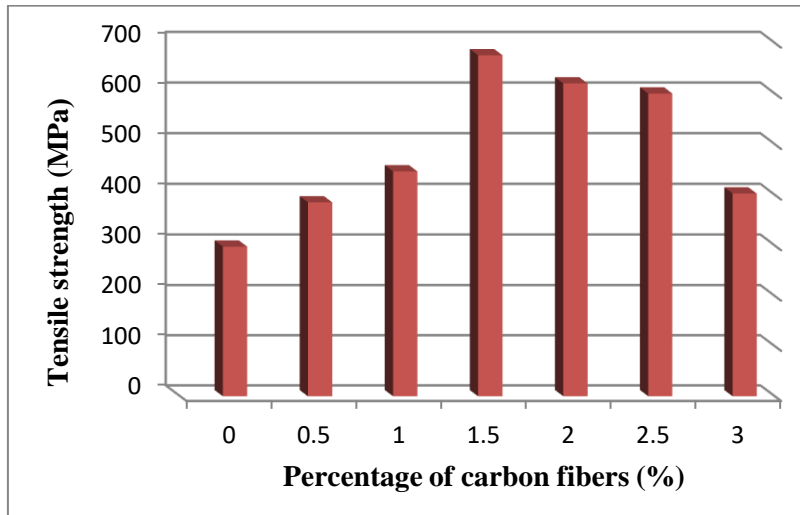


Figure 15. The effect of fiber content on the indirect tensile strength of the mixtures

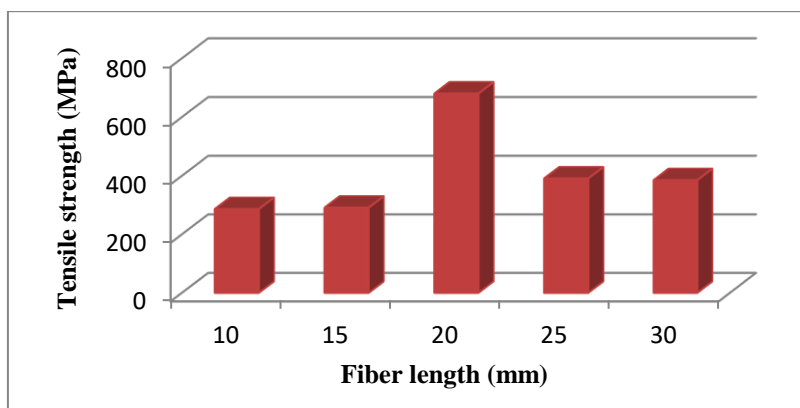


Figure 16. The effect of fiber length on the indirect tensile strength of the mixtures

4.4. Resilient Modulus Test

The resilient modulus test results are presented in Figs 17 and 18. The results of the resilient

modulus tests approve the ITS results and the resilient modulus of the mixtures reaches its summit when 1.5% of the fiber material is

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added to the mixture. The increase in the resilient modulus occurs due to the higher stiffness of the mixtures as a result of fiber reinforcing. In other words, the fibers bind the aggregates together and prevent them from deformation, which leads to a higher resilient modulus value. However, excessive fiber content leads to a reduction in the resilient modulus of the mixtures due to the agglomeration.

Fig 18, which compares the resilient modulus of the mixtures containing different fiber lengths also shows that the maximum resilient

modulus belongs to the mixtures reinforced with fibers with 20 mm length. The resilient modulus severely drops when the fiber length is increased to 30 mm. When short fiber materials are used, the fibers cannot bridge the aggregates and bond them together. On the other hand, when the fiber length becomes too long, the fibers tend to agglomerate. Therefore, the resilient modulus of the fiber-modified mixtures is low when too short or too long fibers are used.

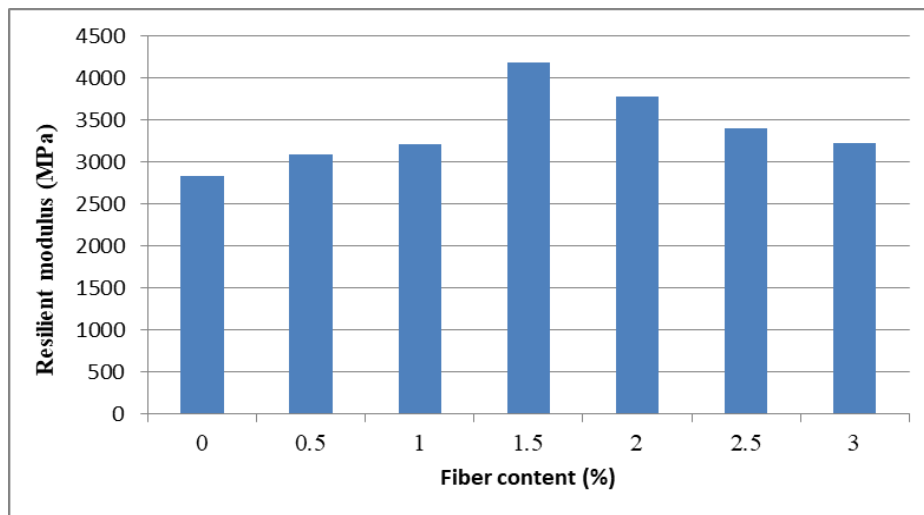


Figure 17. The effect of fiber content on the resilient modulus of the mixtures

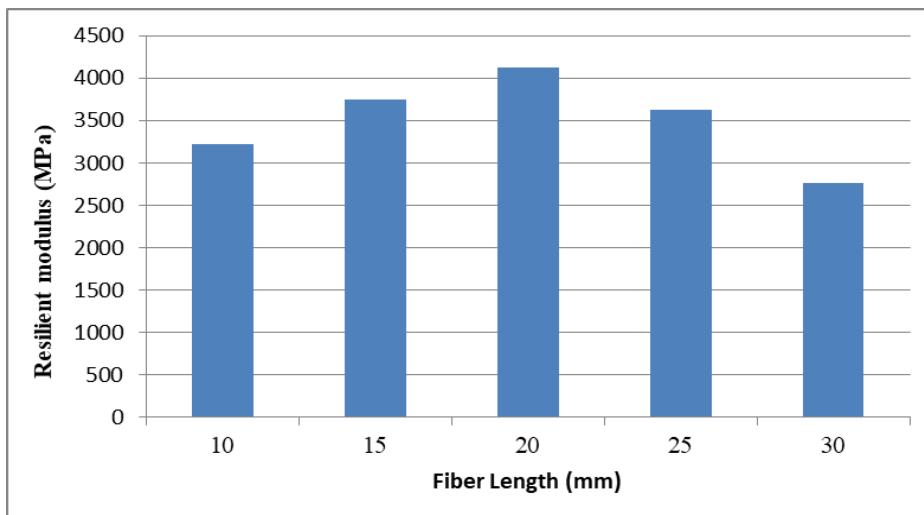


Figure 18. The effect of fiber length on the resilient modulus of the mixtures

4.5. Asphalt Binder Bending Test

The force-deformation curves resulting from asphalt binder bending tests are plotted in Fig

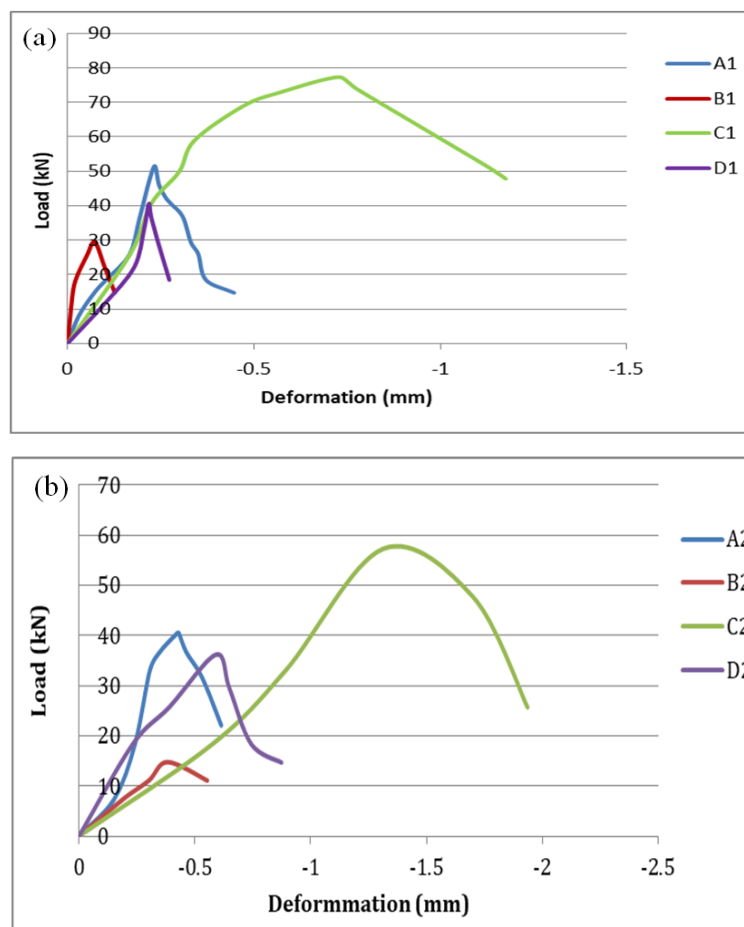
19. It is apparent in the results that the fiber reinforcement has a great impact on the flexural properties of the asphalt binders and

asphalt mastics. This improvement is thoroughly noticeable by comparing the results of mixture A and C for bitumen as well as comparing B and D diagrams for mastic. The improvement is because of the high tensile strength of the fibers which are distributed uniformly in three dimensions in the specimens. The fibers prevent the mastics to undergo large deformations, which results in a higher peak load and deformation in the asphalt binder bending test.

For better comparison and conclusion, diagrams were plotted as bar charts in Figs 20 and 21. These charts compare the peak load and maximum deformation tolerated at each loading rate for all mixtures. As indicated, using fibers lead to an increase in the amount of peak load and deformation of both asphalt binder and mastics, which shows the positive impact of the fibers on the flexural strength of the asphalt binders. It is seen in the charts that

at the loading rate of 1.5 mm/min, the fiber reinforcement leads to an improvement in the maximum deformation and the peak load of the asphalt binders by almost 300% and 60% respectively. Moreover, the peak load and maximum deformation of the mastics are also improved by almost twice for the asphalt mastics. It is also observed that all mixtures follow the similar trend when the rate of the loading changes in the asphalt binder bending test.

It is also noted that the mastics have a lower peak load and deformation than the asphalt binder specimens. This is due to the effect of filler material on the flexibility of the mixtures. The binders are more flexible than the mastics and as a result, they perform better in the asphalt binder bending test.



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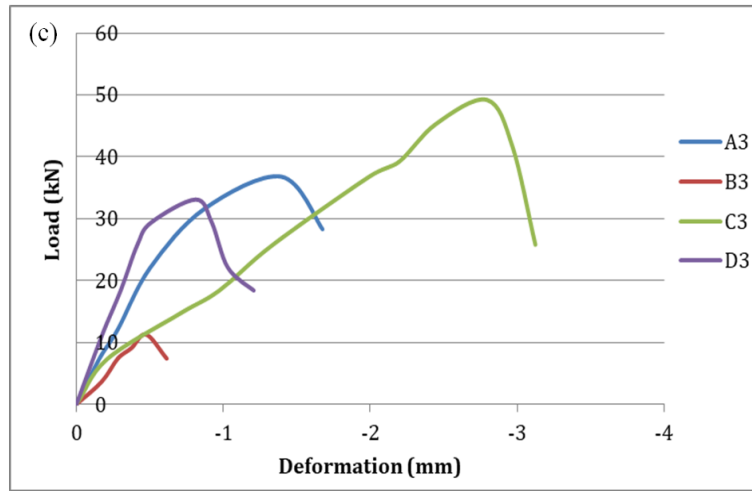


Figure 19. The asphalt binder bending test results at the rates of 0.5 mm/min (a) 2 mm/min (b) and 5 mm/min (c)

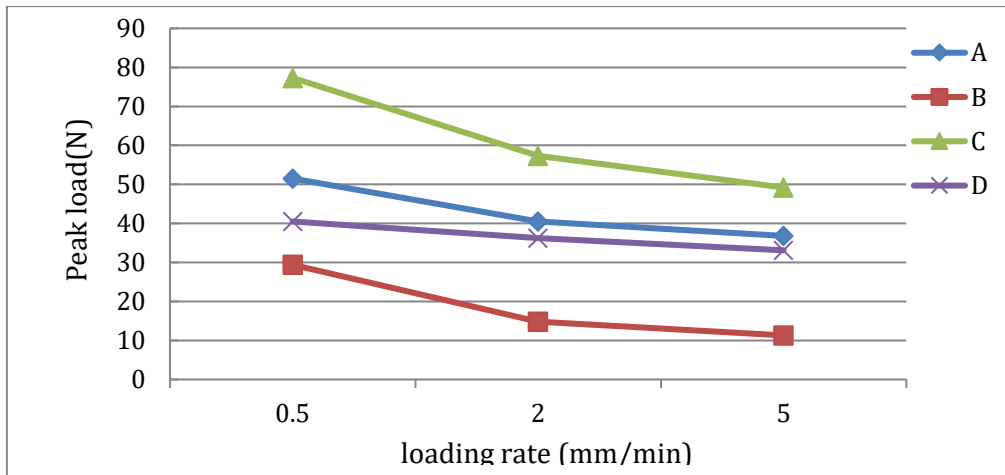


Figure 20. The peak load tolerated by the asphalt binder and mastic specimens in different loading rates

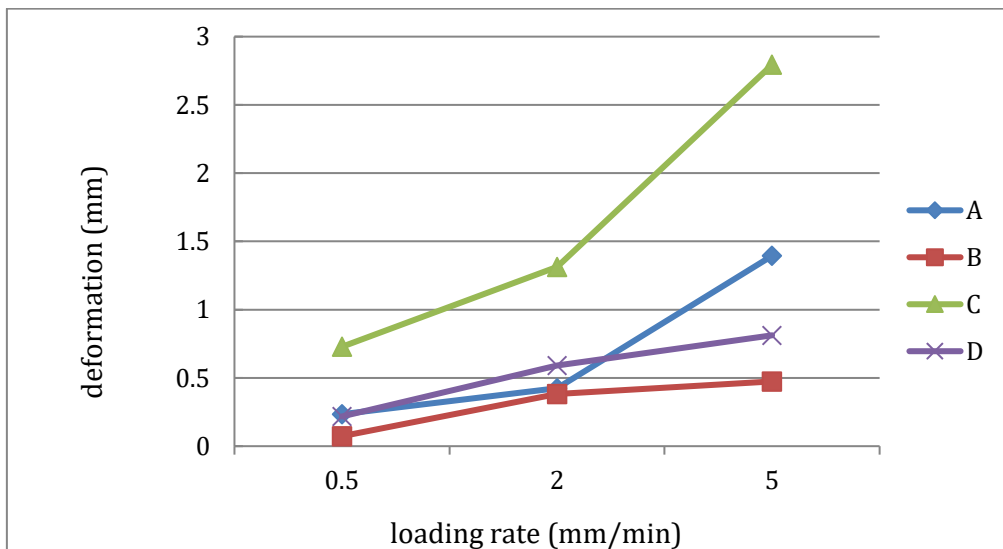


Figure 21. The maximum deformation tolerated by the asphalt binder and mastic specimens in different loading rates

4.6. Data Analysis

The two-way analysis of variance (ANOVA) was employed in order to investigate the significance of the results from a statistical viewpoint. The two-way ANOVA was employed for evaluating the results of the SCB fracture, R-SCB fatigue, ITS, and resilient modulus tests and the results are indicated in Table 6. The fixed parameters are chosen as

fiber length and content. It is observed from the ANOVA results that the P-value, which shows the significance of the results, is less than the threshold of 0.05 for all tests, which shows that the results are statistically significant.

Table 6. Two-way ANOVA analysis for fatigue life versus fiber content and stress level, and J_c versus fiber content and temperature

	Source	DF	Adj SS	Adj MS	F-Value	P-Value
SCB test	Fiber content	7	16.51	5.8376	12.39	0.032
	Fiber length	5	52.021	24.3497	43.58	0.012
	Error	14	9.425	0.347		
	Total	105	56.737			
R-SCB test	Fiber content	7	44.34	6.3729	34.38	0.021
	Fiber length	5	48.59	37.4748	36.37	0.002
	Error	12	6.429	0.632		
	Total	105	92.570			
IDT	Fiber content	7	15.38	6.2212	24.69	0.042
	Fiber length	5	26.84	46.8981	46.328	0.031
	Error	26	4.7912	0.828		
	Total	105	63.38			
Resilient modulus	Fiber content	7	13.45	8.4947	74.92	0.023
	Fiber length	5	47.39	45.79	87.343	0.013
	Error	12	5.1789	0.234		
	Total	105	67.38			

5. Conclusion

Carbon fibers are used as a modifier of asphalt binders and mixtures in the previous literature, however, little is known about the effect of the change in the length and content of these fibers on the fracture and fatigue performance of asphalt binders and mixtures. Therefore, in this research, the SCB fracture test, repeated loading SCB test, and the indirect tensile strength test were conducted on the asphalt mixtures containing different percentages of carbon fibers with different lengths. Moreover, in order to investigate the effect of the fibers on the properties of the asphalt binders and mastics, the asphalt binder bending test also was conducted on the asphalt binders and mastics containing the optimum amount and

length of fibers. The conclusions are as follows:

- The fracture test results show that using up to 1.5% of fibers leads to an increase in the fracture toughness of the mixtures, and using more than 1.5% of fibers leads to a substantial decrease in the fracture resistance of the mixtures.
- The fracture toughness improves when the fiber length increases to 20 mm. increasing the fiber length to 30 mm results in a reduction in the fracture toughness of the mixtures.
- The R-SCB test results approve the fracture tests results and the fatigue life of the mixtures improves when the fiber content increases to 1.5 %. Moreover, the mixtures

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containing fibers with a length of 20 mm have the highest fatigue life.

- The results of the mixed-mode SCB fracture and the RSCB tests of the mixtures reinforced with the optimum fiber length and content show that the highest fatigue and fracture resistance happens in the pure mode II condition. The effective fracture toughness and fatigue life decline by approaching the mode I condition.

- The indirect tensile strength reaches its summit when the fiber content increases to 1.5%, then it falls slightly.

- Based on the asphalt mixture tests conducted in this research, the optimum length and content of the carbon fibers in asphalt mixtures are recommended as about 20 mm and 1.5 % respectively. However, more investigations on other properties of the asphalt mixtures are required to provide a more reliable recommendation.

- The results of the asphalt binder bending test showed that fiber reinforcement leads to a substantial improvement in the flexural performance of the asphalt binders and mastics.

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