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Experimental Study on the Effect of Glass and Carbon Fibers on Physical and Micro-Structure Behavior of Asphalt

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Abstract: Performance failures in asphalt pavements, which are related to the use of traditional asphalt materials has made pavement scientists to adopt new strategies in utilizing new materials in pavement industry. Some of additive materials are like fiber or yarn including natural and synthetic fiber such as glass and carbon fiber. These materials reinforce the mix and cause increase in tensile strength. In this study, two yarn types were chosen to investigate on; namely, glass and carbon. The aim of this study was to investigate the properties of reinforced asphalt mixtures with carbon and glass fibers. To evaluate the effect of carbon and glass fibers on asphalt mixtures Physical Performance, Marshal Stability and indirect tensile tests were carried out according to international standards on the samples with and without fibers through the dry method. The results of study showed that fiber glass had greater effect on increasing rutting resistance and increase the percentage of glass fiber in the mix which causes to increase the ratio of Marshall and in other words cause to rutting reduction. The results also indicated that the behavior of fracture for fibrous samples were somewhat different from fracture of non-fibrous samples and does not create a manifest failure screen. Examining indirect tensile strength samples, constructed of optimal fiber percentages were obtained for glass fiber and carbon fiber content of 2% and of 3%, respectively. Results also showed that adding fiber to mixtures resulted in increased length of failure screen.

Keywords: Glass fiber, Carbon fiber, Physical Performance, Indirect Tensile Strength (ITS), Asphalt Microstructure.

1. Introduction

Improving pavement surface quality will increase abrasion resistance; therefore, low attention to this matter may cause massive national capital waste and lower road user level of service. In recent years, different types of additives have been used by researchers to improve asphalt mixture performance. These additive types include ashes such fly ash and date seed ash, polymers such as SBS, fibers such as carbon or glass fibers etc. [1-3]. Since most fibers such as glass, polyester, carbon and etc. have more tensile strength compared to asphalt mixtures; therefore, it is expected that adding them to the mixture can increase its tensile strength [4]. The addition of fiber can decrease moisture susceptibility and damage caused by moisture in the asphalt mixture [5].

A comprehensive literature review showed that generally, fibers are promoted for use in asphalt for three main reasons: to improve the mechanical properties of the mix (i.e. tensile strength, Marshall, fatigue life, reflective cracking resistance and etc.), to increase electrical conductivity of the mixes, and to reusing different waste fibers [6]. The fiber type uses in asphalt is important in asphalt mixture reinforcement. Thus, it is necessary to provide fibers which not only have sufficient tensile strength and flexibility, but also have significant thermal resistance against high temperature at mixing time. Accordingly, in this study the glass and carbon fibers are used. Rutting which is largely due to lack of shear strength of pavement surface is the permanent deformation due to roughness in road longitudinal profile and other undesirable effects that causes pavement deterioration propagation, [7]. In this study, the effects of glass and carbon fibers on rutting reduction as well as microstructure behavior of asphalt mixture were investigated.

Fibrous composites are formed by combining different materials. The fibers made from composite materials are insoluble, can sustain their identities within the composite and can either be continuous or discontinuous. It’s believed that reinforces with diameter between 0.025-0.813 mm are classified as fibers whereas reinforces with larger diameters are categorized as wire cluster. Therefore, reinforced composite materials are consists of a matrix (i.e. asphalt mixture in this research) and reinforces (i.e. carbon and glass fibers in this study). In micro-mechanical analysis basic components of the composites are identified, which are the fibers and the matrix, while macro-mechanical analyses, determine the average properties of fiber and matrix [8]. Equation (1) shows the modulus of a unidirectional fiber-reinforced composite:

$$E_l = E_f V_f + E_m V_m \qquad (1)$$

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Where E and v are the modulus of elasticity and volumetric fraction, respectively, and the "f" and "m" indices represents the fiber and matrix, separately.

There are high accurate micromechanical relationships that may not be possible to directly use by designer. Therefore, some other fast computing methods are used with simplified fiber geometry, the geometry of a compound of the fibers in the mixture and loading conditions. Validity of these simplifications can be measured by comparing the results of simplified equations with the results of more detailed micromechanical analysis [8].The mechanism of crack microstructure in the asphalt materials containing fibers, explain by the event of bridging and crack deviation.

1.1 Bridging

Directly after adding fibers to asphalt mixture, its strength increases and "bridging" phenomenon occurs between the components of asphalt mixture. Fig. 1 illustrates the separation of a material with fiber into two parts with directional distribution at fracture. The part of the fibers which goes through the both sides of the crack surface will grow a bridge shape which can postpone more asphalt cracking. Due to the tendency of the mixture to open cracks under external stresses, part of the stress transmits to the fibers in form of tensile stress. Enduring tensions by bridge fibers can sew the cracks and reduce the crack tips and stress -intensity coefficients which stops or reduces crack propagation rates [9].

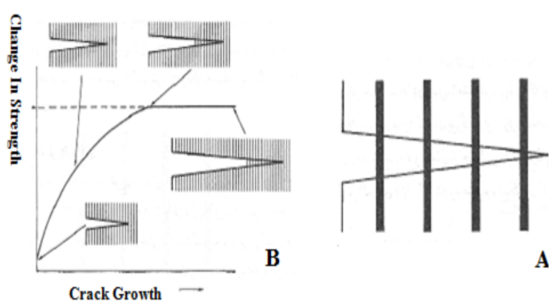

Fig. 1 Bridging phenomena at the cracked plates (a) The effect of aligned fibers at the cracked plate (b) The effect of fibers on strength increase of fibered aggregate [9]

1.2 Crack Deviation

The reaction between the fibers and the base material at the cracked plate will cause the crack to be deviated from its original plane and make a non-planar crack (Fig. 2). Typically, a crack begins to open at its mouth and grows. But after the opening it will deviates from the plane and its growth in each of the crack deviation decreases and stops. This event increases the mixtures resistance against loading.

The fiber types which uses in asphalt are important in the fiber-reinforced asphalt mixture. Thus, it is necessary to provide fibers which not only have sufficient tensile strength and flexibility, but also have significant thermal resistance against high temperature at mixing time. Accordingly, in this study the glass and carbon fibers are used. Rutting which is largely due to lack of shear strength of pavement surface is the permanent deformation due to roughness in road longitudinal profile and other undesirable effects that causes pavement deterioration propagation.

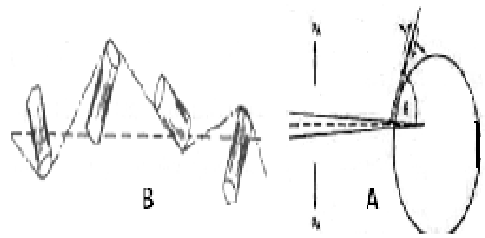

Fig. 2 Deviations on crack propagation (a) the crack tip meets the fiber (b) The effect of non-aligned fibers in crack deviation [6]

Carbon fiber is defined as a fiber which contains at least 90 percent carbon. Large varieties of fibers with specific characteristics are used to produce carbon fibers. The most commonly used precursors are poly acrylonitrile (PAN) , cellulose fibers, petroleum or coal tar pitch and some phenolic fibers. Actually, the mechanical and physical properties of these fibers are appropriate enough to conserve energy and resources [10].

Glass fiber is one of the most important fibers used in the different composite. Glass fibers are widely used due to mechanical properties and of course affordable price compared to different carbon fibers, aramid and basalt as they are limited to very specific applications. Moreover, many industries, from large industries such as the production of wind turbines and aerospace vehicles to small industries such as the production of tub and sinks have used various categories of these fibers including mat, rolling, single or multi-directional fabrics and etc.[11].

2. Literature Review

In recent years, several studies investigated the effects of fibers on asphalt mixtures. In previous studies, efforts were made to identify the underlying factor that is responsible for improving the behavior of glass fiber modified asphalt mixes. Asphalt concrete samples were prepared and tested to evaluate the mixture characteristics such as its fatigue life, skid resistance and rutting resistance. Results of testing of glass fiber modified asphalt mixes indicated increased stiffness and resistance to permanent deformation compared to conventional asphalt mix [12].

Several researchers examined the effect of glass fiber and Nano-clay on some various engineering properties including; Marshall Stability, flow, Marshall Quotient, volumetric characteristics and indirect tensile strength. Different percentages of glass fiber and Nano-clay added to the mixture. Results indicated that glass fiber was superior performer in tensile strength increase compared to Nano-clay additive. However, resulted permanent deformation of mixtures contained Nano-clay was somewhat lower than that of glass fiber asphalt mixtures. Among all investigated mixtures, highest Marshall Quotient determined when it was reinforced by 0.2% and 6% of glass fiber and Nano-clay additives, respectively. Also mixture with 0.6% and 2% of glass fiber and Nano-clay proofed to have the highest indirect tensile strength [13].

In another study, rutting and fatigue performance of asphalt mixtures containing glass fiber and waste plastic bottles were evaluated. Effect of waste plastic bottles on rutting and fatigue performance and dynamic features improvement of glassphalt contained waste plastic bottles were investigated. Results of 54 investigated samples showed improvement in elasticity and reversibility of asphalt after unloading and optimum waste material percent has founded to be 10%. In addition, modulus of resilience as well as fatigue and creep resistance has increased [14].

A study was carried out to investigate the used of waste glass as a substitute part of the aggregate. Moisture sensitivity, stiffness modulus and the cyclic triaxial compression tests were implemented in order to determine glass and filler effects on moisture sociability and plastic deformation. Results showed that 8% use of waste glass as substitute to the sand part of asphalt aggregate had best mechanical performance for road surface course [15].

Researchers previously investigated dynamic properties of asphalt concrete performance contained crush glass as finer material using fatigue life, stiffness modulus and creep compliance determination. Results indicated that using crushed glass can efficiently improve dynamic characteristics of asphalt [16].

The characteristics and properties of carbon fiber-reinforced asphalt mixtures were assessed in a research. It found that the addition of carbon fibers increases the mix's stability and voids in the mix while decreases flow value. They also found that the addition of fibers can improve the fatigue life and permanent deformation of the mixtures [17].

In another investigation, the volumetric and mechanical properties (specific gravity, air void, etc.) of fiber-reinforced asphalt mixtures were examined. Results showed that void mineral aggregate (VMA) increases after adding fiber into asphalt mixtures [18]. The mixtures with lignin and asbestos fibers demonstrated greater VMAs than mixtures contained other fibers. This was due to their lower bulk specific gravity. Voids filled with asphalt (VFAs) of mixtures at their optimum asphalt content (OAC) have shown to increase a little after adding fibers into mixture. VFAs of ordinary mixtures at their optimum asphalt content decreased while VMAs of mixtures increased. The Marshall stability (MS) of all mixtures using the OAC increased by 5.05%, 7.47%, 1.11%, and 2.22% after adding polyester, poly acrylonitrile, lignin and asbestos fibers, respectively. In addition, found flow values of mixtures increased after adding fibers [15].

In another study, two types of fibers (polypropylene (PP) and glass fiber) were used simultaneously to improve the performance of the asphalt-concrete mixtures. In this way, The PP fibers were blended into the liquid asphalt and the glass fibers were added to the aggregates; both fibers were 12 mm in length. They reported that the increase in the amount of polypropylene fiber additive of all amounts of glass fibers led to increase in Marshall Stability while this trend is reversed for flow. Increased amount of glass fiber for all amounts of polypropylene fibers, led to increase in Marshall Stability. However by adding 0.2% glass fibers, the Marshall stability of samples was decreased [19].

Some scientists studied the use of thermoplastic polymer-coated glass fiber in asphalt mixtures and found threefold increase in rutting resistance measured by Hamburg wheel test. Also, it was found that indirect tensile strength and moisture susceptibility of the fibrous mixtures were nearly two times higher than those of the plain mixtures [7]. Fig. 3 shows two modes of micro-mechanic behavior of fiber-reinforced mixtures used in this study.

Some researchers utilized the block styrene-butadiene rubber (SBR) composites and Nano-clay to improve the moisture susceptibility of hot asphalt mixtures. The asphalt mixtures were made by of blending the SBR polymer with two different weight ratios of Nano-clay and three different bitumen percentages. The indirect tensile tests were used to calculate the moisture susceptibility of asphalt mixtures. It was observed that by increasing the amount of additive content, the indirect tensile strength ratio increases, which clearly shows the improvement in moisture susceptibility of asphalt mixtures containing these additives [20].

Yet, the comparison study between the performance of glass and carbon fibers have not been conducted .Also the effects of these two types of fibers on the Marshall Quotient have not been evaluated. The primary objectives of this paper was to comparative study of the effect of these two types of fiber on the properties of tensile strength of asphalt, Marshall Quotient as a variable that is representative of rutting resistance performance and the properties of cracking behavior of these mixtures.

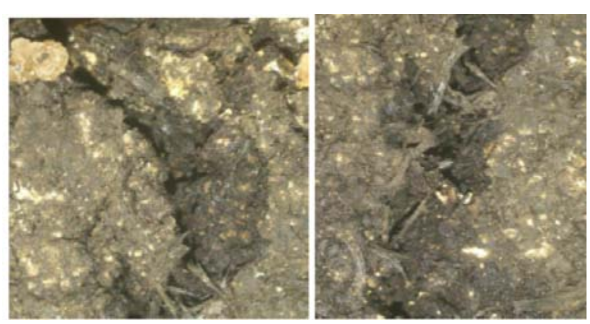

Fig. 3 Bridging in fiber-reinforced asphalt mix (right: bridging) (left: crack deviation)

3. Materials and Methods

At first, preliminary Marshal tests were carried to determine the optimum bitumen content of mixes contained different percentages of fiber. Then, Marshall Stability tests (ASTM-D1559) and Indirect Tensile Tests (ITS) were undertaken on the samples according to (AASHTO-T283). The large-scale photographs were then used in order to investigate the behavior of cracks in fiber-reinforced asphalt mix. Tests were carried out in Pavement Laboratory of Yazd University.

3-1 Properties of materials used in this study

Materials used in this research were bitumen, aggregate and fibers. The most important physical properties of natural aggregates for asphalt concrete production are summarized in Table 1.The continuous gradation for pavement layer (Topeka) recommended by the Iran code No.234 were used for preparing asphalt specimens[21]. Properties of this gradation to create Marshal Specimens are shown in Fig. 4.

Table 1 Specifications of aggregate used

Aggregate Characteristics	Test Standard Method	Result
Abrasion Percent	ASTMC131	17.2
Elongated Factor For Size 12.7mm	BS 812	23.2
Flat Factor For Size 12.7mm	BS812	12.3
The Density Of Stone Materials (Kg/m^3)	ASTM C127	2685
Fractured Particles (one face)	ASTM D 5821	88
Fractured Particles (two face)	ASTM D 5821	83
Water Absorption Stone Materials	ASTM C128	3.9

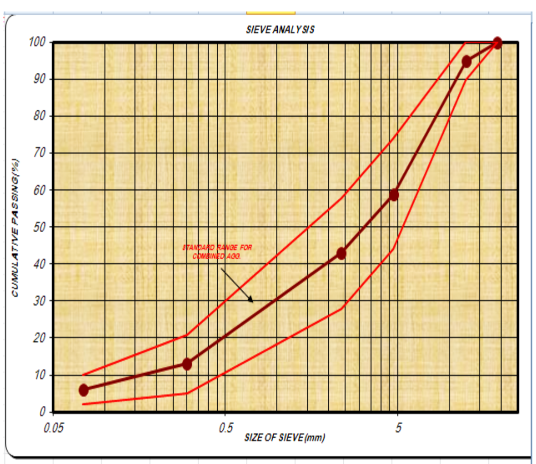

Fig. 4 Gradation of the used aggregate

The bitumen used in this research was provided from Isfahan refinery. The properties of the bitumen in accordance with standard laboratory measurements [22] are shown in Table 2.

Table 2 Specifications of bitumen used

Test Standard Method	Specification	Result
ASTM D-70	Specific gravity at 25° C	1.02
ASTM D-5	Penetration grade 25° C	63
ASTM D-36	Softening point (° C)	53
ASTM D-92	Flash point(° C)	298
ASTMD-1754	Weight loss on heating (percent)	0.35

3.2 The Properties of Fibers

Physical and mechanical properties of glass and carbon fibers used in this study are presented in Table 3. Figure 5 shows carbon and glass fibers which were provided from Turkey companies and Crystal Company in Karaj, respectively.

Table 3 Specifications of Carbon and glass fibers used

Specifications of Fibers	Sample length (mm)	Fiber diameter (μm)	Tensile strength (Gpa)	Modulus of elasticity (Gpa)	Special Weight (g/cm3)	Softening temperature C°
Glass	10	15	3	70	2.6	550
Carbon	6	10	4.2	240	2.76	-

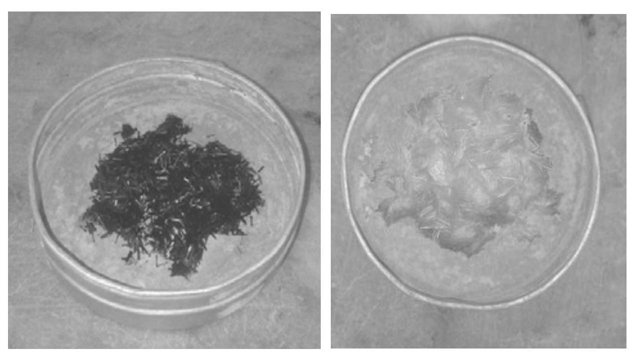

Fig. 5 Carbon fiber (left) glass fiber (right)

3-3 Preparation of Specimens and choice of the percentage of fibers

Selecting the appropriate amount of fiber content in asphalt mixtures is important. Too low fiber content may increase the probability of creating a weak cross section for cracks propagation in the surface. Also, use of too high fiber content may reduce the cohesion between aggregates and shrink all fibers in one place. The maximum efficiency of fibers is when it's placed along the surface of the samples perpendicular to the longitudinal and transverse cracks. These fibers prevent crack propagation. However, after adding fibers during sample preparation, their alignments cannot be controlled.

135 different samples were constructed of different percentages of carbon and glass fiber, which 27 of them were used to determine optimum bitumen content. After that, Marshall tests were carried out to determine the optimum bitumen content for different percentages of fiber. Then, in order to investigate performance of different mixtures, Marshall and indirect tensile tests were performed on 108 samples at their optimum bitumen content and different percentages of fiber.

Generally, fiber containing samples are produced in two common ways: wet-mixing and dry-mixing [7, 19]. In this study, in order to choose more efficient procedure, firstly both approaches were implemented and by visually comparing, it was realized that dry-mixing process was more practical in fiber dispersion and fiber placement through the mix. As a result, dry procedure was chosen to use. Four distinct percentages of carbon and glass fiber were added to mixes according to previous studies [17, 23].

Table 4 Percentage weight values and optimum bitumen for asphalt mixtures with different percentages of glass fiber and carbon

Row	The percentage of fiber (%)	Fiber weight (g)	The percentage Of optimum bitumen mixed with glass fibers	The percentage Of optimum bitumen mixed with carbon fibers
1	0.1	1.2	5.5	5.4
2	0.2	2.4	5.6	5.5
3	0.3	3.6	5.7	5.6
4	0.4	4.8	5.8	5.7

The higher percentage of optimum bitumen content of mixtures with glass fibers compared to the mixtures with carbon fibers stemmed from the greater length of glass fibers. The greater the length of fibers, the higher specific surface areas and therefore the more need of bitumen to coat fiber.

Indirect tensile strength (ITS) tests were carried out according to AASHTO-T283 []. Cylindrical specimens were loaded diametrically across section. The loading caused a tensile deformation perpendicular to the loading direction, which yielded a tensile failure. The maximum tensile strength can be expressed by the equation (2).

$$S_r = \left(\frac{2P_{max}}{\pi td}\right) \qquad (2)$$

Where:

S_r = Tensile strength of specimen (N/mm^2)

P_{max} = The maximum vertical force exerted (N)

t = Thickness of specimen (mm)

d = Diameter of specimen (mm)

4. Result and disunions

4-1 investigation of rutting behavior of asphalt mixtures

In order to control rutting resistance directly, rutting apparatus such as Hamburg Wheel Tracking Test and other similar standard methods is being used by researchers [17, 19]; however, this method was not used in this research due to limitations of laboratory equipment. Others recommend parameters such as the Marshall Ratio based on limited access to rutting testing equipment, used by some other research institutions such as the UK Transport Research Laboratory. This study used the latter case. Marshall Ratio (MR) is the ratio of stability to flow value of the mixture which used to determine the potential of rutting [24].

Values of Marshall Ratio (MR) for different percentages of fiber versus different bitumen contents are illustrated in Figure 6. Generally, mixes containing carbon fiber had lower MR in comparison with glass fiber samples. Less rutting resistance could be predicted for these samples. In addition, it can be seen from the figure that by increasing in bitumen content, MR value decreases in both types of samples. Also, there can be seen a good correlation between results of this research with the ones obtained from another research, in which Hamburg wheel tracking test was used to evaluate similar parameters of the effect of glass fiber on asphalt mixes [7].

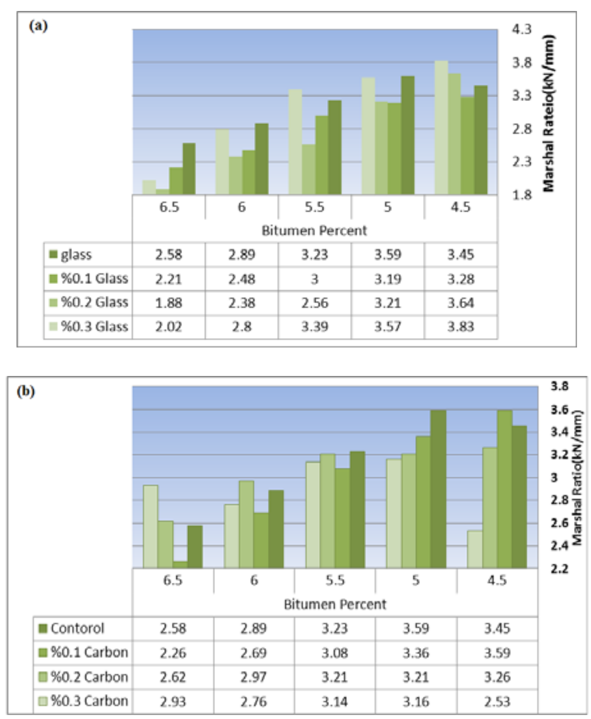

Fig. 6 Marshall Ratios comparison of different mixtures constructed of varied bitumen and fiber percentages; a) glass fiber, b) carbon fiber

4-2 Microstructure of asphalt mixtures containing carbon and glass fiber

Figure 7 illustrates the microstructure (large-scale image) of asphalt mixtures containing glass fiber. In this image, crack propagation appears to be deviated and the deviation angles are showed by parallel-conductor line. In this image the bridge of fibers between the two fracture planes at the cracking point are shown with arrows. This image is taken from the glass fibers which has the lighter color and is in black background of the asphalt mixture. The mechanism of fibrous fibers which improves the strength and avoids stress concentration at the crack tip can be explained by the above definitions. When the crack tip reaches to the scattered fibers on the asphalt (like description of Fig. 2 (a)) deviation occurs. At the same time, the presence of fibers on both sides of the fracture plane with respect to the elastic modulus and high tensile strength, leads to reduce the fracture energy and promote the reaction mixture against the total tensile force of this zone. As a result, the speed of crack growth reduces with increase in the external tensile strength of fibers (For example, fibers with lumpy and twisted surface).

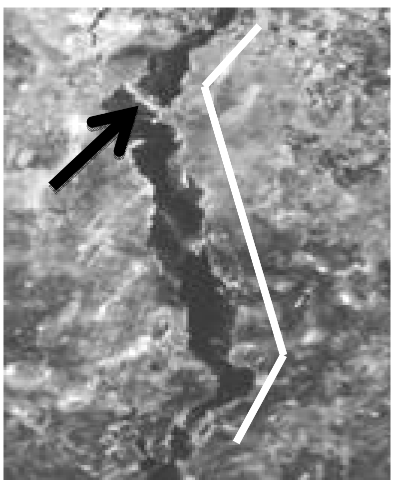

Fig. 7 Large-scale image of diversion of crack propagation (white line) and bridging (black arrow) in the asphalt mixture.

The best direction for the placement of fibers for reinforced mixtures were along the surface of the samples, meaning perpendicular to the longitudinal and transverse cracks which prevented crack propagation. After asphalt samples contained fibers compaction process, the most effective fibers were those placed in the stated direction and parallel to the surface; while, the angled fibers were less effective. However, the placement of fibers cannot be controlled in samples preparation. The amounts of fibers should not be so low which create a weak cross section for the production of cracks in the surface. Also their amounts should not be so high which leads to reduce the cohesion between aggregates and to avoid fibers to be gathered in one place.

4-3 Fracture behavior of asphalt mixture

Generally, the fracture of asphalt mixture specimens can occur in one of the above modes:

(I) Opening fractures along a diameter of specimen which is sometimes associated with triangular pieces in the loading bar.

(II) Sliding fractures which prevent the formation of an opening failure plane.

(III) The mixed-mode fracture i.e., the combination of an opening mode and a shearing mode of [25, 26] which large displacement can be seen near the loading bar and center of specimen

As can be seen in Fig. 8, the specimens without fiber are as mode I and the specimens with fibers are as mode III.

The bridging in the fracture plane in indirect tensile loading leads to the uniformly distributed stress and deformation distribution in all failure zones due to the tight string within the mixture containing fibers.

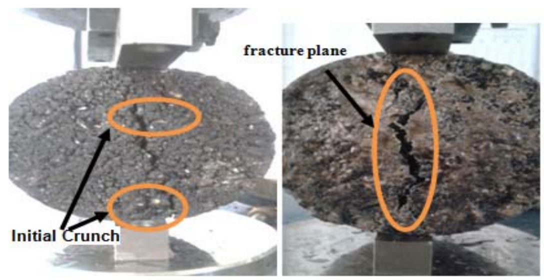

Fig. 8 The fracture of the specimen; with fiber (right: scattered crack) and without fiber (left: fracture plane)

4-4 indirect tensile strength

ITS test results are depicted in figure 9.

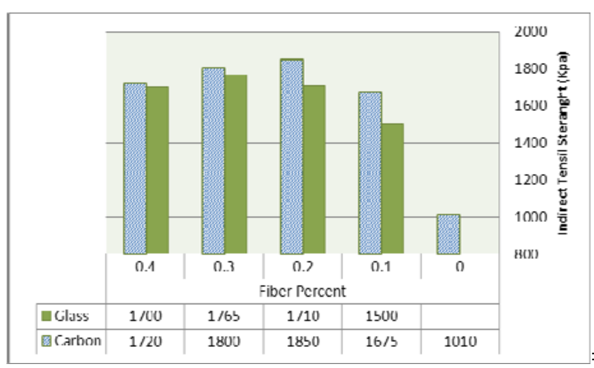

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Fig. 9 Effect of different percentage of two types of fiber on dry aggregate tensile strength.

In addition, the analysis of the results demonstrated the presence of glass and carbon fibers can improve the cohesion of asphalt mixtures and when cracking appears on asphalt mixtures, these fibers can act as a connector to the bridging performance [7], and then can prevent the crack propagation.

5. Conclusions

This experimental Study aimed to evaluate the effect of carbon and glass fibers on tensile strength, rutting resistance and the behavior of the crack propagation. In this paper, indirect tensile and Marshal Tests were used to identify the properties of asphalt mixtures before and after adding fibers. The following results were obtained based on laboratory investigations.

1- The tensile strength initially increases and then decreases with increasing glass and carbon fibers content. So, the highest tensile strength can be achieved for mixtures containing glass fiber content of 0.3% and carbon content of 0.2%. Increasing the tensile strength can put off asphalt cracking occurrences.

2- The asphalt samples mixed with carbon fibers have proven to have less rutting resistance compared to samples contained carbon fibers. Also, the average of rutting resistance improved when the percentage of glass fiber in the mixtures increased.

3- Samples containing fibers have longer and nonlinear failure screens and therefore, resulted in higher loading capacity.

For the future research, the authors suggest the investigation of the effect of the shape, length and the ratio of diameter to length of fibers, as well as the effect of gradation of aggregate and the bitumen types on different parameters of asphalt mix reinforced with glass and carbon fibers. Also the effect of glass and carbon fibers on the frictional resistance of asphalt mixtures can be a good choice of future attempts.

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