The Effect of Carbon Nano-tube on the Fatigue Life of Asphalt Mixtures

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Abstract

The fatigue cracks are observed in asphalt surfaces much more than ruts. This paper deals with the influence of carbon nano-tube on the fatigue life of asphalt mixtures. These samples are made up of the slabs cut by the asphalt cutting saw. Fatigue beams contain 0, 0.3, 0.6, 0.9, 1.2, and 1.5 percent of Carbon Nano-tube. The fatigue experiment was conducted using a 4-point semi-sinusoidal loading on a flexural beam for a constant strain (600 micro-strain) at 20oC. The end of these samples, fatigue life is assumed to be when 50% reduction in the initial rigidity happens. The results show that with an increase in the percentage of carbon nano-tube in the fatigue samples, the fatigue life of asphalt mixtures and the amount of cumulative dissipated energy increase noticeably, and the rate of damage propagation is reduced. Also rut depth, Fracture Energy density, Marshall Stability, Indirect Tensile strength have been improved excellently.

Keywords: Fatigue life, carbon nano-tube, experiment of flexural beam, rate of damage propagation

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1. Introduction

Asphalt has been widely used for pavement building for a long time. Actually, the increase in traffic loading and number of vehicles together with the adverse environmental conditions, leads to a rapid structural damage in pavements. In order to enhance the mechanical properties and the long time behavior, a new generation of blend asphaltic has been developed through the incorporation of different kinds of polymers [Zhanping et al. 1991; Ghaffarpour et al. 2009; Collins et al. 2011; Sengoz et al., 2007; Lu et al. 2001].

Fatigue cracking is one of the three major distresses (fatigue cracking, low temperature cracking, and rutting) of flexible pavements. Fatigue cracking is mainly caused by repeated traffic loading and it can lead to significant reduction in the serviceability of flexible pavements. The cracking resistance of hot-mix asphalt (HMA) mixtures is directly related to the fatigue performance of flexible pavements. Therefore, the laboratory characterization of the fatigue behavior of HMA mixtures has been an issue of intensive studies for many years. Many laboratory testing methods are available to characterize the fatigue behavior of HMA mixtures. Probably the one that has the most similar stress condition to HMA field mixtures under traffic loading is the repeated flexural test (also called beam fatigue test) [Roberts et al. 1996].

This distress is considered one of the most important problems in bituminous mixtures. It occurs when pavement is stressed to the limit of its service life by repetitive load applications [Brown et al. 2001].

Vehicle wheels load applied on a road pavement may result in permanent deformation in the form of imprints, tracks, corrugations, shoving and ruts. Deformations considerably impair road service properties. Ruts are much more dangerous since they might cause vehicles to skid during precipitation. The ability of bituminous mixes to accumulate damage allows gradual failure instead of fragile failure [Gonzlez et al. 2006; Radziszewski, 2007]. During the fatigue process, resistance decreases and materials undergo continuous degradation, resulting in the formation of micro cracks and eventual complete failure [Castro et al., 2005; Kanitpong et al. 2008].

Among the various Nano-sized materials, Carbon Nano-tube (CNT) probably represent the most promising additive for the improvement of performance characteristics of structural and construction materials[Kuchibhatla et al. 2007]. In this study, the fatigue life of asphalt mixtures containing various percentages of CNT was evaluated. On the basis of the obtained experimental results, the effects of CNT on fatigue life of asphalt mixtures were analyzed and discussed.

2. Literature Review

Many researches have been conducted on Nanoclay modified bitumen, but little published information is available about Carbon Nano-tube modified bitumen. Some researches were also performed on bitumen modification by polymer materials such as SBS (Styrene Butadiene Styrene Block Copolymer), SBR (Styrene Butadiene Rubber Latex) and EVA (Ethyl Vinyl Acetate). Studies on SBS show that SBS improves the rheological properties and fatigue life of asphalt bitumen due to the polymer network formation in the bitumen. This network forms in two stages first at low concentrations, the SBS acts as a dispersed polymer and does not significantly affect the properties second at the higher concentrations, local SBS networks begin to form and are accompanied by a sharp increase in the complex modulus, softening point temperatures, and toughness [Sadeghpour Galooyak et al. 2010]. Ghile performed mechanical tests on asphalt mixture modified by Cloisite. The result showed that Nanoclay modification improves the mechanical behavior properties of the mixture such as indirect tensile strength, creep and fatigue resistance [Ghile, 2005]. Chow investigated surface modified Montmorillonite Nanoclay and compatibilizer, and came to the conclusion that the strength and stiffness of Polyamide polypropylene Nanocomposites improves due to the synergistic effects of surface modified Montmorillonite Nanoclay and compatibilizer [Chow, 2003]. Khattak found that the addition of Nanofiber into bitumen improves rheological properties of modified bitumen [Khattak et al. 2011].

3. Materials and Methods

The bitumen with PG58-16 of degree of performance from Isfahan Refinery has been used to mix with Carbon Nano-tube with ultrasonic mixer. Ziari [Ziari et al,2012] developed a dispersion technique of Carbon Nano-tube (CNT) by combining sonication, high shear and mechanical mixing techniques to achieve the highest degree of dispersion. In their study, several sonication periods with several power rates and several mixing speeds were investigated in order to optimize the dispersion process. The characteristics of bitumen and Carbon Nano-tube are presented in Tables 1 and 2, respectively.

Table 1. Characteristics of used bitumen.

Ductility (cm)	Softening point (^{0}c)	Penetration at 25 ^{0}c (0.1mm)	Pure bitumen
Over 100	51	68	60/70

Table 2. Characteristics of used CNT

length	purity	ash	SSA	Density
30 μm	> 95%	< 1.5 %	200 m^2/gr	2.1 gr/cm^2

Table 3. The properties of the used aggregates in asphalt preparation

Standard Methods	Test Result	Standard limited	Test
ASTM			
C 131	12	25	Maximum Los-Angeles (%)
C88	2	8	Maximum weight loss with sodium sulphate (%)
C127	0.8	2.5	Maximum water absorption (%)
D 4791	1	15	Maximum percentage of flat and aggregates

To investigate the effect of CNT on the properties of bitumen and asphalt, it is initially mixed with the standard bitumen in different weight percentages. To combine the outcome of this mixing was 6 types of standard and modified bitumen including 0.3, 0.6, 0.9, 1.2 and 1.5 percent of CNT. Then, the samples were divided into 3 main groups. Some samples were used to carry out the rheological tests, some for the classical tests of bitumen, and the rest for preparing asphalt samples. To prepare the asphalt samples, the aggregates which had the properties presented in table 3 were employed.

In addition, the grading provided by the publication No. 234 of Management and Planning Organization of Iran, which is also suggested for pavement layer, was taken into account to prepare the asphalt samples.

Table 4. The grading used in asphalt samples preparation

Average passing	Percent passing	Sieve size
100	100	19 mm
95	90-100	12.5 mm
59	44-74	4.75 mm (N0. 4)
43	28-58	2.36 mm (No. 8)
13	5-21	0.3 mm (No. 50)
6	2-10	0.075 mm (No. 200)

4. Test Description

4.1 Introduction of IPC, the Test Rig for the Experiment of Fatigue Behaviour of a Beam

This test setup is able to apply repetitive flexural loads on asphalt samples (or other materials) and calculate both the loads and the resultant deflections. The experiment can be performed in the case of either controlled stress or controlled strain. In the first case, the applied load is considered constant and the deflection is recorded. If creep occurs, the maximum and minimum levels of load are modified in order to keep the beam at the straight state. Different parameters can be calculated from the obtained data including the loading time, repetitions of the applied load, maximum and minimum values of the applied load, maximum and minimum values of beam deflection, tensile stress and strain values, and flexural rigidity.

Figure 1. The schematic view of fatigue life test setup

4.2 The Experiment of Flexural Beam

The experiment of flexural beam can be conducted in two cases of controlled stress and controlled strain. The loading waveform is usually sinusoidal in the case of controlled stress. However it is sinusoidal and semi-sinusoidal in the case of controlled strain. In the case of controlled stress, a specific amount of stress is applied on the sample up to the failure point. For the case of controlled strain, however, the embedded system in the test rig of the beam fatigue experiment modifies the stress after each loading in order to keep the strain constant at a specific value. Fig.2. displays a typical rigidity plot vs. the repetition times of the fatigue experiment done in the case of controlled strain. The plot can be divided into three stages.

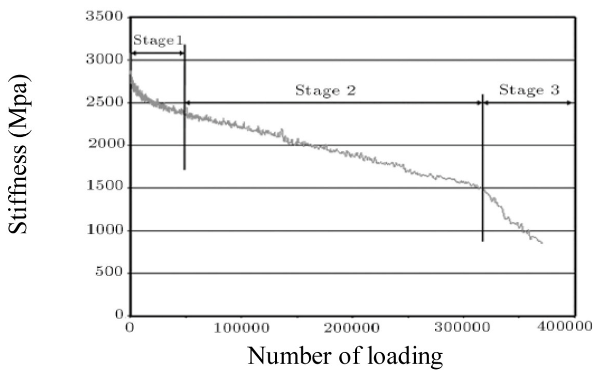

Figure 2. A typical diagram of rigidity vs. load repetition [Hosseini et al.,2009]

First stage

The main characteristic of this stage is a steep decrease in the flexural rigidity of sample. This stage contains 10% of the fatigue life.

Second stage

The predominant property of this stage is the linear decrease in the flexural rigidity of the sample. This stage contains 90% of the fatigue life. In addition, it is the stage of tiny cracks propagation.

Third stage

The main characteristic of this stage is the sudden decrease in the flexural rigidity of the sample. In this stage, the sample approaches the fracture and large cracks are propagated.

In the case of controlled stress, the sample can survive the third stage for a long time without a remarkable decrease in its rigidity, due to a decrease in stress. For this reason, the fracture criterion is usually defined as the reduction in the sample's rigidity to a specific percentage (usually 50%). According to AASHTO-TP8-94, this reduction is 50%. Nonetheless, the best criterion for determining the fracture point of a sample is considering the diagram of flexural rigidity reduction vs. load repetition due to the existed discrepancy in calculation the initial value of rigidity and sometimes, the results dispersion. According to another definition, considering the end of stage 2 and the start of stage 3 determines the fracture point of the sample.

5. Results Analysis

According to the number of obtained samples in the operation of cutting the created slabs, four samples with 600 micro-strains at 20 0.8 oC were tested for each case. To have a better modeling of crack propagation compared to the real situation, the semi-sinusoidal loading with the frequency of 10Hz was used. The experiments were carried out up to the beginning of the third stage of the diagram of rigidity modulus vs. load repetition.

Figure 3. The fractured sample in the fatigue experiment

In the first step of analyzing the obtained results, the fatigue life of different samples was extracted, which is shown in figs.7 and 8. The basis of fatigue life, which is considered in further analyses, is the rigidity reduction down to 50% of its initial value. Then, the diagram of flexural rigidity vs. fatigue life for each case was drawn and by employing the software MINITAB, the exponential regression was performed on these diagrams. Using the obtained diagrams and equations, the correlation coefficient (R2) was acquired for each plot. Some of these diagrams are presented in figs 4, 5, and 6.

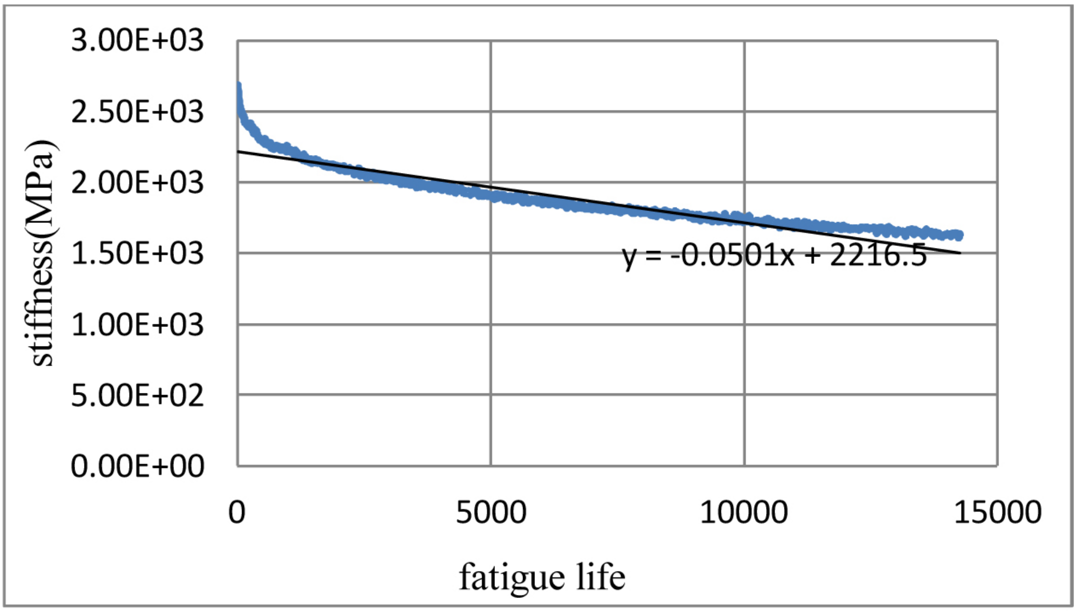

Figure 4. The diagram of flexural rigidity vs. the fatigue life for the beams made up of the standard bitumen

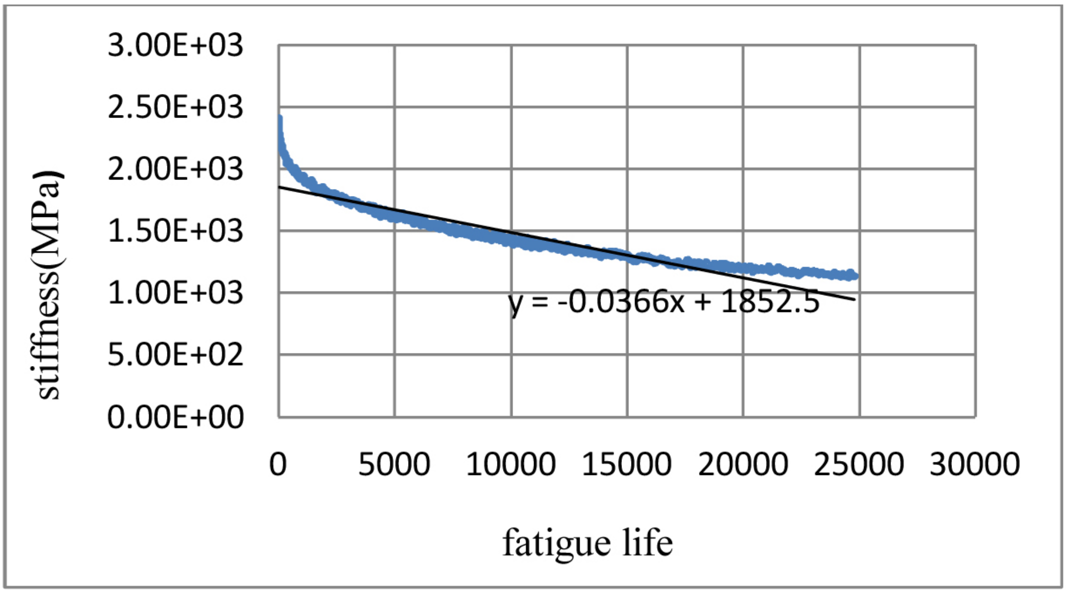

Figure 5. The diagram of flexural rigidity vs. the fatigue life for the beams made up of bitumen containing 0.6% of Carbon Nano-tube

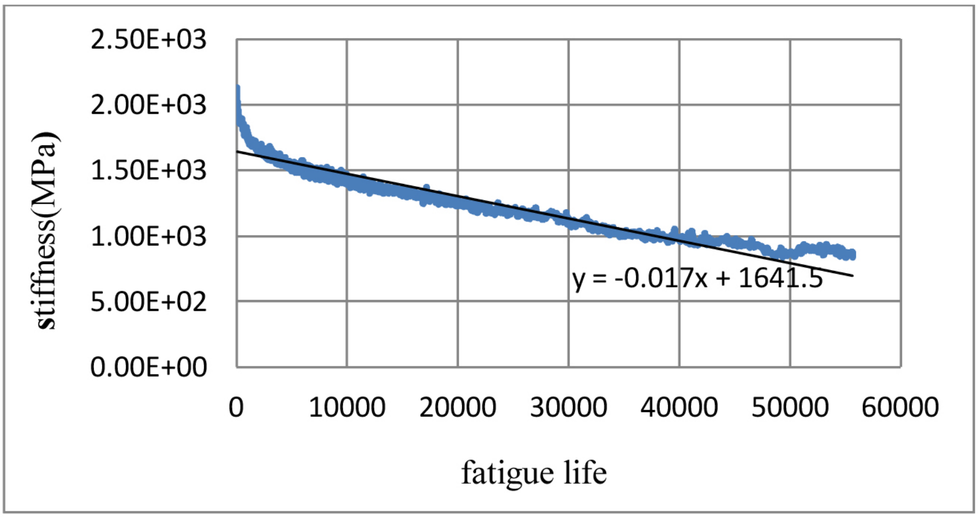

Figure 6.The diagram of flexural rigidity vs. the fatigue life for the beams made up of bitumen containing 1.5% of Carbon Nano-tube

The diagram of fatigue life vs. flexural rigidity for all data is depicted in fig.7. As can be seen in this diagram, when the percentage of the Carbon Nano-tube increases, the fatigue life of asphalt samples increases too, because Carbon Nano-tube has improved the microscopic structure of bitumen and since the fatigue cracks are tiny and are created in extremely small scales, and by considering the fact that adding Carbon Nano-tube to bitumen has improved the fatigue life of asphalt mixture, it can be deduced that these Nano material are effective in preventing such tiny cracks from propagating and can keep them closed. In addition, the average fatigue life for different percentages of Carbon Nano-tube is plotted in figure 8.

In the second step, then, it was tried to employ the fracture mechanic approach in a simple way. According to the previous contents in the section of experiment introduction, the second stage in the diagram of flexural modulus vs. load repetition has an approximately linear slope. This means that the rate of damage propagation is almost constant. As a result, a linear equation can be fitted to the data in this range for different samples. The hypothetical point at which this line crosses the axis of the flexural rigidity is denoted by S0, and the slope of this line, dD/dN, is considered to be the rate of damage propagation[Choi et al.,2002]. Figs. 4, 5, and 6 show the obtained results for a couple of tests. Finally, the diagram of the CNTs percent vs. dD/dN was plotted for each case and these points are fitted using the exponential regression. The rate of damage propagation for different samples is comparatively presented in figs. 9 and 10.

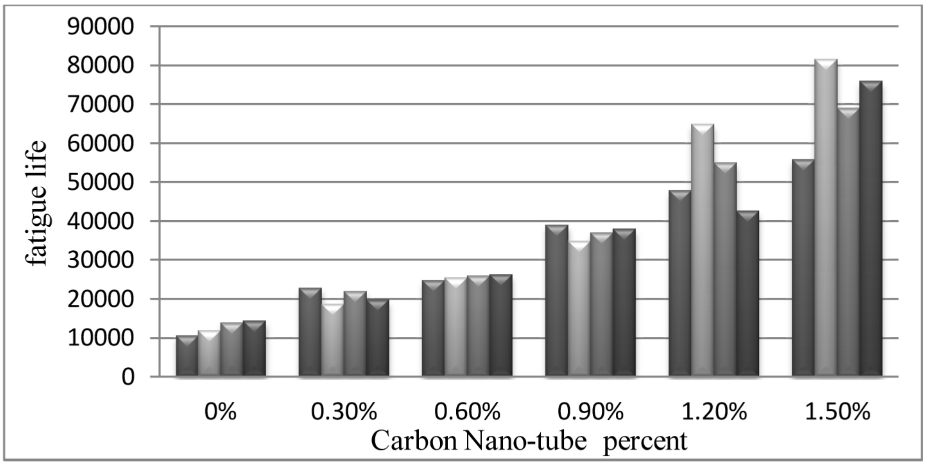

Figure 7.The diagram of the fatigue life vs. the percentage of Carbon Nano-tube

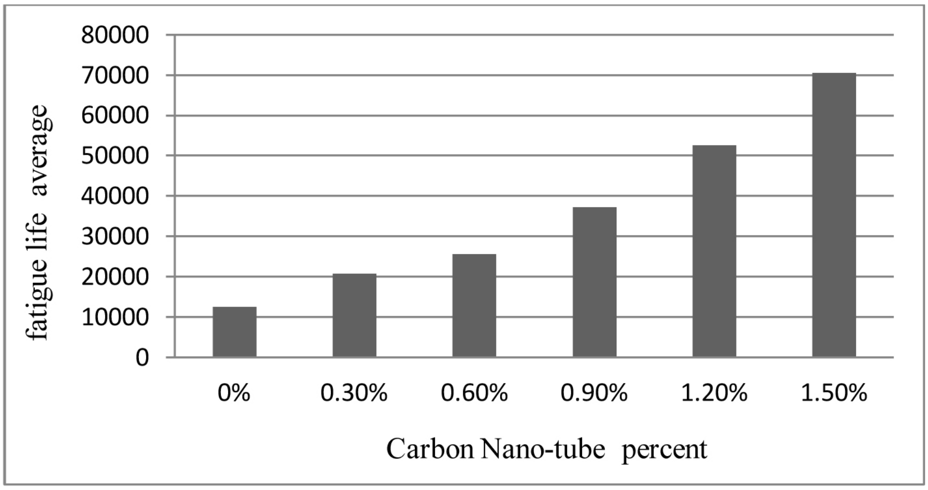

Figure 8.The diagram of fatigue life vs. the percentage of Carbon Nano-tube

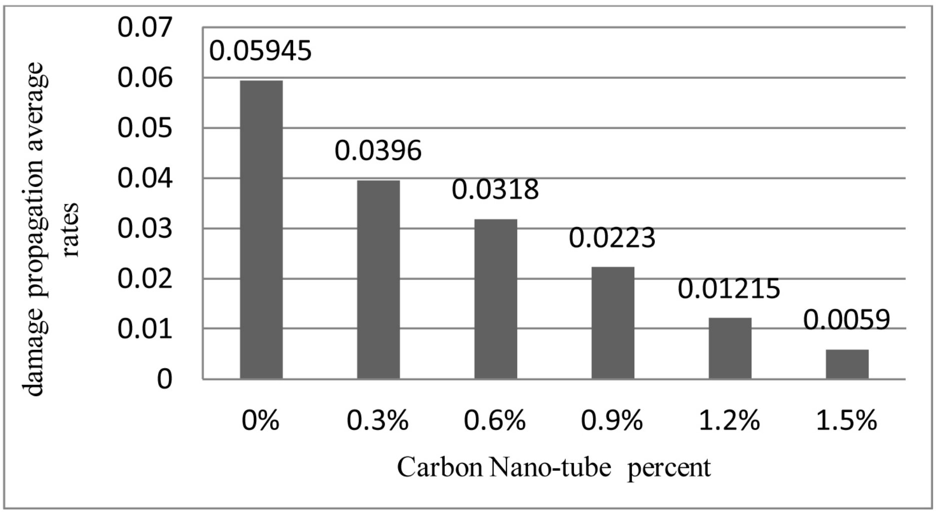

Figure 9.The diagram of the average damage propagation vs. the percentage of Carbon Nano-tube

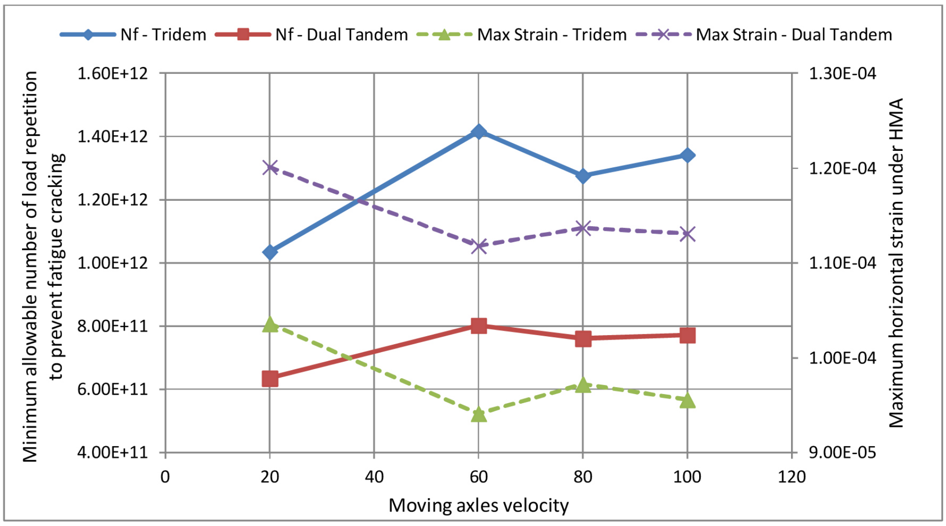

Figure 10.The diagram of the fatigue life vs. the average damage propagation

In the third step, eventually, the cumulative dissipated energy was calculated for each sample. The concept of the dissipated energy is the area under the curve of stress-strain diagram when a material experiences an external loading. The process of loading-unloading for a non-elastic material always includes some dissipated energy as the loading and unloading paths are not coincident. This phenomenon is called hysteresis. The area inside the hysteresis loop of stress-strain for a loading-unloading process is indicative of the dissipated energy for a loading cycle. A typical stress-strain hysteresis loop is depicted in fig. 11. A comprehensive study on the nature of energy dissipation while considering the fundamental properties for all non-elastic materials experiencing energy dissipation during the loading process might make it an extremely acceptable approach for investigating the fatigue properties of materials.

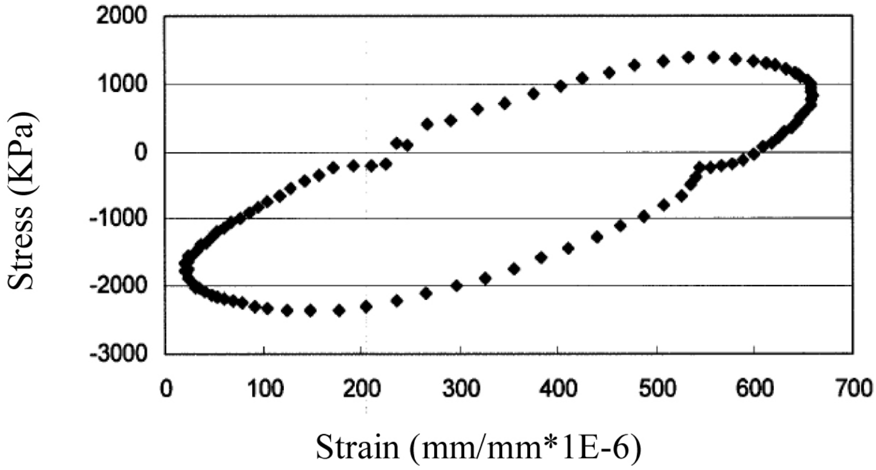

Figure 11. The stress-strain hysteresis loop in the experiment of controlled strain [Danial,N.,2011]

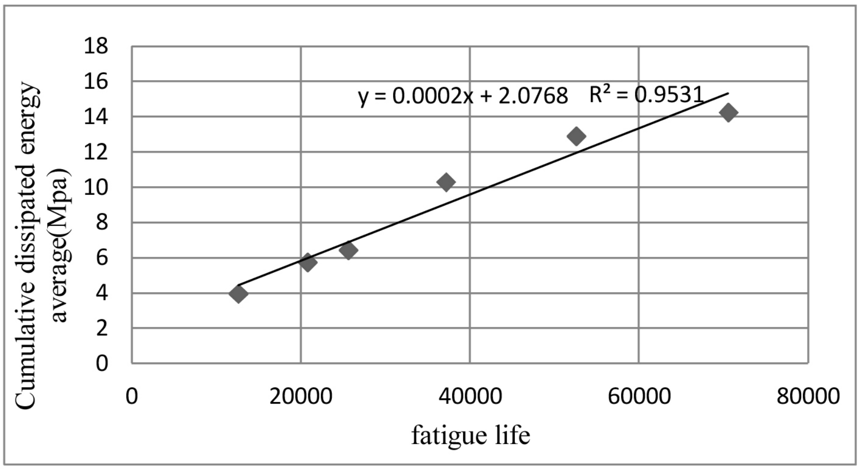

Figure 12. The diagram of the average cumulative dissipated energy vs. the average fatigue life

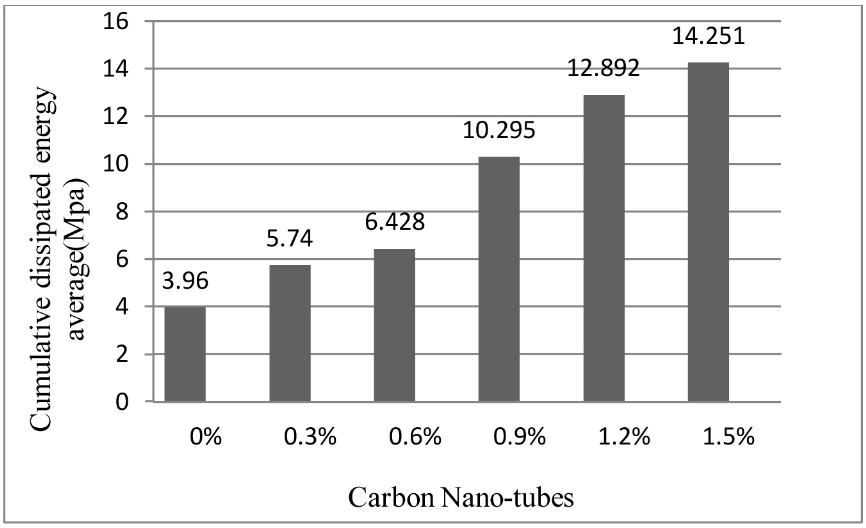

Figure 13. The diagram of the average dissipated energy vs. the average fatigue life.

The diagrams of the average cumulative dissipated energy and also, the average dissipated energy vs. the average fatigue life are displayed in figs. 12 and 13, respectively.

As can be seen, the sample containing 1.5% of Carbon Nano-tube has the maximum dissipated energy and as we know, with an increase in fatigue life, the dissipated energy increases which means that the damping capability increases as the percentage of Carbon Nano-tube increases.

Marshall Stability experiment is conducted according to ASTM-1559. This experiment is performed to investigate the stability and persistence of asphalt mixtures by measuring two parameters of Marshall Stability and Flow. As it is shown in fig.14., with increasing the percentage of CNT, Marshall Stability has also increased so that, this increase is approximately 40% for the samples prepared by adding 1.5% of CNT in comparison to those prepared by the standard bitumen, while the fluency of all samples is within the standard range. The last matter can be indicative of a greater performance of asphalt under traffic loading.

The experiment of Indirect Tensile Strain (ITS) causes tensile stress in the asphalt sample due to the specific loading conditions. Since the major part of the tensile stress in asphalt is sustained by bitumen, as the binder of aggregates, the binding between bitumen and aggregates can be deduced from the result of this experiment. As it is observed in fig.15., as the percentage of CNT increases, the values regarding the experiment of indirect tensile strength increase, too. This issue reveals that adding CNT to bitumen makes the bonding between bitumen and aggregates stronger which is effective in preventing aggregates from striping. And fig.16. indicates the fracture energy density vs. Carbon Nano-tube percent, which show by increasing the CNT percent, fracture energy density goes up.

The experiment of wheel track is indicative of pavement durability in its life cycle. This experiment is definitely one of the most important experiments for comparing the long-term performance of asphalt pavement. As it is shown in fig. 17., the samples with higher percentage of CNT have smaller ruting depth so that this decrease is approximately 74% for the samples prepared by adding 1.5% of CNT in comparison to those prepared by the standard bitumen. Based on the results of rutting experiment, it can be claimed that the use of this material in areas having hot weather or experiencing extremely heavy traffic (the effective parameters in asphalt deformation) has a perfect efficiency.

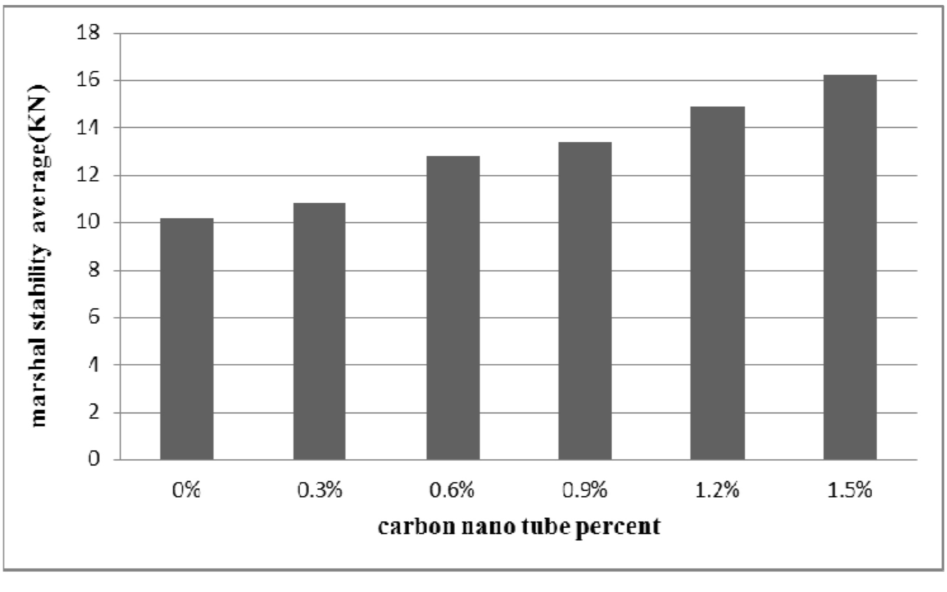

Figure 14. Marshall Stability for different cases

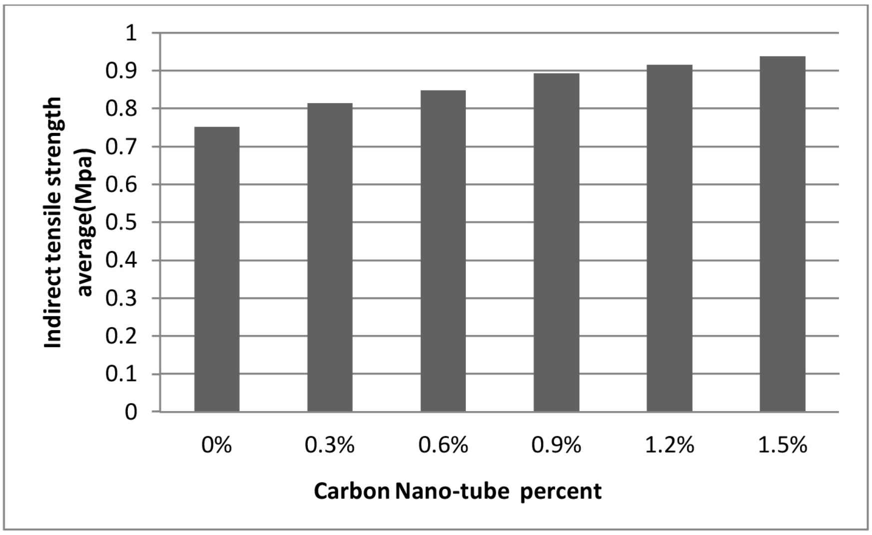

Figure 15. Indirect tensile strength for different cases

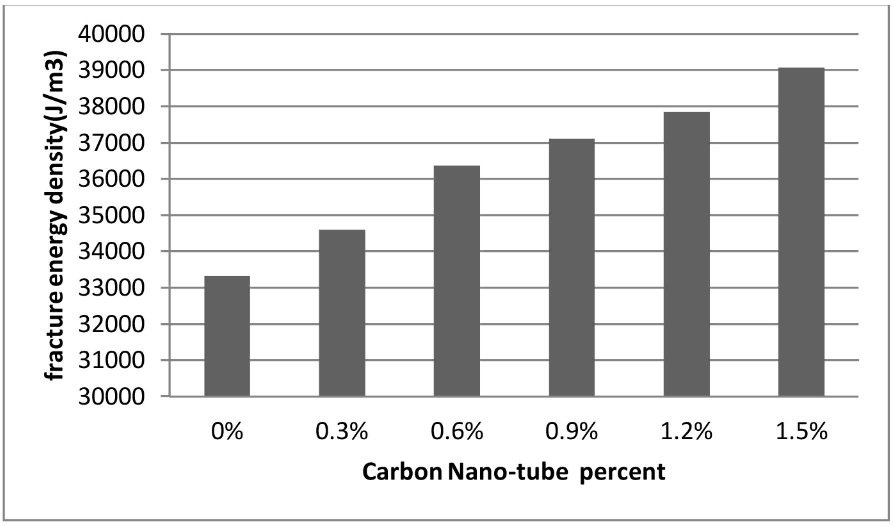

Figure 16. Fracture energy density for different cases

5. Conclusion

Although there has been growing interest and field applications of strengthening pavement structures using Nano-materials, very little information exists regarding the flexural fatigue behaviour of reinforced pavement strengthened with nano materials. This paper presents the results of an investigation into the fatigue behaviour of asphalt pavement strengthened with Carbon Nano-tube (CNT).

The experiment of the 4-point flexural beam is known as one of the best existed experiments, in terms of reliability and fundamentality, for determining the fatigue properties of asphalt layers. The present research indicates that the use of Nano-materials such as Carbon Nano-tube has a remarkable effect on the long-term efficiency of asphalt. In this study, the experi-

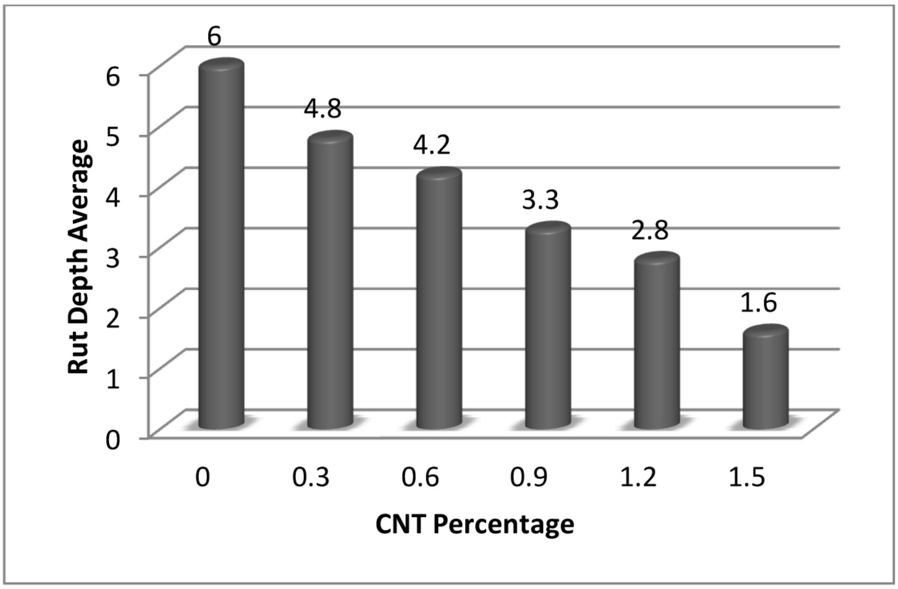

Figure 17. Rut depth for different cases

ment of 4-point flexural beam was conducted for different asphalt samples using the semi-sinusoidal loading at 20oC with 600 micro-strain. Using the obtained data, several parameters were calculated including the fatigue life, the concept of dissipated energy with the criterion of 50% reduction in the initial value of rigidity, the average rate of damage propagation for different percentages of Carbon Nano-tube. It was observed that with an increase in the percentage of Carbon Nano-tube , the fatigue life of the asphalt mixture and also, the cumulative dissipated energy increase and the average rate of damage propagation decreases.

Furthermore, the results of the experiments performed on the asphalt samples indicate that the use of this modifier has improved the Marshal stability, fracture modulus, indirect tensile strain, and rutting of wheels' track.

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