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Effect of Carbon Nanofiber on Mechanical Behavior of Asphalt Concrete

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Abstract

Uses of fibers to improve material properties have a scientific background in recent years in civil engineering. Use of Nanofiber reinforcement of materials refers to incorporating materials with desired properties within some other materials lacking those properties. Use of fibers for improvement is not a new phenomenon as the technique of fiber-reinforced bitumen began as early as 1950, but using nanofiber is a new idea. In this research the mechanical properties of asphalt mixture that have been modified with carbon nanofiber were investigated using mechanical tests, which can improve the performance of flexible pavements. To evaluate the effect of nanofiber contents on bituminous mixtures, laboratory investigations were carried out on the samples with and without nanofibers. During the course of this study, various tests were undertaken applying the Marshall test, indirect tensile test, resistance to fatigue cracking by using repeated load indirect tensile test and creep test. Carbon nanofiber exhibited consistency in results and it was observed that the addition of nanofiber can change the properties of bituminous mixtures, increase its stability and decrease the flow value. Results indicate that nanofiber have the potential to resist structural distress in the pavement and thus improve fatigue by increasing resistance to cracks or permanent deformation, when growing traffic loads. On the whole, the results show that the addition of carbon nanofiber will improve some of the mechanical properties such as fatigue and deformation in the flexible pavement.

Keywords: *Fatigue Life, Resilient Modulus, Modified Asphalt Mixture; Carbon Nanofiber, Permanent Deformation*.

1.0 Introduction

Engineers are trying to improve the performance of asphalt pavements and as such they applied different procedures for modification of asphalt binder. At present, the addition of polymers is a usual method applied for binder modification, but uses of different types of fibers have also been evaluated. Researches are widely believed that the addition of fibers to asphalt improves material strength as well as fatigue characteristics and ductility. Likewise, carbon fibers may also offer excellent role for bitumen modification due to their inherent compatibility with asphalt cement and mechanical properties. Carbon modified binder is more competitive with polymer modified binders that improve the properties of hot asphalt mixtures. Further, it was expected that carbon nanofiber-modified asphalt mixtures would increase resistance to permanent deformation, stiffness and fatigue characteristics of the mixture. Because of high tensile strength of carbon nanofibers, cold and hot temperature behavior of asphalt mixtures was also expected to improve. Finally, carbon nanofiber modified asphalt could indicate a higher quality asphalt mixture for pavements.

Nano reinforced materials hold the potential to redefine the use of traditional materials, both in terms of performance and potential applications [1-5]. Hussain et al. believed that chemical compatibility with matrix materials and the dispersion and sprawl of nanoparticles is a difficult approach in developing nanocomposite [1]. Aggregation of the nanofibers should not be appearing and suitable dispersion of fibers is one of the important stages. Khattab et al. by combining sonication and high shear mixing methods introduce a new technique for achieving the highest degree dispersion of carbon nanofiber [6]. In this study, different power rates, several sonic action frequencies and various mixing speeds were investigated to find the best dispersion process .

Some researchers have shown that use of nanocalcium carbonate (nano-CaCO3) to modified asphalt can increase rutting resistance and improves low-temperature toughness properties [7 and 8]. Use of some nanoclays, modify some characteristics of asphalt binders, such as rutting, however, cannot suitable effect of the fatigue [9]. Organophilic montmoriilonite and sodium montmoriiionite Nanoclays can be improve the viscosity, phase angles and complex shear modulus of styrene butadiene styrene copolymer modified asphalt [10]. Carbon nanofiber has high modulus, high aspect ratio and tensile strength; so use of this material lead to significant improvement in the mechanical properties of polymer composites [11-14.[

In this research use of carbon nanofibers to modify mechanical properties of asphalt mixtures were investigated. Carbon nanofiber modification produces a good network of fibers in the asphalt mixtures that retardation micro-cracks propagation and can enhance the mechanical properties. This paper focuses on the effect of carbon nanofiber to modify hot asphalt mixtures and evaluate the mechanical properties such as strength, fatigue and creep characteristics of the asphalt mixtures.

2.0 Literature Review

Use of fibers to improve the behavior of materials is not a new concept; fibers are widely used as reinforcing method in concrete [15–19]. Use of fiber to reinforce started in the 1950s. Zube was the first researchers that investigate the reinforcement of asphalt. In an attempt of obstruction reflection cracking, the study evaluated various types of wire mesh placed under an asphalt overlay [20]. Metal wires were also used for reinforcement, but they were found to be susceptible to rust, with the penetration of water [21]. Many researches try to use non-synthetic fibers for modification purpose. Use of asbestos shown that can be degradable and unsuitable as a long-term reinforcement and a health hazard [22, 23 and 24]. As a reinforcing material, the principal action of the fiber is to provide additional tensile strength in the consequential composite. When the fatigue and fracture process started, fibers can increase the rate of strain absorbed of the mixture [25]. Field studies represent that the addition of fiber will help produce more flexible mixtures and the one that is more resistant to cracking [26].

A multitude of fibers and fiber materials are being introduced as new applicants such as asbestos fibers, polyester fiber, polypropylene fiber, glass fiber, cellulose fiber, carbon fiber, etc. [27]. Ohio State Department of Transportation has reported a method for using polypropylene fibers to modify the performance of hot asphalt mixes [28]. This particular fiber provides three-dimensional reinforcement of the asphalt concrete, making it tougher and durable [29, 30]. Glass fiber can improve the mechanical and physical properties of SMA mixtures such as flow value, stability and the voids. The addition of fiber also improves fatigue by increasing resistance to cracking and permanent deformation of bituminous mixtures [31]. Suitable dispersion of fibers determines the strength of the modified mixtures [32]. Here, asphalt mixture containing fiber indicates a negligible increase in the optimum binder content compared to the control mix; Such as the addition of very fine aggregates. The bitumen value is dependent on absorption and surface area of the fibers and not affected, only by different fiber types and also by different fiber concentrations [33].

Use of these fibers to make high performance reinforced asphalt mixes is yet to be improved due to lack of understanding on reinforcing mechanisms and ways of optimizing fiber properties (i.e., diameter, length, surface texture, etc.). Considering the fiber characteristics, its addition to asphalt mixes could be very different. Researches show that if fibers are too long, it can make “balling” problem (some fibers may lump together) and the fibers may not have suitable blend in the asphalt concrete. Also too short fibers cannot provide suitable reinforcing effect in the mix.

Use of Nanomaterial to improve the performance and durability of materials is very common. For asphalt modification, nano-SiO2 and SBS were used together. The reasearch showed that the asphalt mixture modified by 2% nano- SiO2 and 5% SBS can improve the physical and mechanical properties of asphalt binders and mixtures [34]. Carbon nanofibers were mixed with asphalt cement, and viscoelastic and fatigue characteristics of carbon nanofiber-modified asphalt binder was investigated. The rutting resistance of modified asphalt cement was improved; the fatigue life of carbon nanofiber-modified asphalt cement was also increased [35, 36]. Modify the asphalt binder with polymer modified nanoclay and non-modified nanoclay was conducted and the microstructure images of asphalt binders were investigated. Use of non-modified nanoclay increase the complex shear modulus of the asphalt binder but addition of polymer modified nanoclay decreased this parameter [37]. In other research, Polysiloxane modified montmorillonite and carbon microfibers were investigated to modify the asphalt binders and mixtures. Relative to the control asphalt mixture, the modified asphalt mixture improved the tensile strength, fracture energy, decreased the moisture susceptibility, and reduces the risk of cracking [38].

3.0 Laboratory Evaluation and Investigation

3.1 Materials

The materials used in the this research include 60/70 penetration grade bitumen(AC-10), aggregates with gradation characterized by 12 mm as shown in Fig. 1 (accordance with the Pavement Guidelines of Iran), carbon nanofiber and limestone mineral filler.

This functionalized carbon nanofiber has a diameter of 65-155 nm, length of 35-95 μm, tensile modulus of 620 GPa and tensile strength of 7.1 GPa. The carbon nanofiber has a surface area of 47 m2/g, dispersive surface energy of 86 mJ/m2, moisture content <5 with an Iron and Polyaromatic Hydrocarbon content of <1400 ppm and <1 mg PAH/g, respectively. The carbon nanofiber has suitable performance per cost ratio and good interfacial bonding with matrix materials. In this research kerosene was used as a solvent to disperse the carbon nanofiber and ultimately mixing it with the AC-10 binders. The boiling point of the kerosene and specific gravity are 155 oC and 0.75, respectively.

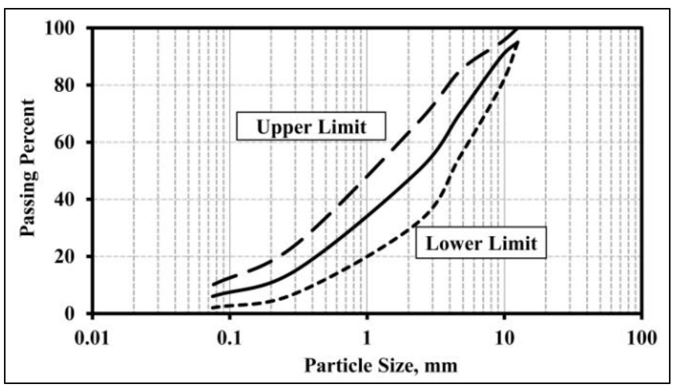

Figure 1: Aggregate Gradation

3.2 Experiments

In this research followed the basic experimental approach to evaluate the properties of carbon nanofiber reinforced bituminous mixtures. For this matter, standard laboratory tests were carried out such as Marshall test (ASTM D 1559), dynamic creep test (AS 2891.12.1), indirect tensile modulus test (IDT-ASTM D 4123-95) and fatigue test using indirect repeated tensile loading (BSI; 2nd draft-DD ABF, method for the evaluation of the fatigue characteristics of bituminous mixtures using indirect tensile fatigue)[39]. UTM-15 equipment and standard Marshall apparatus were applied for the above mentioned tests. Creep tests at 40ºC were conducted, while IDT and fatigue tests were carried out at a maximum temperature of 25ºC.

3.3 Sample Test Preparation

Bitumen mixture were prepared by graded aggregates, 60/70-penetration grade bitumen and carbon nanofiber. The wet blending method was applied where carbon nanofibers were blended with AC-10 binders. Here, nanofiber contents and without optimization were selected arbitrarily. Previous researchers, however had selected carbon fiber content between 0.3%-0.8% by weight of the mixture (Aren et al., 2000). Further, in this research, the filler content was 4%, while carbon nanofiber contents were 0.1, 0.2, 0.3, 0.4 and 0.5 percent by weight of bitumen. The optimum binder content of the original mixture was 5.4 percent by weight, while the modified mixtures were found to have an optimum binder content of 5.4, 5.5, 5.5, 5.6 and 5.6 percent, corresponding to nanofiber content, 0.1, 0.2, 0.3, 0.4 and 0.5 percent, respectively.

Samples were prepared using a Marshall Compactor machine with 75 compaction blows on the top and bottom of specimens. Compaction temperatures and Mixing were designated respectively at 140ºC and 160ºC.

For the creep test, specimens were cut from both ends to 50 mm height smoothly and then were capped using grease and powder. This help to minimize friction of sample with loading plates and ensuring uniaxial stress condition.

4.0 Results and Discussion

4.1 Marshall Stability

In this test, the height of the samples was measured and specimens were immersed in a water bath at 60°C for 35±5 minutes. In continuance, sample quickly placed in the Marshall loading head with the constant rate of 50.8 mm per minute. Stability was identified as the peak load sustained by the sample. The deformation at maximum load named “flow”. The stability values should be adjusted with respect to sample height.

Fig. 2 shows an increase in stability values once the nanofiber content increased in the mixture, but it becomes constant with higher nanofiber contents. To increase stability, it seems that there is the optimum percentage of nanofiber content.

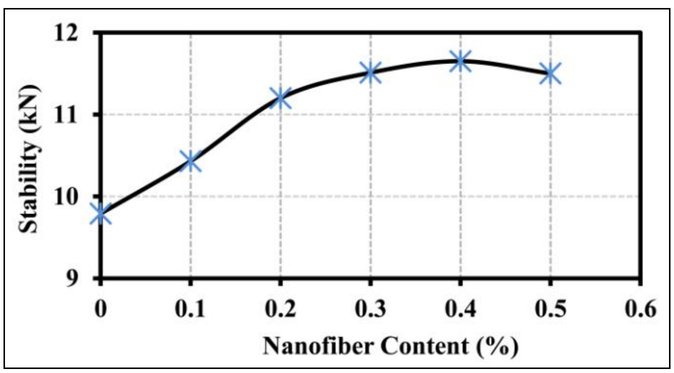

Figure 2: Stability of mixtures and nanofiber Content

4.2 Flow Values

Fig. 3 shows that an increase in nanofiber content decreases the flow value and as such, when the nanofiber content is more than 0.30 percent (i.e. 0.4 and 0.5 percent), the flow values start to increase.

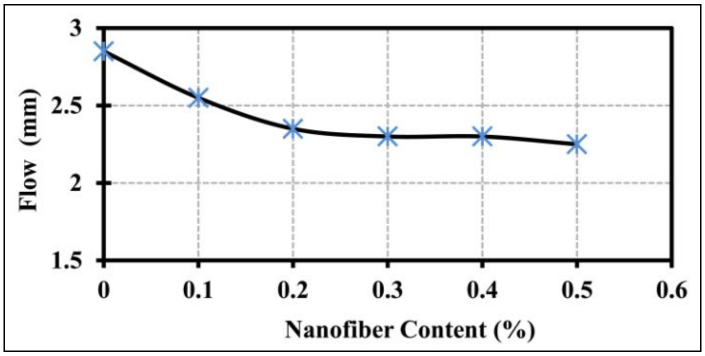

Figure 3: Flow of mixtures and nanofiber Content

4.3 Voids in Total Mix (VTM)

Fig. 4 shows consistent results concerning the effect of nanofiber content on the Voids in Total Mix (VTM). Accordingly, an increase in nanofiber content in the mixture, followed an increase in the Voids in Total Mix (VTM). This property is very important for the design of the pavements in the hot regions, because asphalt may be prone to bleeding and mounting void ratio could restrict bleeding by providing more spaces for the bitumen to move into. This can probably due to greater surface areas to be coated. Nanofiber absorbs binder and then leads to increase the voids in the mixture.

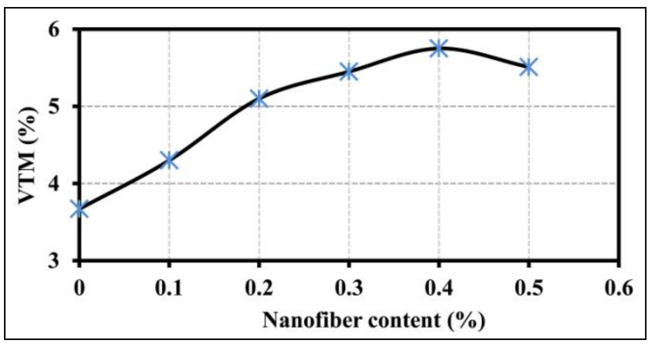

Figure 4: Total Voids of mixtures and nanofiber Content

4.4 Resilient Modulus Results

This test was conducted using cyclic indirect tensile test; thus along the vertical diameter of the specimen a cyclic load is applied and the response deformations along the horizontal diameters are measured. The pulse load selected for this test is a half sine with a 0.125 second pulse width and 1.25 second rest period. Using the principle of plane stress in elasticity theory for homogeneous and isotropic materials, the resilient modulus is calculated as:

$$M_r = \frac{P}{t.\Delta d}(0.27 + \upsilon) \qquad (1)$$

Where; P is the maximum force (15 percent of the tensile strength), t is the thickness of the sample, υ is Poisson's ratio (assumed 0.35) and Δd is the horizontal diametric deformations. However, the assumption of an elastic response is reasonable if the tests are done in the linear viscoelastic range using a very small loading rate which produces low permanent deformations (elastic zone). 5 pulse loading applied and the average results express the resilient modulus.

Regardless of nanofiber content, addition of nanofiber can increase the resilient modulus in the mixture (Fig. 5). The findings show that the resilient modulus increases with the increase of nanofiber content up to 0.4% and remains constant when the nanofiber content increases above 0.4 percent (i.e. 0.4 and 0.5 percent).

It should be noted that the increase of resilient modulus can be due to high tensile modulus of elasticity of carbon nanofibers and lower ability of extension. In the proposed sample, nanofibers in a different direction have a random orientation, which firmly bind aggregate particles inside the matrix and prevent aggregates from moving, hence making the mixture stiffer. However, large amounts of nanofiber leads to the higher surface area that should be coated with bitumen; consequently, the aggregate particles and nanofiber would not be fully coated with bitumen and thereby loose more and less resilient modulus would be obtained.

Compared to the original sample the resilient modulus increased significantly about 29% with the inclusion of 0.4% of nanofiber content.

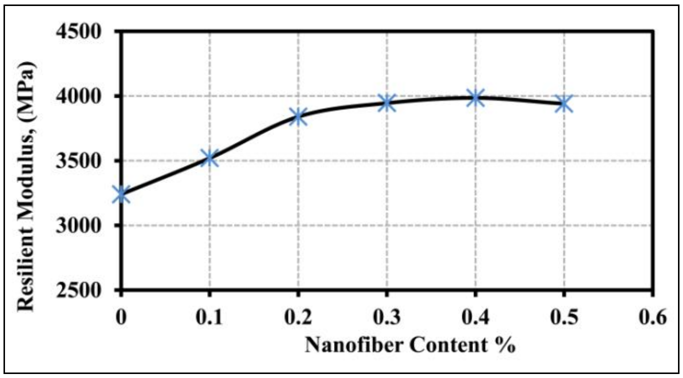

Figure 5: Resilient Modulus of mixtures and nanofiber Content

4.5 Dynamic Creep Test

In this test with applying a repetitive uniaxial compression load, the permanent deformation of the asphalt mixtures was evaluated. The repetitive load is constant and permanent deformation is measured in relation the pulse counts (time). The pulse form selected is half sine with duration of 0.2 second and a rest period of 0.8 second; hence one pulse period is *1* second. Two axial LVDT's are used to measure the axial displacement; the average of them reported as the results. Usually the permanent strain that named accumulated permanent strain is reported which is computed as average permanent deformation divided by sample thickness. By evaluation of permanent strain under repeated load of 200 kPa, the creep test results indicated that the nanofiber content affects the creep properties of the bituminous mixtures.

As illustrated in Fig. 6, increasing nanofiber contents evidently decreases the permanent strains at 7000 cycles. The result of the creep test showed that the addition of a small amount of carbon nanofiber reasonably can improve its deformation characteristics, compared to the non-fiber bituminous mixture, which could deform more easily under the same cyclic loading and temperature conditions. In contrast, a higher percent of carbon nanofiber into the mixture cannot have a beneficial effect and might deteriorate its deformation characteristics due to the same reasons we mentioned the previous sections.

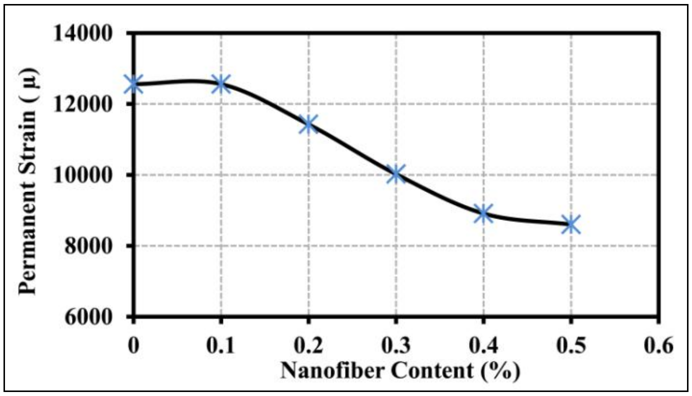

Figure 6: Permanent Strain of mixtures at 7000 Cycles and nanofiber Content

4.6 Fatigue Test

This test, conducted using indirect tensile test with diametric compression load to evaluate the fatigue resistance of the mixtures (ITT fatigue). The applied load is repetitive and constant; so the resulting vertical deflection is measured in relation to pulse counts (time). The number of load cycles corresponding to fracture of specimen was reported as the fatigue life. Usually the results are illustrated as strain or stress versus the resulting fatigue life that commonly referred as S-N curve. This research is reported the number of cycles at which specimen fracture occurs. Repeated load indirect tensile test was conducted using half sine pulse of 5 Hz frequency, 0.15 second loading period and 0.05 second rest period with constant repeated stress of 350 kPa.

Fig. 7 illustrates the results obtained through laboratory fatigue testing (ITT tests). It indicates that the use of carbon nanofibers significantly improves fatigue life and performance of mixtures. Further, carbon nanofiber reinforced mixtures are considerably for fatigue more resistant than the original mixes.

With the addition of 0.1, 0.2 and 0.3 percent carbon nanofiber, fatigue life increased to about 39.4, 41.3 and 48.2 percent, respectively. This was probably due to carbon nanofibers that were distributed in different directions of the bitumen matrix, which prevented aggregate particles from any movement and resisted the shear displacement, thus by efficiently delaying initial cracks and its propagation, the fatigue life increasing.

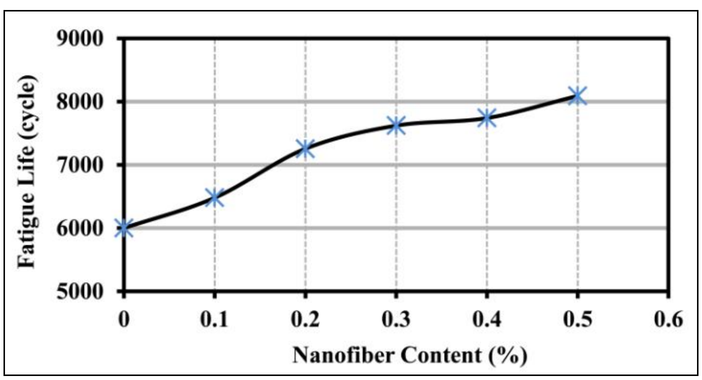

Figure 7: Fatigue life of mixtures and nanofiber Content

4.7 Correlation between Permanent Deformation, Resilient Modulus and Fatigue Life.

It can develop a correlation between permanent deformation, resilient modulus and fatigue life using the results mentioned in the previous section and Figures 5, 6 and 7. Fig. 8 shows that fatigue life of reinforced bituminous mix with nanofiber has good correlation with resilient modulus properties of the mixture. It was observed that, between permanent deformation and stiffness was an inverse correlation. The increase in resilient modulus properties of the samples was followed by a decrease in the permanent deformation as shown in Fig. 9. It was proof that there is a significant linear relationship between resilient modulus and permanent deformation.

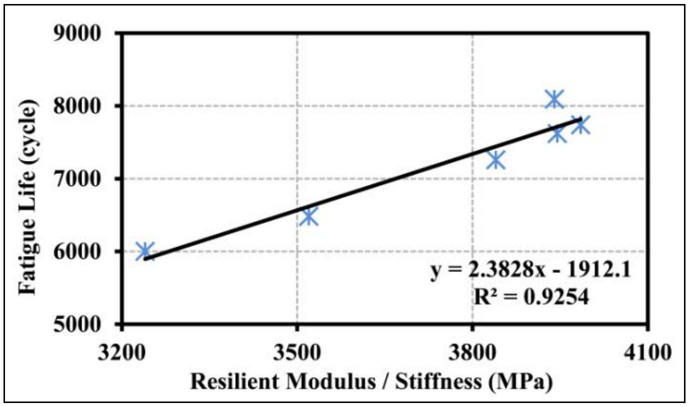

Figure 8: Fatigue Life and Stiffness of mixtures

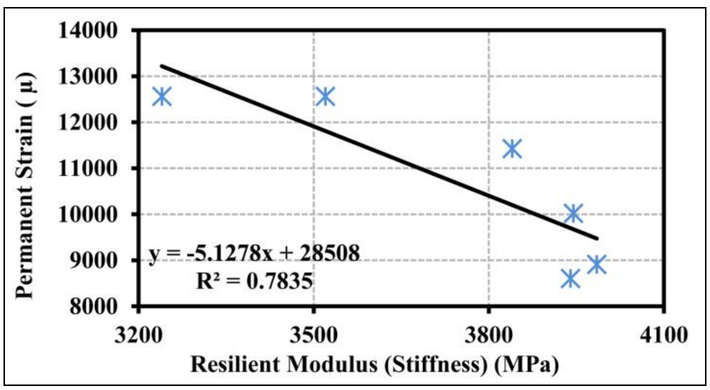

Figure 9: Permanent Deformation at 7000 Cycles and Stiffness of mixtures

5.0 Conclusion

The use of carbon nanofiber showed the consistency of results in the present study. It was observed that the addition of nanofiber has suitable effects on properties of bitumen mixtures by decreasing the flow value and increasing its stability and voids volume. As such, it can be expressed that the use of carbon nanofiber probably improves resistance properties to distress occurring in road pavement due to traffic loads. Further, the addition of nanofiber improves fatigue life and permanent deformation of bitumen mixtures by improving the stiffness of the mix. With adding the 0.4 percent of nanofiber by weight of total mix lead to achieve the highest performance in terms of resistance to permanent deformation, stiffness, and fatigue; however, some mechanical properties of the same mix may be compromised when the nanofiber content exceeds 0.4% level. Since the length of the nanofiber is a critical factor affecting the performance of carbon nanofiber modified asphalt mixtures, it must be ensured that individual nanofibers keep their linear configuration intact after the mixing process. To achieve these improvements, proper attention must be paid to ensure that the nanofibers are uniformly dispersed in the mixture.

The results indicated that nanofiber shows better mechanical behavior than the carbon fiber, which may lead to "balling" phenomenon in the mix and therefore it may lose its beneficial effects. Modified carbon nanofiber mixtures show significant increase in rutting resistance, stiffness and fatigue life. The results of this research indicate good correlation between stiffness with fatigue life and permanent deformation. Characteristics of reinforce mixture is directly related to the addition of nanofiber, its contents and properties.

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