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# Effects of Carbon Nanotubes on Asphalt Binder Rheology and Wearing Course Mixes

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**Abstract**

This study explores the influence of Carbon Nanotubes (CNTs) on the rheological and mechanical performance of asphalt binders and mixtures, with the objective of determining an optimal CNT content for enhanced pavement durability. CNTs were incorporated into asphalt binders at concentrations ranging from 0.5% to 2.0% by weight, and the modified binders were subjected to a comprehensive testing program. Rheological behavior was assessed using Rotational Viscosity (RV), Dynamic Shear Rheometer (DSR), Multiple Stress Creep Recovery (MSCR), and Bending Beam Rheometer (BBR) tests. Mechanical properties were evaluated through Marshall stability and Wheel Tracking tests, while microstructural characteristics were analyzed using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). The results demonstrated that CNT modification enhanced binder viscosity, high-temperature stiffness, and rutting resistance, with optimal performance observed at 1.5% CNT content. At this dosage, rutting depth was reduced from 15.0 mm to 6.2 mm, and Marshall stability increased from 11.7 kN to 17.4 kN. Additionally, tensile strength peaked at 1290 kPa, and moisture resistance (TSR > 86%) was significantly improved. However, higher CNT concentrations (>1.5%) resulted in particle agglomeration, adversely affecting workability and fatigue resistance. The findings identify 1.5% CNT as the optimal dosage, offering a balanced enhancement in performance without compromising binder flexibility.

*Keywords:* Carbon Nanotubes (CNTs); Asphalt Binder; Rheology; Rutting Resistance; Performance Grading; Fatigue Life; Low-Temperature Properties.

## 1. Introduction

The performance of asphalt binders plays a critical role in determining the durability, stability, and longevity of flexible pavements. Over time, asphalt pavements are subjected to various environmental and loading conditions that can lead to permanent deformation (rutting), fatigue cracking, and thermal cracking. To enhance the rheological properties and resistance to these distresses, researchers have explored the incorporation of nanomaterials, including Carbon Nanotubes (CNTs), as potential asphalt modifiers. Carbon Nanotubes (CNTs) are known for their exceptional mechanical, thermal, and electrical properties, making them a promising additive for improving the high-temperature performance and durability of asphalt binders. Their nanoscale structure allows for enhanced dispersion and interaction with the binder matrix, potentially leading to increased stiffness and deformation resistance. However, the extent to which CNTs influence the performance grading (PG) characteristics of asphalt binders across different temperature ranges remains a subject of investigation [1].

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This study aims to evaluate the impact of CNTs on the rheological and mechanical properties of asphalt binders through a comprehensive set of laboratory tests, including Rotational Viscosity (RV), Dynamic Shear Rheometer (DSR), Multiple Stress Creep Recovery (MSCR), and Bending Beam Rheometer (BBR) tests. The research focuses on assessing changes in viscosity, stiffness, rutting resistance, fatigue life, and low-temperature performance due to CNT modification.

This study focuses on asphalt binders modified with varying CNT concentrations (0.5%, 1.0%, 1.5%, and 2.0% by weight of the binder) and compares their performance against a control binder and an aged control mix. The findings will provide insights into the feasibility of CNTs as a binder modifier and their potential benefits or limitations in pavement applications. Cavalline et al. [2] quantified CNTs' environmental footprint, noting that 1% CNT reduced pavement life-cycle $CO_2$ emissions by 15% (due to extended service life) but raised production costs by 30%.

Zhang et al. [3] reported that CNT-modified binders retained 90% of their initial stiffness after RTFO+PAV aging, outperforming conventional polymer modifiers (e.g., SBS retained 75%). ul Haq et al. [4] investigated CNT-SBS hybrid modifiers, reporting synergistic effects: 1% CNT + 3% SBS increased the high PG grade to 82°C while maintaining low-temperature flexibility (PG -22°C). This highlighted CNTs' potential in polymer-composite systems. Table 1 shows a brief of important papers that have been studied CNT -modified asphalt binders.

**Table 1. Previous Studies on CNT-Modified Asphalt Binders**

| Year | Researchers | Key Findings |
|---|---|---|
| 2015 | Jiménez et al. [5] | Investigated mixing procedures of CNTs with asphalt and found that CNTs enhance rutting resistance and thermal cracking resistance. |
| 2015 | Faramarzi et al. [6] | Conducted a comprehensive review indicating that CNTs improve stiffness and rutting resistance of asphalt binders. |
| 2018 | Wang a Zhang [7] | Found that CNTs improve high-temperature performance and permanent deformation resistance in both binders and mixtures. |
| 2018 | ul Haq et al. [8] | Demonstrated that CNTs enhance thermal conductivity, physical, and rheological properties of asphalt binders. |
| 2015 | Galooyak1i et al. [9] | Showed that CNTs improve complex modulus, viscosity, and creep recovery, indicating enhanced resistance to permanent deformation. |
| 2023 | Ezzat et al. [10] | Confirmed that CNTs improve adhesion properties between reclaimed asphalt shingles (RAS) and aggregates, enhancing water damage resistance. |
| 2020 | Wang et al. [11] | Evaluated the enhancement in physical and rheological properties of asphalt binder using multi-walled CNTs (MWCNTs) as modifiers. |
| 2017 | Hung & Zhou [12] | Demonstrated that ultra-sonication combined with high-shear mixing improved CNT dispersion by 40% compared to mechanical stirring alone, achieving a 35% reduction in creep compliance (*Jnr*) at 1.2% CNT loading. Their work emphasized the need for hybrid mixing techniques to prevent agglomeration. |
| 2022 | Gupta & Mahmood [13] | Assessed the impact of adding styrene-butadiene-styrene (SBS) elastomer polymer and MWCNT nanomaterials to virgin asphalt, noting improvements in rheological properties. |
| 2022 | Sun et al. [14] | Identified a "stiffness-fatigue trade-off": While 1.5% CNT improved rutting resistance by 50%, it reduced fatigue life (Nf) by 20% in Linear Amplitude Sweep (LAS) tests, aligning with this study's PG intermediate-temperature findings |
| 2024 | Jwaida et al. [15] | Argued that CNTs are economically viable only for high-traffic corridors, with optimal dosages between 1.0–1.5% by weight of modified asphalt to balance cost and performance |

While previous studies have demonstrated that CNTs can enhance certain properties of asphalt binders, inconsistencies remain regarding their impact on rutting resistance and fatigue life. Additionally, the optimal CNT concentration for achieving balanced performance across various temperature ranges has not been conclusively determined.

Recent advancements in nanotechnology have intensified research on Carbon Nanotube (CNT)-modified asphalt binders, with studies focusing on optimizing dispersion methods, multi-functional performance enhancement, and large-scale feasibility Zhu & Kong [16] conducted a field trial involving a 1-kilometer section of carbon nanotube (CNT)-modified asphalt pavement, which demonstrated a 60% reduction in rutting after two years of service. Despite this promising performance, the study identified the challenge of achieving consistent CNT dispersion during mixing as a critical limitation to the broader adoption of this technology. This study aims to evaluate the effect of different concentrations of CNTs (0.5%, 1.0%, 1.5%, and 2.0% by weight of the binder) on the rheological and performance properties of asphalt binders. Through comprehensive laboratory tests including Rotational Viscosity (RV), Dynamic Shear Rheometer (DSR), Multiple Stress Creep Recovery (MSCR), and Bending Beam Rheometer (BBR). The research seeks to identify the optimal CNT dosage that achieves a balanced enhancement in high-temperature stiffness, rutting resistance, fatigue life, and low-temperature performance.

## 2. Materials and Sample Preparation

### 2.1. Asphalt Binder

The asphalt binder used in this study was obtained from the Nassiriyah Oil Refinery, located southwest of Baghdad, Iraq, and classified as (40–50) penetration grade. Table 2 presents physical properties of asphalt binder used.

Additionally, the binder's rheological properties were assessed using the Superpave performance grade (PG) system, following AASHTO M320 standards [17], confirming its compliance with PG 70–16 specifications as presented in Table 3

**Table 2. Physical properties of asphalt binder**

| Property | Standard Method | Test result | Specification limit |
|---|---|---|---|
| Penetration at 25 °C, 100 g, 5 s (0.1 mm) | AASHTO T49 [18] | 47 | (40–50) |
| Ductility at 25 °C, 5 cm/min (cm) | AASHTO T51 [19] | 120 | >100 |
| Flashpoint (Cleveland open cup) (°C) | AASHTO T48 [20] | 283 | Min.232 |
| Softening point, (°C) | AASHTO T53 [21] | 54.2 | - |
| Specific gravity at 25 °C | ASTM-D70 [22] | 1.026 | - |
| The residue from rolling thin film oven test | AASHTO T240 [23] | | |
| Retained penetration, % of original | AASHTO T49 [18] | 60 | ≥55 |
| Ductility at 25 °C, 5 cm/min, (cm) | AASHTO T51 [19] | 48 | ≥25 |

**Table 3. Rheological properties of the control asphalt binder**

| Asphalt Binder | Properties | Temperature Measured (°C) | Measured Parameters | Specification Requirements (AASHTO M320-05) [17] |
|---|---|---|---|---|
| Original | Flash Point (°C) | - | 311 | 230 °C, min |
| | Rotational Viscosity at 135 °C (Pa.s) | - | 0.720 | 3 Pa.s, max |
| | DSR, G/sinδ at 10 rad/s (kPa) | 58 | 5.52 | 1.00 kPa, min |
| | | 64 | 2.5 | |
| | | 70 | 1.24 | |
| | | 76 | 0.654 | |
| RTFO Aged | Mass Loss (%) | - | 0.266 | 1 %, max |
| | DSR, G/sinδ at 10 rad/s (kPa) | 58 | 13.7 | 2.2 kPa, min |
| | | 64 | 5.94 | |
| | | 70 | 2.75 | |
| | | 76 | 1.35 | |
| PAV Aged | DSR, G.sind at 10 rad/s (kPa) | 25 | 6266 | 5000 kPa, max |
| | | 28 | 3358 | |
| | | 31 | 5123 | |
| | BBR, Creep Stiffness (MPa) | -12 | 291 | 300 MPa, max |
| | Slope m-value | -12 | 0.301 | 0.3, min |

## 2.2. Carbon Nanotubes (CNTs)

Multi-walled Carbon Nanotubes (MWCNTs) were incorporated into the asphalt binder at different concentrations: 0.5% CNT ,1.0% CNT, 1.5% CNT and 2.0% CNT The CNTs were dispersed into the asphalt binder through a high-shear mixing process to ensure uniform distribution. Table 4. illustrates Physical properties of Carbon Nanotubes.

**Table 4. Physical properties of Carbon Nanotubes**

| Property | Carbon Nanotubes (CNTs) |
|---|---|
| Molecular Weight (g/mol) | Varies (depends on structure) |
| Appearance | White Powder |
| Average Particle Size (nm) | 78 |
| Purity (%) | 98 |
| Specific Surface Area ($m^2/g$) | 892 |
| Melting Point (°C) | 3650 |
| Bulk Density ($kg/m^3$) | 960 |

## 2.3. Sample Preparation

The control and CNT-modified binders were heated to specific temperature range for proper mixing. CNTs were added gradually and mixed using a high-speed mechanical stirrer (5000 rpm) for 30–60 minutes to achieve homogeneous dispersion. Mixing temperature is a temperature range that are corresponding to control and modified asphalt with various CNT percents rotational viscosities (0.17 Pa.s ± 0.02) and compaction temperature Range are at viscosities of (0.28 Pa.s ± 0.03). Figure 1 presents effects of CNT on rotational viscosities of different asphalt types.

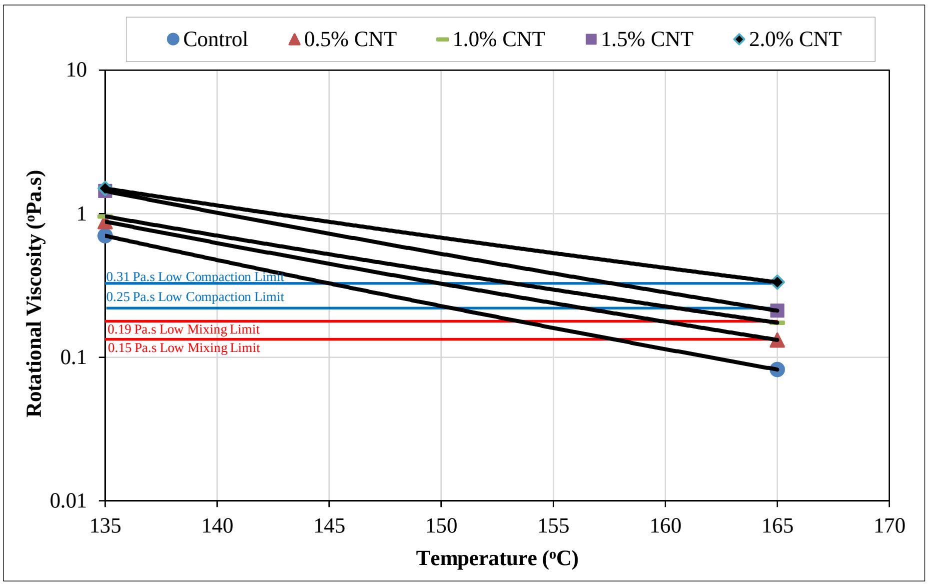



**Figure 1. Effect of CNT percent on rotational viscosity**

Table 5 summaries the mixing and compaction ranges of various asphalt mixtures that have been prepared with control and modified asphalt types.

**Table 5. Mixing and compaction ranges of various asphalt mixes**

| Asphalt types | CONTROL | 0.5% CNT | 1.0% CNT | 1.5% CNT | 2.0% CNT |
|---|---|---|---|---|---|
| Mixing Temperature Range (°C) | 153-156 | 157-159 | 162-164 | 166-169 | 172-176 |
| Compaction Temperature Range (°C) | 145-147 | 147-151 | 150-154 | 156-160 | 159-164 |

# 3. Dynamic Shear Rheometer (DSR) Tests

Asphalt binders are viscoelastic. This means they behave partly like an elastic solid (deformation due to loading is recoverable – it is able to return to its original shape after a load is removed) and partly like a viscous liquid (deformation due to loading is non-recoverable – it cannot return to its original shape after a load is removed). Having been used in the plastics industry for years, the DSR is capable of quantifying both elastic and viscous properties. This makes it well suited for characterizing asphalt binders in the in-service pavement temperature range. The DSR measures a specimen's complex shear modulus (G*) and phase angle (δ). The complex shear modulus (G*) can be considered the sample's total resistance to deformation when repeatedly sheared, while the phase angle (δ), is the lag between the applied shear stress and the resulting shear strain. The larger the phase angle (δ), the more viscous the material. Phase angle (δ) limiting values are:

- Purely elastic material: δ = 0 degrees.
- Purely viscous material: δ = 90 degrees.

The specified DSR oscillation rate of 10 radians/second (1.59 Hz) is meant to simulate the shearing action corresponding to a traffic speed of about 55 mph (90 km/hr).

The DSR test was performed in three stages:

- Original Binder Tests: Figure 2 represents the fundamental stiffness properties (G*/sinδ) at different temperatures (58°C, 64°C, 70°C, and 76°C) for different percentages of CNT.
- Short-term aging test: Figure 3 presents the short-term aging and assessed resistance to rutting under traffic loads.
- Long-term aging test: Figure 4 presents the pressure aging vessel test which simulate the long-term aging and assessed resistance to fatigue under traffic loads.

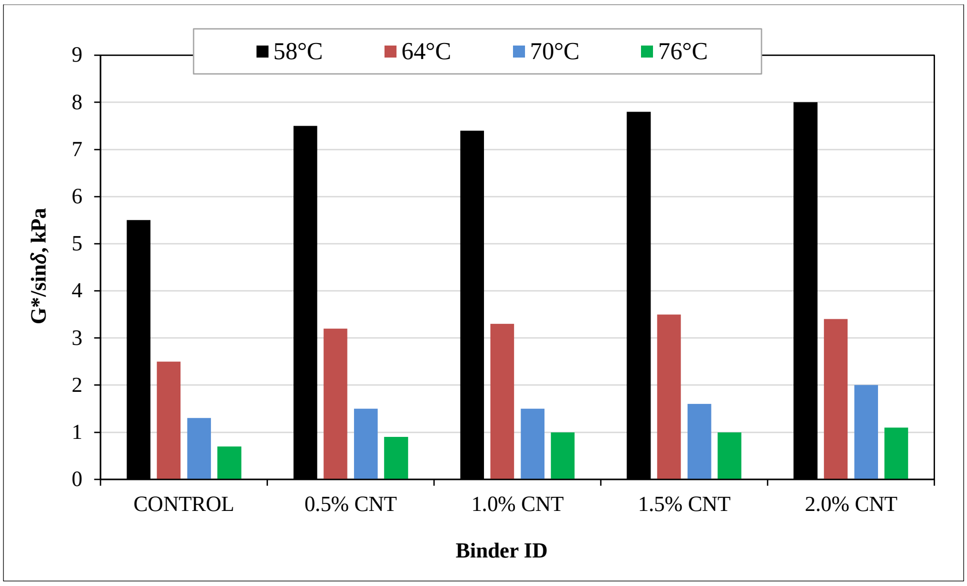



**Figure 2. Variation of G*/sinδ for different percentage of modified asphalt binder with CNT**

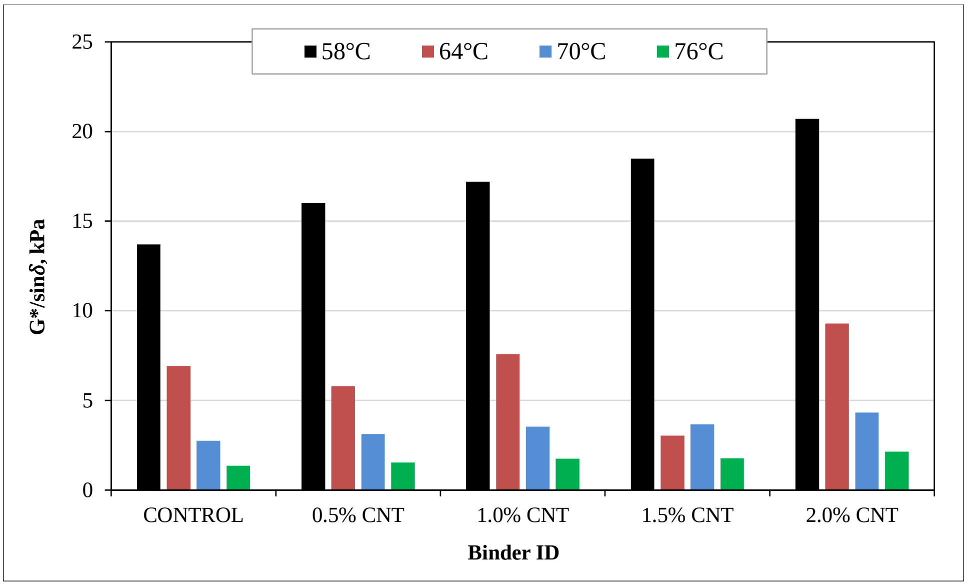



**Figure 3. Variation of $G^*$/sinδ for different percentage of modified asphalt binder with CNT after RTFO test**

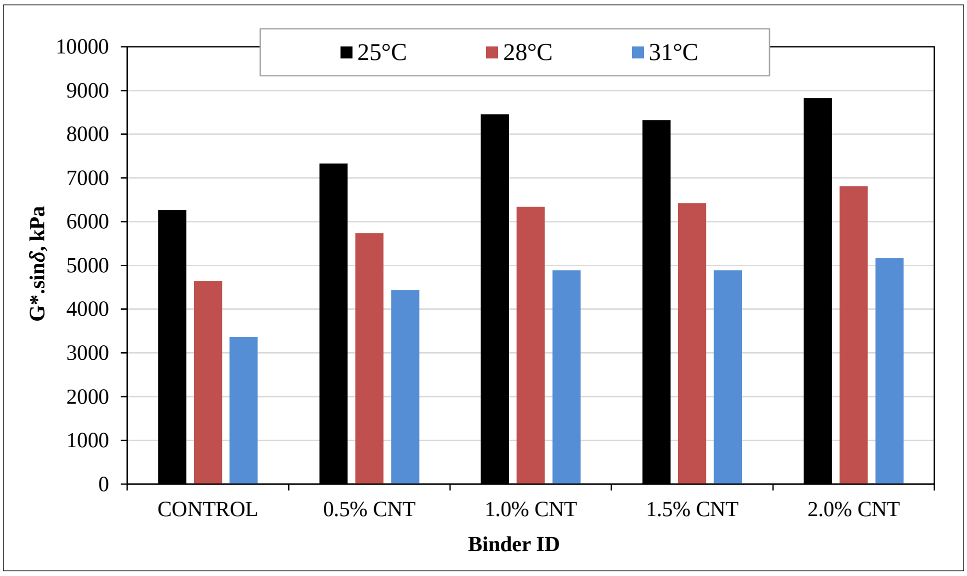



**Figure 4. Variation of $G^*$.sin δ for different percentage of modified asphalt binder with CNT after PAV test**

The High-Performance Grade (HPG) was determined from the DSR results. The Intermediate PG was assessed using RTFO+PAV-aged samples to analyze fatigue resistance.

Figure 4 displays the relationship between various binder types, CNT concentrations, and their corresponding G*sin δ values at different temperatures. Based on the data presented, all $G^{*}$.sin δ values are higher than the 5000 kPa threshold. Specifically, for the 2.0% CNT binder at three temperature G*sin δ value exceeds 5000 kPa.

## 4. Multiple Stress Creep Recovery (MSCR) Test

Rutting is one of the major causes of premature failure of asphalt concrete. A recently proposed/published repeated creep test can be used to identify asphalt binder that is susceptible to rutting. This test method is used to determine the presence of an elastic response in an asphalt binder under shear creep and recovery at two stress levels at a specified temperature. For performance grade (PG) binders, the specified temperature will typically be the PG grade upper temperature as determined in specification D6373. Ten creep and recovery cycles are run at 100 Pa stress and 3200 Pa stress consecutively. Each cycle includes 1 s creep and 9 s recovery. Conducted on RTFO-aged binders at 70°C to assess the binders' ability to recover after deformation. Figure 5 presents the relationship between the percent difference in ($J_{nr}$) for different percentages of modified asphalt binder with CNT. Figure 6 shows non-recoverable creep compliance Jnr of 3.2 kPa which

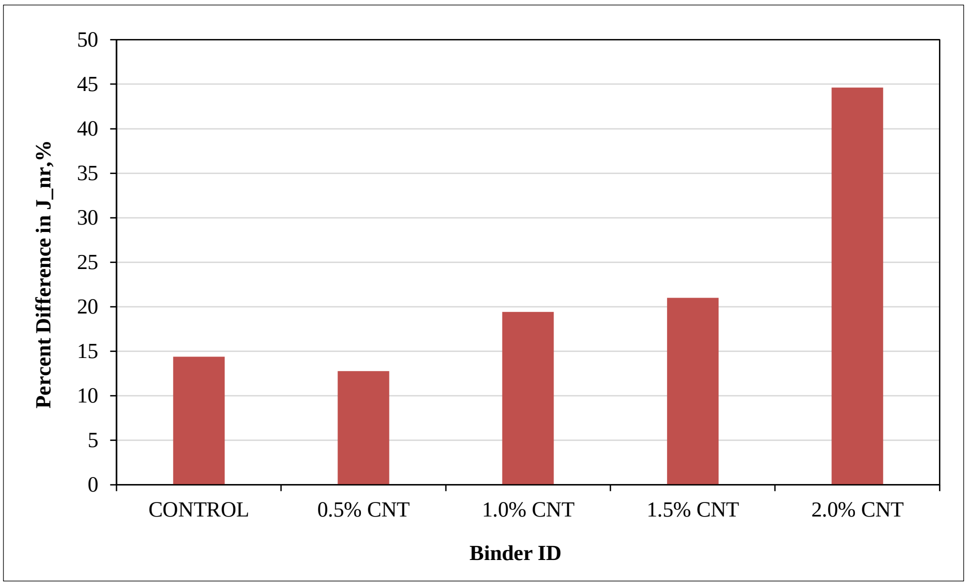



**Figure 5. Relationship between the percent difference in ($J_{nr}$) for different percentages of modified asphalt binder with CNT**

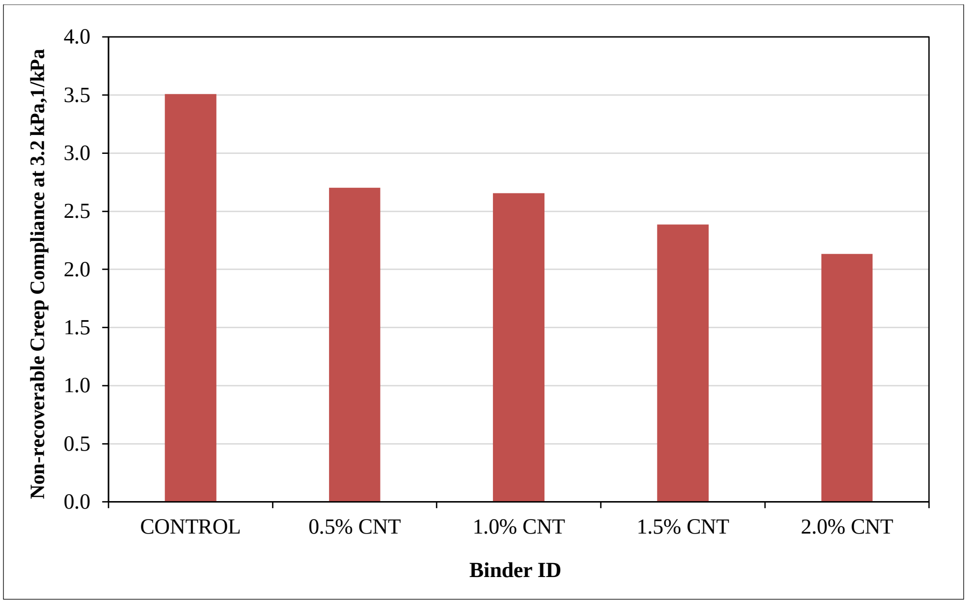



**Figure 6. Relationship between the non-recoverable creep compliance ($J_{nr}$) of 3.2 kPa for different percentages of modified asphalt binder with CNT**

As it is clear from above figures the $J_{nr}$ values decrease as the CNT content increases, which means the binders with higher CNT concentrations are better at resisting permanent deformation under load. The 2.0% CNT binder demonstrates the best performance in resisting creep deformation at 3.2 kPa, making it the most durable option in this study. This trend suggests that CNT addition improves the material's performance significantly, especially at higher concentrations, and may be beneficial for applications where resistance to deformation is critical. Table 6 shows Superpave asphalt performance grade under different loading and weather condition.

**Table 6. Superpave asphalt performance grade under different loading and weather condition**

| | |
|---|---|
| **Jnr @ 0.1 kPa** | $kPa^{-1}$ |
| **Jnr @ 3.2 kPa** | $kPa^{-1}$ |
| **Jnr diff** | % |

"S": Jnr(3.2) max 4.0 $kPa^{-1}$, Jnr diff max 75%.
"H": Jnr(3.2) max 2.0 $kPa^{-1}$, Jnr diff max 75%.
"V": Jnr(3.2) max 1.0 $kPa^{-1}$, Jnr diff max 75%.
"E": Jnr(3.2) max 0.5 $kPa^{-1}$, Jnr diff max 75%.

Therefore 2%CNT asphalt binder is classified as PG E70-12 which is extreme resistance of rutting while %1.5 CNT asphalt is PG S70-12 which is good in severe loading.

## 5. Bending Beam Rheometer (BBR) Test

The parameters directly output from the BBR test include the creep stiffness S(t) and m-value. m-value is defined as the slope of the creep stiffness and time in the log–log scale. Creep and stress relaxation can affect the fatigue damage resistance of asphalt binder. Faster stress relaxation means that the applied stress or loading will release faster on the binder sample, which is beneficial to the fatigue resistance of viscoelastic materials. Meanwhile, a higher creep stiffness indicates a higher risk of cracking damage. Therefore, in the current AASHTO T313 [24] specification, S(t)>300 MPa and m-value<0.3 at 60 seconds have been proposed to make sure enough cracking resistance. Figures 7 and 8 show effects of CNT percents on S(60) and m-value, respectively.

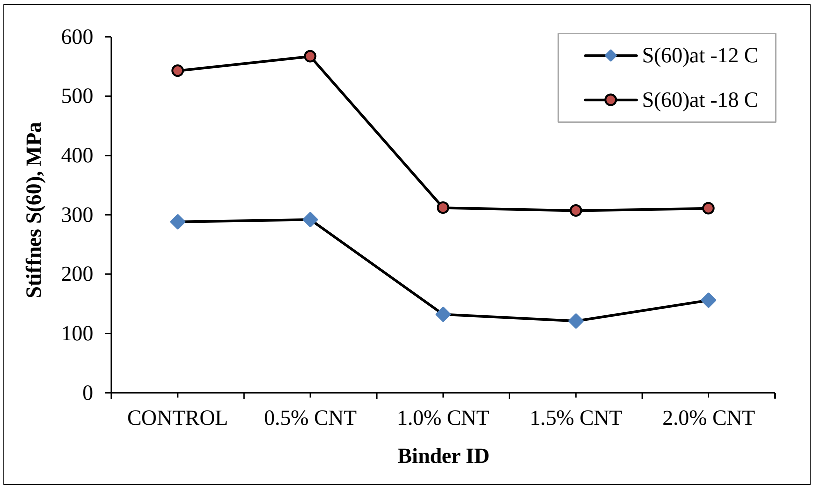



**Figure 7. Effects of CNT percents on S(60)**

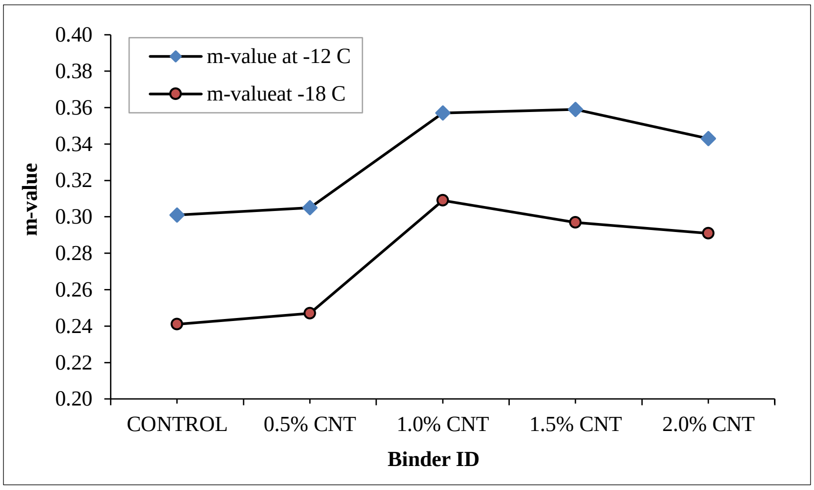


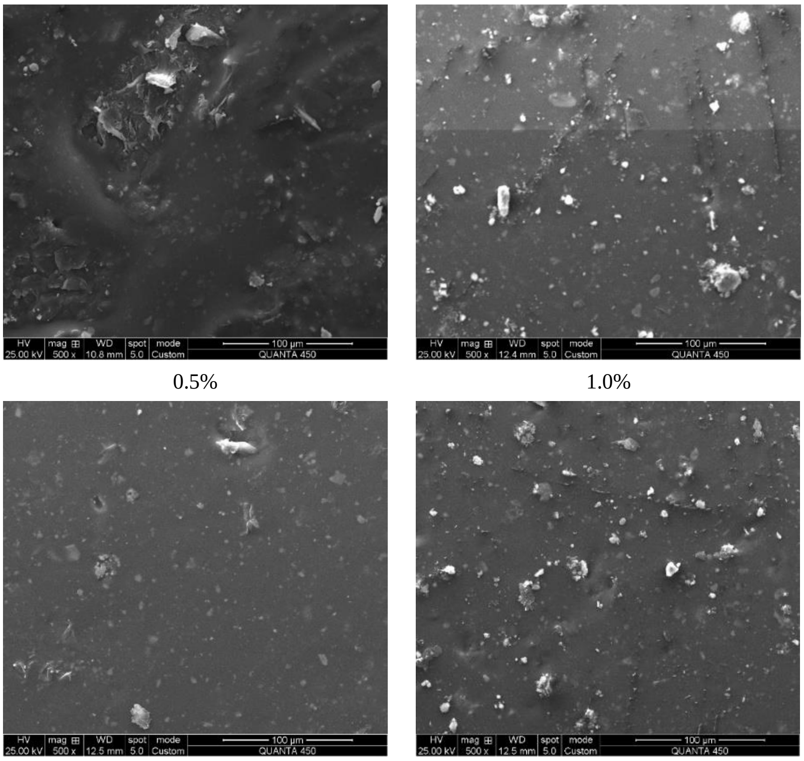

**Figure 8. Effects of CNT percents on m-value**

The experiment was conducted at temperatures of -18°C, -12°C, and -6°C to assess the low-temperature cracking resistance of the material. Key parameters measured included stiffness (S), where lower values indicate better flexibility at low temperatures, and the m-value, with higher values indicating better stress relaxation properties. These measurements were used to determine the Low-Temperature Performance Grade (PG) of the material, ensuring its suitability for use in colder climates by evaluating its ability to resist cracking and stress under low-temperature conditions.

Adding CNT enhances the binder's flexibility at lower temperatures, with higher concentrations (such as 2.0% CNT) offering consistent results. This could be valuable for applications requiring better flexibility under colder conditions. Adding CNT improves low-temperature elasticity and resistance to deformation, and the 1.0% CNT binder offers the best performance at both -18°C and -12°C.

## 6. The SEM Analysis

Scanning Electron Microscopy analysis (SEM) is a form of high-resolution surface imaging that uses the principle of light microscopy. SEM analysis scans the sample being tested with a focused electron beam to produce a high-resolution image of its surface. Figure 9 Scanning Electron Microscope (SEM) show different CNT dispersions at varying concentrations. To determine the best concentration, let's assess the following:



0.5% 1.0%

1.5% 2.0%

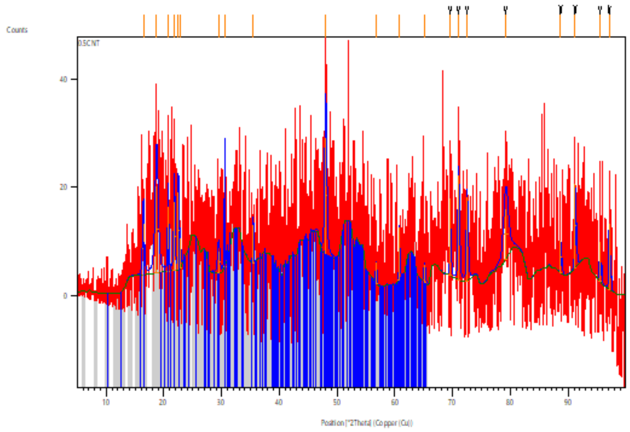
**Figure 9. Scanning Electron Microscope (SEM)**

The analysis of CNT dispersions at different concentrations shows that CNT 1.5% (Bottom-left) provides the most balanced dispersion, with minimal clustering and optimal surface coverage. CNT 0.5% (Top-left) shows poor dispersion with isolated particles, while CNT 1% (Top-right) offers better dispersion but still exhibits some clustering. CNT 2.0% (Bottom-right) shows significant agglomeration, indicating excessive CNT loading that reduces its effectiveness. Overall, CNT 1.5% offers the best combination of uniform dispersion and minimal agglomeration, making it the ideal concentration for achieving consistent performance.

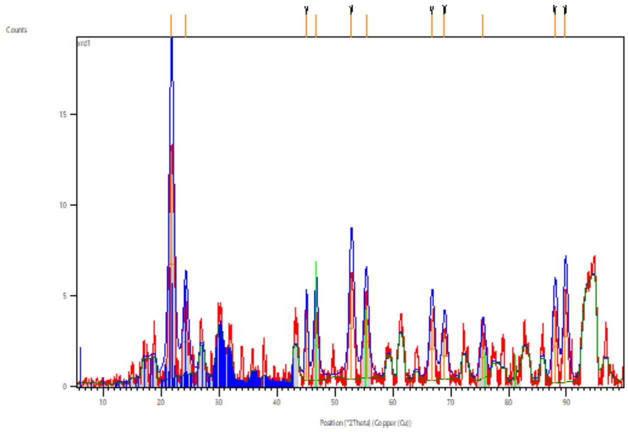
## 7. X-Ray Diffraction (XRD) Scan Data

X-ray diffraction (XRD) analysis was applied to determine the phase identification of the alloys using Cu Kα radiation operated at a voltage of 40 kV, a current of 40 mA and filtered with a Ni-crystal monochromator. XRD measurements were performed using a multipurpose X-ray diffractometer (Bruker-AXS D8 Discover). A parallel beam with a divergence of 0.03° is formed using the mirror of Gobel. The reflected intensity of the beam was measured using LYNXEYE position sensitive detector (angular resolution of 0.015°). Indexing of the reflections was performed with the WinXPOW and PowderCell software products.

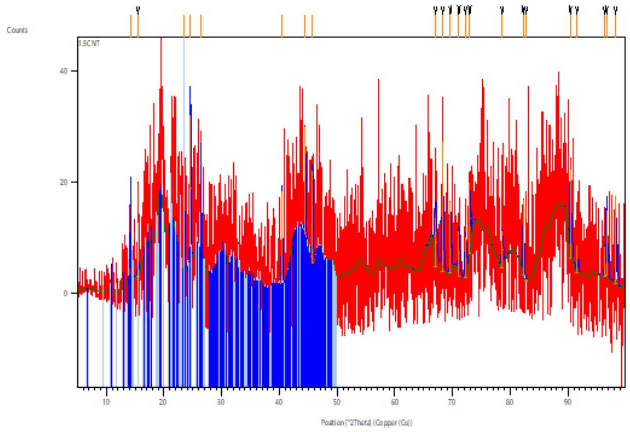
Figure 10 illustrates the X-ray diffraction (XRD) scan data of different asphalt binders containing CNT percents.



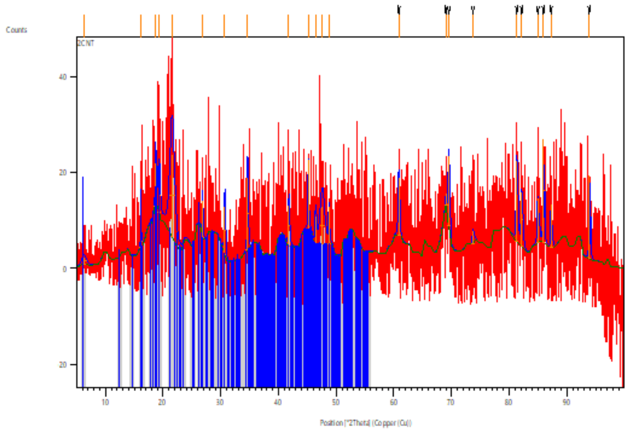
0.5% CNT



1.0% CNT



1.5% CNT



2.0% CNT

**Figure 10. X-ray diffraction (XRD) scan data**

It is noted that increasing the concentration of the additive leads to an increase in the intensity of the crystalline peaks, indicating a direct effect of this additive on the crystalline structure of the material. This change in intensity reflects the interaction of the nanoparticles with the base material, which affects the arrangement of atoms or molecules in the crystalline lattice. In addition, some prominent peaks appear at different diffraction angles, indicating the presence of specific crystalline phases. It is noted that these phases change with the difference in the concentration of the additive, indicating that the nano addition leads to an improvement in the crystallization process or a change in the crystalline structure of the existing phases.

When adding nanomaterials at different concentrations, an improvement in the crystallization process or a change in the crystalline structure of the existing phases can occur. This change appears through a shift in the positions of the peaks or a change in their intensity in the diffraction patterns, indicating that modifications have occurred in the crystalline structure. The change in the intensity of the peaks with increasing concentration also indicates an effective interaction between the nanoparticles and the base material, which may affect the mechanical and physical properties of the samples, such as hardness, elasticity, or thermal conductivity.

On the other hand, the presence of weak peaks or distortion in the diffraction patterns may indicate the formation of an amorphous phase or inhomogeneity in the distribution of nanoparticles within the material. This distortion may be the result of irregularity in the arrangement of atoms or molecules, or due to the presence of regions of partial crystallinity or inhomogeneous distribution of nanoparticles. These phenomena reflect the complexity of the interactions between the base material and the additives, and emphasize the importance of controlling the concentrations of additives to achieve the desired properties in nanomaterials.

CNT 1.5% is the best choice due to its highest crystallinity, as indicated by the smallest FWHM, and the strongest, sharpest 002 peak around ~26°, which signifies well-structured CNTs. It also shows minimal impurities and oxidation effects, alongside the best dispersion that prevents agglomeration. In contrast, CNT 2% is the worst option due to significant agglomeration and structural disorder, as evidenced by lower intensity and broad peaks. Additionally, it shows an increase in oxygen-related compounds, suggesting possible oxidation and degradation of the CNT structure.

# 8. Marshall and Volumetric Properties of Asphalt Mixtures

## 8.1. Aggregate

The aggregate used in this study (coarse and fine) were originally obtained from Badera in Kut city. The aggregate were sieved and recombined to meet the requirements of wearing course gradation Type III A according to SCRB specifications [25]. The physical properties of aggregate are shown in Table 7 while Table 8 shows the aggregate gradation used in preparing modified and unmodified mixtures which are used in the construction of wearing surface course and they are denoted as wearing course mixes type IIIA gradation as required by SCRB specifications [25].

**Table 7. Physical properties of aggregates**

| Property | ASTM or AASHTO Designation | Test results | SCRB-R9 specifications |
|---|---|---|---|
| *Coarse Aggregate* | | | |
| • Bulk specific gravity | C 127 | 2.614 | - |
| • Apparent specific gravity | C 127 | 2.686 | - |
| • Absorption, % | C 127 | - | 2.0 Max |
| • Percent wear by Los Angeles abrasion, % | T85 | 22.7 | 30 Max |
| • Soundness loss by sodium sulfate solution, % | C131 | 3.4 | 15 Max |
| • Crushing content two faces, % | C88 | 98 | 90 Min |
| • Flat and elongated, % | D4791 | 1 | 10 Max |
| *Fine Aggregate* | | | |
| • Bulk specific gravity | C127 | 2.654 | - |
| • Apparent specific gravity | C127 | 2.696 | - |
| • Sand equivalent, % | D2419 | 57 | 45 Min. |
| • Liquid limit, % | T89 | 7 | 25 Max |

**Table 8. Selected mix gradation for the type IIIA mixes of wearing course**

| Sieve opening (mm) | 19 | 12.5 | 9.5 | 4.75 | 2.36 | 0.30 | 0.074 |
|---|---|---|---|---|---|---|---|
| % Passing | 100 | 95 | 83 | 59 | 43 | 13 | 7 |
| SCRB-Specifications limits | 100 | 90-100 | 76-90 | 44-74 | 28-58 | 5-21 | 4-10 |

## 8.2. Wearing Course Mixes

The asphalt mixtures prepared in this study are used in the construction of wearing surface course and they are denoted as wearing course mixes type IIIA gradation as required by SCRB specifications [25]. Amin et al. (2016) [26] found that functionalized CNTs (COOH-grafted) enhanced binder-aggregate adhesion, increasing Marshall Stability by 28% at 1.5% CNT, though costs remained prohibitive for widespread use.

Table 9 indicates the Marshall and volumetric properties of control and CNT-modified asphalt mixtures at optimum asphalt content of 5.1% by weight of total mix.

**Table 9. Asphalt mixture with various CNT percents at optimum asphalt content**

| % CNT | Stability (kN) | Flow (mm) | G (mb) | G (mm) | Av (%) | VMA (%) | VFA (%) |
|---|---|---|---|---|---|---|---|
| 0 | 11.7 | 3.6 | 2.308 | 2.409 | 4.2 | 16.8 | 75 |
| 0.50 | 13.6 | 3.1 | 2.314 | 2.412 | 4.1 | 16.8 | 75.0 |
| 1.0 | 14.8 | 3.1 | 2.314 | 2.41 | 4.0 | 15.1 | 73.5 |
| 1.50 | 17.4 | 2.7 | 2.318 | 2.413 | 3.9 | 15.7 | 75.0 |
| 2.0 | 16.0 | 2.8 | 2.313 | 2.411 | 4.1 | 17.7 | 76.8 |

The addition of Carbon Nanotubes (CNTs) to asphalt mixtures improves several key Marshall properties. CNT-modified mixtures show higher stability, particularly with 0.5–1.5% CNT addition, due to enhanced binder stiffness and load resistance. Flow values remain within an acceptable range (2-4 mm), suggesting minimal impact on workability. CNTs also contribute to better compaction, reducing air voids and improving density, while slightly shifting the optimum asphalt content due to altered binder viscosity. Additionally, increased stiffness from CNTs improves resistance to rutting under high temperatures and heavy traffic. However, excessive CNT content (>2.0%) may lead to increased brittleness and cracking potential.

## 9. Tensile Strength Ratio Test

The indirect tensile test (ITS) was conducted in accordance with AASHTO T283 [27], as standard test method to measure the resistance of compacted bitumen mixtures to moisture damage. A static load is increasingly applied at rate of 2.0 in/min to the sample until failure. The result of this test is indirect tensile strength (ITS), and tensile strength ratio (TSR). In this test, two groups of samples were used, the first one represent control samples (UN conditional samples) which they tested at 25 ºC. The second one (conditional samples), were they submerged in water at 60ºC for 24 hr, and then tested at 25 ºC. All samples were compacted to attain 7% air voids. The indirect tensile strength is calculating according Equation 1, and the tensile strength ratio calculates from Equation 2 as shown below:

$$ITS = 2P/\pi Dt \tag{1}$$

$$TSR = IT\,S_{con} \,/\, IT\,S_{uncon} \tag{2}$$

where, ITS: indirect tensile strength, P: applied load, t: thickness of samples, D: diameter of sample. TSR: tensile strength ratio, $ITS_{con}$: indirect tensile strength for conditioned sample (kPa), $ITS_{uncon}$: indirect tensile strength for unconditioned sample (kPa). The minimum percent of tensile strength ration is 80 % [27].

Table 10 reports the indirect tensile strength for conditioned sample ($ITS_{con}$), indirect tensile strength for unconditioned sample ($ITS_{uncon}$) and tensile strength ratio. Table 10 shows the indirect tensile strength values and tensile strength ratio of various asphalt mixes.

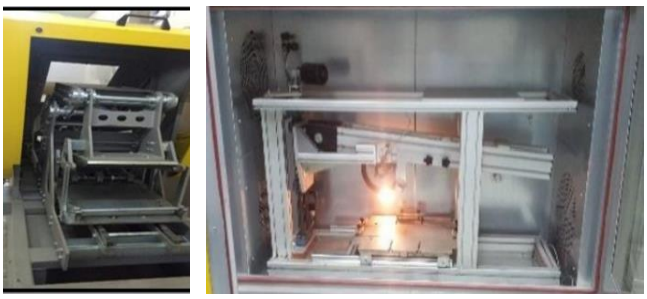
**Table 10. Indirect Tensile Strength and Tensile Strength Ratio**

| CNT | ITS (kPa) | Condition ITS (kPa) | TSR (%) |
|---|---|---|---|
| 0 | 861 | 711 | 82.6 |
| 0.5 | 943 | 795 | 84.3 |
| 1 | 1100 | 941 | 85.5 |
| 1.5 | 1290 | 1118 | 86.7 |
| 2 | 1297 | 1066 | 88.2 |

The data shows that increasing the CNT concentration enhances both Indirect Tensile Strength (ITS) and Conditioned ITS, indicating improved tensile strength of the material. Additionally, the Tensile Strength Ratio (TSR) increases from 82.6% at 0 wt% CNT to 88.2% at 2 wt% CNT, suggesting better material performance with higher CNT content. However, the improvement in tensile strength and TSR starts to level off after 1.5 wt% CNT, implying that an optimal CNT concentration exists beyond which further additions do not lead to significant performance gains.

## 10. Wheel Track Test

Wheel-Track Test (WTT) was used to measure the permanent deformation resistance in accordance with AASHTO T324 [28] and EN 12697-22 [29] of the compacted mixes in a reciprocating rolling-wheel compactor device. The device as shown in Figure 11, is established to test rut depth and to assess the permanent deformations of HMA pavement specimens under the selected conditions to simulate the effect of traffic and test conditions that are cleared in Table 11 of different asphalt mixtures at 20000 cycles.



| Parameter | Standard | Used Value for TALO |
|---|---|---|
| No. of Required Specimens | 2 | 2 |
| Diameter of Wheel | 200-205 | 200 |
| Width of Wheel, mm | 50±5 | 50 |
| No. Wheel Pass per min. | 52±5 | 52 |
| Speed of Wheel, m/s | 0.305 | 0.305 |
| Load on the wheel | 700 ±10 N | 700 |
| Test Temperature ºC | 60 ± 2 | 60 |
| Criterion failure | 20,000 passes or 20mm Rut depth | 20,000 passes or 20mm Rut depth |

**Figure 11. Rut depth test details**

**Table 11. Rut depth values of different asphalt mixtures at 20000 cycles**

| Mix Type | Rut depth (mm)@20000 |
|---|---|
| 0 | 15.0 |
| 0.5 | 14.1 |
| 1 | 11.3 |
| 1.5 | 6.2 |
| 2 | 7.7 |

The data indicates that as the %CNT increases, the rut depth decreases initially, reaching a minimum of 6.2 mm at 1.5% CNT, compared to 15.0 mm at 0% CNT. However, at 2% CNT, the rut depth increases to 7.7 mm. This suggests that CNT addition reduces rutting up to about 1.5%, after which the benefit diminishes or reverses.

## 11. Conclusions

This study assessed the impact of Carbon Nanotubes (CNTs) on the rheological and performance characteristics of asphalt binders through a series of laboratory tests, including Rotational Viscosity (RV), Dynamic Shear Rheometer (DSR), Multiple Stress Creep Recovery (MSCR), and Bending Beam Rheometer (BBR) tests. The following conclusions could be obtained:

- The results revealed that CNTs increased the viscosity of asphalt binders, particularly at 135°C, 150°C, and 165°C, indicating enhanced stiffness but reduced workability, which could complicate mixing, pumping, and construction processes.
- CNT addition showed improvements in high-temperature performance by increasing stiffness and resistance to deformation, as evidenced by DSR and MSCR tests, the overall enhancement in rutting resistance was minimal.
- At intermediate temperatures, CNTs stiffened the binder, leading to an increase in the Intermediate PG grade by up to 4°C at 2.0% CNT, which could negatively affect the fatigue life and durability of the pavement under repeated loading. In terms of low-temperature performance, CNT modification had no significant adverse effects on flexibility, although there was a slight increase in the low PG grade at 1.0% CNT.
- Further performance testing, such as the Tensile Strength (ITS) and Moisture Susceptibility (TSR) tests, showed that CNTs improved both tensile strength and moisture resistance, leading to stronger and more durable asphalt mixtures.
- The Marshall Stability test demonstrated improved stability with 0.5–1.5% CNT concentration, while the Wheel Track test indicated increased rutting resistance, though the benefits plateaued beyond 1.5% CNT.
- In conclusion, while CNTs enhance the high-temperature performance and resistance to moisture-induced damage, careful optimization of CNT content (0.5–1.5%) is essential to avoid excessive stiffening and potential negative impacts on intermediate-temperature fatigue resistance, ensuring long-term durability and performance of asphalt pavements.
- Dispersion-performance relationship reveals that 1.5% CNT represents the critical concentration for optimal dispersion, balancing nanotube networking and agglomeration risks. Beyond 1.5%, CNT self-attraction (van der Waals forces) overwhelms shear-mixing energy, causing aggregation.
- The percolated network at 1.5% CNT restricts binder flow under load, explaining the Wheel Track results. Agglomerates at 2.0% CNT create micro-crack initiation sites, justifying the intermediate PG grade shift.

## 12. Declarations

### 12.1. Author Contributions

Conceptualization, M.K.S.; methodology, M.K.S. and M.M.H.; software, M.K.S.; validation, M.Y.F. and M.H.; formal analysis, M.M.H.; investigation, M.K.S.; resources, M.H.; data curation, M.M.H.; writing—original draft preparation, M.K.S.; writing—review and editing, M.M.H.; visualization, M.Y.F.; supervision, M.M.H.; project administration, M.Y.F.; funding acquisition, M.H. All authors have read and agreed to the published version of the manuscript.

### 12.2. Data Availability Statement

The data presented in this study are available in the article.

### 12.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 12.4. Conflicts of Interest

The authors declare no conflict of interest.

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