Experimental and Theoretical Investigation on the Effect of Carbon Nanotubes on Flexible Pavement

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Abstract. One of the most recently application for pavement performance improvement is the application of nonmaterial technology. The objectives of this research are to study the beneficial effect of using Nano Carbon Tube (NCTs) on the behaviour of asphalt mixture as preliminary indications and on the performance behaviour of flexible pavement system as a final investigation. The obtained experimental and finite element modelling results showed that adding (0.1%) and (1%) NCTs improved the stability value of asphalt mixture about (15%) and the addition of 0.5 % reduced the flow value around (2% ) which means providing enhancement for rutting resistance. High elastic modulus value of (14000 MPa) are obtained at (0.5%) NCTs. This demonstrated the significant improvement of mechanical properties of modified asphalt mixtures as compared with control mix. The experimental results demonstrated the beneficial applications of carbon nanotubes NCTs additives to minimize the effect of moisture susceptibility for hot asphalt mixtures at (0.1%). The modified asphalt mixture with NCTs decreased the resistance to fatigue damage life of flexible pavement at (0.1%) and (0.5 % ) NCTs but provide improve the fatigue resistance by about (10%) at (1%) NCTs and improved the resistance to rutting damage significantly about (83%), (233%), and (250%) for (0.1%), (0.5%) and (1%) NCTs respectively.

1. Introduction
In recent years the utilization of nanomaterial have been used widely to improve the mechanical and rheological properties of asphalt mixtures. Carbon Nanotubes materials have special properties in terms of high Young’s modulus, tensile stability and high surface density. Several researches used NCTs as modifier for asphalt binder with different percentages due to their low weight and easy to process. You (2015) stated that the addition of nanomaterials improved the rutting resistance and strength of asphalt mixtures and increased the dynamic modulus of asphalt mixtures as compared to control mix [1]. Benan (2017) stated that the optimum multiwall NCTs content WAS (1%) for asphalt binder based on the results obtained from Brookfield viscosity, bending beam rheometer, and dynamic shear rheometer tests at high and low temperatures [2]. Motlagh (2012) investigated the asphalt binder parameters such as bitumen's penetration degree, softening point, flash point, ductility, Marshall stability, Marshall flow, Marshall ration and specific gravity with modified NCTs. They concluded that sample containing 0.01% carbon nanotubes by weight of bitumen presented the best results[3].
2. Carbon Nanotubes Material
Carbon nanotubes consist of carbon atoms linked to hexagonal shapes, with each carbon atom covalently bound to three other carbon atoms. Carbon nanotubes with diameters of not less than 1 nm and lengths of up to several centimeters. Multi Wall Carbon Nanotubes (IMWCNTs). The origin of carbon nanotubes are carbon and they have high specific surface area (700-1000 m²/gm), and due to their high stability and high strength which is about 10 times greater than steel, they used for several building application such as bridges, airplanes[3].

![Multi-Wall Carbon Nanotubes](image)

Figure 1. Multi-Wall Carbon Nanotubes(IMWCNTs).

3. Experimental work

3.1 Marshall Test
In order to investigate the effect of NCTs on mechanical properties of asphalt mixtures, Marshall design method test (ASTM D 1559) [4] is used for testing the prepared samples. Fifteen samples of asphalt mixtures were prepared with different NCTs percentages (0%, 0.1%, 0.5%, and 1%) by wt. of asphalt as shown in Figure 2. based on a study about unaged binder, recommended the use of a relatively high percentage of CNFs (>1%) to increase resistance to permanent deformation at high temperatures[9]. Marshall test are applied for hot mixture specimens to determine stability and flow values using the loading frame shown in Figure 3. A constant rate of deformation of 5 mm per minute until failure is applied. The total maximum in kN (that causes failure of the specimen) is taken as Marshall Stability and the total amount of deformation that occurs at maximum load is recorded as Flow Value. Before conducting the stability test, the specimen is immersed in a bath of water at a temperature of 60°± 1°C for a period of 30 minutes then its placed in the Marshall stability testing machine. The scope of work presented in figure 1.

3.2 Indirect Tensile Strength Test
The static indirect tensile strength of a specimen is determined using the procedure outlined in (ASTM D 6931)[5]. A loading rate of 51mm/minute is adopted. The tensile failure occurs in the sample rather than the compressive failure. Steel strips are used so that the load is applied uniformly along the length of the cylinder. The compressive load indirectly creates a tensile load in the horizontal direction of the sample. The peak load is recorded and divided by appropriate geometrical factors to obtain the split tensile strength using Eq. (1):

\[ IDT = \frac{2000P}{\pi t D} \] (1)
Where: IDT = indirect tensile strength, kPa, \( P \) = maximum load (N), \( t \) = specimen height immediately before test (mm), and \( D \) = specimen diameter, (mm).

And moisture sensitivity was evaluated as follows:

\[
TSR = \left( \frac{IDTW}{IDTD} \right) \times 100 \tag{2}
\]

Where: TSR the tensile strength ratio (%), \( IDTW \) = tensile strength of five conditioned (wet) specimens (MPa) and \( IDTD \) = tensile strength of five unconditioned (dry) specimens (MPa).

Figure 2. Scope of Experimental Work.

4. Finite Element Modelling

To take advantages of experimental test results and get best indication of pavement performance with application of NCTs, the finite element model of flexible pavement system is applied. The finite element meshes, boundary conditions (displacements, rotations, temperatures, etc) and wheel footprint loading simulation using ABAQUS ver.6.12.1 are as presented in Figure. 3, 4, and 5 respectively. The Tire pressure modelled by ABAQUS finite element program using the rectangle footprint shape shown in Figure (6) for standard axel load of one tire (40 kN) is transferred to pavement surface through uniform contact pressure (690 kPa). The contact pressure assumed to be equal to tire pressure due to neglecting the stiffness effect of tire wall, (Huang, 2004)[6].
5. Results and Discussions

5.1 Experimental Part
5.1.1 Effect of Carbon Nanotubes on Marshall Characteristics.
To address the effect of NCTs carbon nanotubes addition on asphalt mixture characteristics, Marshall Test ASTM (D 1559) [1] is used. Fifteen specimens were prepared three samples for each percentage. Marshall specimens are prepared at 5% asphalt content with different percentages of NCTs (0, 0.1,
0.5, 1)% . Figure 7 depicts the variation of Marshall stability with the addition of NCTs. When adding (0.1%) and (1%) NCTs improved the stability value of asphalt mixture about (15%) which attributed to the high surface area of NCTs that provide high stability and tensile strength. The addition of 0.5 % reduce the flow value around (2%) which provide enhancement for rutting resistance as displayed in Figure 6. Figure 7 to 10 presented the effect of NCTs addition on Maximum Theoretical Specific Gravity ($G_{mm}$), Bulk Specific Gravity ($G_{mb}$) and air voids results respectively. Minimum air voids were obtained at (0.5%) NCTs. It can observed that the bulk specific gravity reduced at (0.5%) less than the unconditioned control sample and then start to increase at (1%) NCTs. The addition of micro Carbon nanotubes also effect on the elastic modulus of asphalt mixture as shown in Figure (11). Higher value of (14000 MPa) are obtained at (0.5%) NCTs. This demonstrated the significant improvement of mechanical properties of modified asphalt mixtures as compared with control mix.

5.1.2 Optimum value of NCTs Addition.
Based on the above results for stability, flow, bulk specific gravity, elastic modulus and tensile strength ration. The best optimum value of additives is determined as shown in Table. 1 which presents the optimum value for each mechanical properties of asphalt mixture that have been studies in this research. Finally it can be demonstrated the following:
1. additions of 0.1% NCTs provides remarkable improvement for stability, elastic modulus, bulk specific gravity and resistance to moisture damage of asphalt mixtures.
2. additions of 0.5% NCTs minimized the flow and air voids.

| Mechanical properties       | CNTs Value |
|-----------------------------|------------|
| Stability                   | 1%         |
| Flow                        | 0.5%       |
| Bulk Specific Gravity       | 1%         |
| Air Voids                   | 0.5%       |
| Elastic Modulus             | 0.1%       |

Figure 6. Effect of NCTs on Marshall Stability
Figure 7. Effect of NCTs on Marshall Flow.

Figure 8. Effect of NCTs on Maximum Theoretical Specific Gravity ($G_{mm}$).

Figure 9. Effect of NCTs on Bulk Specific Gravity ($G_{mb}$).

Figure 10. Effect of NCTs on Air voids.
5.2 Theoretical part

In order to get better understanding of the behavior of flexible pavement modified with carbon nanotubes; finite element modeling of flexible pavement with ABAQUS (ver. 6.12-1) [7] computer program using the results obtained from the experimental work was applied to study the overall performance taking into consideration the critical stresses and strains developed in the pavement layer system. Table 2 presents the input material characteristics used for finite element analysis.

Table 2. Pavement Layer Properties.

| Material properties         | Elastic Modulus (MPa) | Poisson's ratio | Bulk Specific Gravity |
|----------------------------|-----------------------|-----------------|-----------------------|
| Asphalt Layer              | 14000                 | 0.35            | 2240                  |
| Subgrade Layer [8]         | 211.53                | 0.4             | 1870                  |

5.2.1 Effect of NCTs on Fatigue Damage.

The fatigue damage of flexible pavement modified with NCTs was observed in terms of critical horizontal tensile strain generated at the bottom of asphalt layer due to the application of tire pressure. Figure 13 presents the distribution of strains in flexible pavement system. As shown from the obtained analysis results of finite element program; a concentration of strains under the loaded area and a maximum horizontal tensile strain is generated within asphalt layer then gradually changed to compressive at the top of subgrade layer. Figure 13 explained the effect of NCTs on critical horizontal tensile strains at bottom of asphalt layer.
Based on the obtained finite element results for horizontal tensile strain presented in Figure (14), the fatigue damage of flexible pavement using NCTs is estimated according to Asphalt Institute (MS-1, 1982)\cite{6} Equation (3) below and presented in Figure (15). It can be observed that NCTs decreased the resistance to fatigue damage life of flexible pavement at (0.1%) and (0.5%) NCTs and then improve the fatigue resistance by about (10%).

\[
N_f = 0.0796 \left( \frac{1}{\varepsilon_t} \right)^{3.291} \left( \frac{1}{E_1} \right)^{0.854} \tag{3}
\]

\(\varepsilon_t\): Horizontal tensile strain at bottom of asphalt layer.
\(E_1\): Elastic Modulus of Asphalt layer.
\(N_f\): Number of repetitions to cause fatigue damage.

Figure 13. Horizontal Strain Distribution within Flexible Pavement System.

Figure 14. Effect of NCTs on Horizontal Tensile Strain at Bottom of Asphalt Layer.

Figure 15. Effect of NCTs on Fatigue Life of Flexible Pavement.
5.2.2 Effect of NCTs on Rutting Damage.
The rutting damage of flexible pavement using NCTs is estimated using the obtained ABAQUS finite element modeling results for vertical compressive strain at top of subgrade layer. Figure.16 explained the distribution of vertical stresses. A maximum vertical compressive strain is concentrated on the top of subgrade layer as shown from the strain distribution figure then decreased gradually as increasing the depth below pavement. Figure 17 presents the variation of vertical compressive strain with the added percentage of NCTs. The vertical compressive strain results reduced significantly with NCTs modified asphalt mixture as compared with control mixture about (38%), (73%), and (71%) for (0.1%), (0.5%) and (1%) NCTs respectively.

![Vertical Strain Distribution within Flexible Pavement System.](image1)

![Effect of NCTs on Vertical Compressive Strain at Top of Subgrade Layer.](image2)

Using the finite element results for compressive vertical strain which presented in Figure (17), the rutting damage of flexible pavement using NCTs is estimated according to Asphalt Institute (MS-1, 1982)[6] Equation. 4 below and presented in Figure (18).

\[ N_r = 1.365 \times 10^{-9} \left( \frac{1}{\epsilon_c} \right)^{4.477} \]  \hspace{1cm} (4)

Where:
- \( N_r \): number of load applications to limit rutting.
- \( \epsilon_c \): vertical compressive strain, at the top of subgrade.

The NCTs modified asphalt mixture improve the resistance to rutting damage significantly about (83%), (233%), and (250%) for (0.1%), (0.5%) and (1%) NCTs respectively and this rate of improvement for rutting is much greater than fatigue. Finally it can demonstrated that the useful application of NCTs nano materials that provide better resistance results for rutting and damage resistance for flexible pavement.
6. Conclusions
In this research the experimental and theoretical investigation of using NCTs in asphalt mixture and on flexible pavement are studied. The following remarks are concluded based on the results:
1. Adding (0.1%) and (1%) NCTs improved the stability value of asphalt mixture about (15%) which attributed to the high surface density of NCTs that provide high stability and tensile strength. And addition of 0.5 % reduce the flow value around (2%) which provide enhancement for rutting resistance. Also minimum air voids are obtained at (0.5%) NCTs carbon nanotubes.
2. The addition of Carbon nanotubes also effect on the elastic modulus of asphalt mixture. Higher value of (14000 MPa) are obtained at (0.5%) NCTs. This demonstrated the significant improvement of mechanical properties of modified asphalt mixtures as compared with control mix.
3. NCTs provides enhancement against moisture susceptibility at (0.1%) and this is due to the high tensile stability of carbon nanotubes. This confirmed the beneficial applications of carbon nanotubes NCTs additives to minimize the effect of moisture susceptibility and enhanced resistance to moisture induced damage for hot asphalt mixtures (0.1%).
4. The modified asphalt mixture with NCTs decreased the resistance to fatigue damage life of flexible pavement at (0.1%) and (0.5 %) NCTs and then improve the fatigue resistance by about (10%) at (1%) NCTs.
5. The vertical compressive strain results reduced significantly with NCTs modified asphalt mixture as compared with control mixture about (38%), (73%), and (71%) for (0.1%) , (0.5%) and (1%) NCTs respectively. And the NCTs modified asphalt mixture improve the resistance to rutting damage significantly about (83%) , (233%) , and (250%) for (0.1%), (0.5%) and (1%) NCTs respectively and this rate of improvement for rutting is much greater than fatigue. As a result, it can demonstrated that the useful application of NCTs nonmaterial that provide better resistance results for rutting and damage resistance for flexible pavement.

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