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# Improvement of Hot Mix Asphalt Resistance to Permanent Deformation at High Temperature Using Nanomaterial Modifiers: A Review

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## ABSTRACT

The integration of nanomaterials in asphalt modification has emerged as a promising approach to enhance the performance of asphalt pavements, particularly under high-temperature conditions. Nanomaterials, due to their unique properties such as high surface area, exceptional mechanical strength, and thermal stability, offer significant improvements in the rheological properties, durability, and resistance to deformation of asphalt binders. This research reviewed the application of various nanomaterials, including nano silica, nano alumina, nano titanium, nano zinc, and carbon nanotubes in asphalt modification. The incorporation of these nanomaterials into asphalt mixtures has shown potential to increase the stiffness and high-temperature performance, thereby reducing rutting potential and improving the overall lifespan of the pavement. The mechanisms by which nanomaterials enhance the thermal and mechanical properties of asphalt were explored. Furthermore, the challenges associated with their implementation were examined, as effective utilization is hindered by agglomeration, inconsistent dispersion, and dosage sensitivity, compounded by the absence of standardized guidelines and the variability in reported contents. The findings indicate that while nanomaterials hold considerable potential for improving high-temperature asphalt performance, further research is needed to optimize their use and fully realize their benefits in large-scale applications.

**Keywords:** Asphalt, Nanomaterials, Permanent deformation.

## 1. INTRODUCTION

Permanent deformation (rutting) is a common form of surface deformation in asphalt roads **(Albayati and Latief, 2017)**, marked by the appearance of longitudinal grooves or depressions along wheel paths. It is primarily caused by the repeated application of traffic loads and can significantly affect road safety, ride quality, and the structural performance of the pavement **(Aljbouri and Albayati, 2024)**. This form of distress often leads to higher maintenance expenses and shortens the pavement service life **(Abd and Latief, 2024)**.

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Rutting develops as the asphalt layer undergoes gradual and irreversible deformation, a process influenced by factors such as heavy traffic, insufficient material performance, and adverse environmental conditions. The mechanical behavior of asphalt under load includes both recoverable (elastic) and non-recoverable (viscous) responses **(Asphalt Institute, 2007)**. Permanent deformation, or rutting, results from the accumulation of these non-recoverable strains under repeated loading, especially at elevated temperatures **(Huang, 2004)**. It is recognized that most paving materials are not fully elastic and undergo some degree of permanent deformation after each load is applied **(Shell Bitumen, 2015)**. If the applied load is relatively low compared to the material's strength and is repeated over a large number of cycles, the resulting deformation from each load cycle is predominantly recoverable, behaves proportionally to the load magnitude, and can be classified as elastic in nature **(Riaz et al., 2013)**. The resilient modulus (MR) is the elastic modulus to be used with the elastic theory. Typically, as speed increases, the resilient modulus becomes larger, leading to reduced deformation in the pavement **(Huang, 2004)**. Rutting failure is the most plausible failure under hot climate conditions **(Albayati and Alani, 2017; Hassan and Ismael, 2025)**.

In recent years, with the increase in traffic loads and modern pavement performance requirements, researchers started to consider additions to traditional Asphalt Concrete (AC) pavements; one of the ways to improve the performance is the addition of nanomaterials. The European Union Observatory for Nanomaterials (EUON) adopted the definition for nanomaterials as A natural, incidental, or engineered material with particles, individually or in aggregates, where at least 50% (by number) have one or more external dimensions between 1 and 100 nm **(European Commission, 2011)**. The ASTM uses an objectively similar terminology **(ASTM E2456-06, 2012)**. Micro and Nano are unit prefixes that are part of the System International (SI) units of measurement; they represent the size of one millionth ($10^{-6}$) and one billionth ($10^{-9}$) for Micro (μ) and Nano (n), respectively **(International Bureau of Weights and Measures, 2006)**. In general, nanotechnology will produce benefits by making existing products and processes more cost-effective, durable, and efficient, and by creating entirely new products **(Buhari et al., 2018)**. Nanomaterial modifications are often added as a percentage of the asphalt binder weight. Due to their extremely small dimensions and large surface area, nanomaterials require only a minimal quantity to produce effects equivalent to those achieved by larger, conventional materials **(Taherkhani et al., 2017)**. Incorporating micro material into the asphalt binder enhanced the stiffness modulus along with resistance of hot mix asphalt (HMA) to permanent deformation **(Shafabakhsh et al., 2015).** Incorporating the sub-Nano-sized (600nm) modifier increased the mechanical properties of hot mix asphalt **(You et al., 2011)**. It was found that when the particle size is reduced from 2 micrometers to 80 nm, the anti-rutting factors of asphalt are improved by 22.3% **(Zhang et al., 2017)**. Nanoparticles are more evenly dispersed in asphalt compared to micro particles, helping to delay the propagation of internal microcracks **(Fu et al., 2022)**. The stiffness modulus of micro and nano-modified asphalt was tested, which resulted in 30% and 90% improvement in micro and nano modifications, respectively **(Meenu and Bindhu, 2018)**. The inclusion of nanomaterials showed promising results to improve the rheological properties of asphalt binder **(Buhari et al., 2018; Aboelmagd et al., 2021)**. Notably, the high surface-to-volume ratio of nanoparticles enhances their potential to improve rheological properties and their adhesion to aggregates **(Yarahmadi et al., 2022)**. **(Enieb and Diab, 2017)** found that nanomodification enhanced the resilient modulus, split tensile strength, and fracture energy.

This review of literature was made to present a reference for the use of nano modifiers to improve rutting resistance to develop a more resilient, reliable, and high-performance asphalt concrete pavement. The general progression of this review of cited literature is shown in **Fig. 1**. Nano [Silica (NS), Alumina (NA), Titanium oxide (NT), Zinc oxide (NZ), and Carbon nanotubes (CNT)] are the focus of this review and are gathered from previous literature and discussed in the following sections.

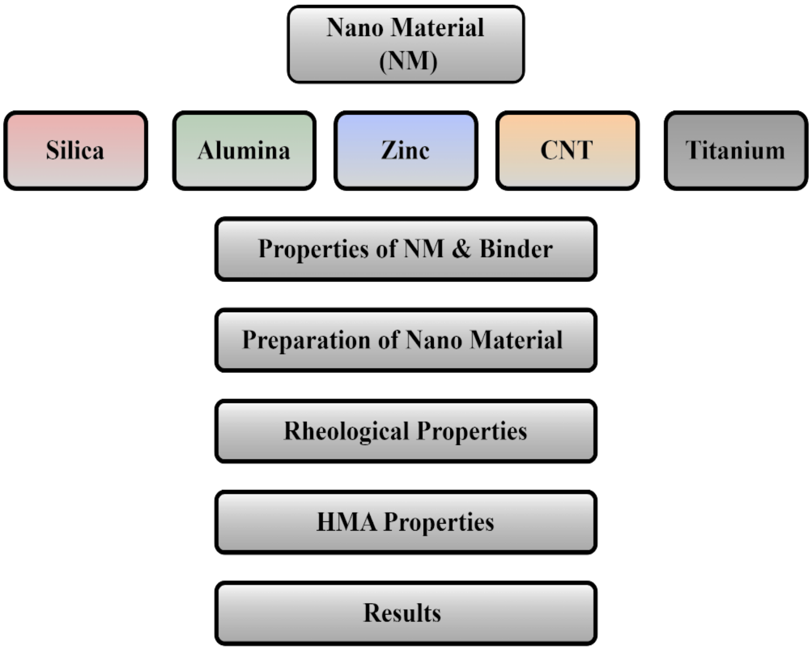


**Figure 1.** Review diagram.

## 2. MATERIALS AND METHODS

### 2.1 Silicon Dioxide ($SiO_2$)

Silica, frequently the main constituent of sand, is present in numerous natural minerals and can also be produced synthetically. In industrial contexts, silica nanoparticles are utilized to reinforce elastomers and serve as rheological agents. The white nano powder form of silica, made up of nanostructured polymorphs of silicon dioxide ($SiO_2$), is distinguished by its large surface area, improved adsorption properties, and excellent stability **(Yousef et al., 2025)**. Naturally occurring as quartz, this nanomaterial offers the significant benefit of low production costs while delivering high performance **(Qasim et al., 2022)**.

### 2.2 Aluminum Oxide ($Al_2O_3$)

Nano $Al_2O_3$ (alumina) is a readily accessible material, since its raw material, bauxite, from which aluminum oxide is extracted, is found in large quantities in nature **(Albayati et al., 2024)**. Nano-alumina exhibits high thermal conductivity, large surface area, superior strength and stiffness, excellent wear resistance, and strong oxidation and thermal stability **(Bhat and Mir, 2021)**. Scanning electron microscopy image of NA features a varied range of agglomerated particles with irregular morphology, indicating a complex structure that may suggest more sophisticated surface interactions with the asphalt **(Albayati et al., 2024)**.

## 2.3 Titanium Dioxide ($TiO_2$)

Titanium Dioxide is a natural oxide in the Earth's crust. Titanium dioxide ($TiO_2$) is a transition metal oxide that exists in three main crystalline forms: anatase, rutile, and brookite **(Chen and Mao, 2007)**.

## 2.4 Zinc Oxide (ZnO)

Zinc oxide (ZnO), the oxide form of zinc, is commonly found as a white crystalline powder and occurs naturally as the mineral zincite. It crystallizes in two forms: hexagonal wurtzite and cubic zincblende **(Fierro, 2005)**.

## 2.5 Carbon Nanotubes (CNT)

There are two types of carbon nanotubes (CNT): single-wall CNT, which consist of individual tubes, and multi-wall CNT, which are composed of coaxial tubes. While multi-wall CNT (MWCNT) are more cost-effective and simpler to produce, they have lower strength and stiffness compared to single-wall CNT (SWCNT) **(Santagata et al., 2012)**. The diameter of carbon nanotubes ranges from 1–4 nm for single-walled (SWCNT) and 5–50 nm for multi-walled (MWCNT), with lengths extending up to several micrometers **(Gong et al., 2017)**. CNTs exhibit a strong tendency to aggregate, forming a random network of interconnected clusters **(Faramarzi et al., 2015)**. Typical properties of nanomaterials are presented in **Tables 1 and 2**.

**Table 1**. Typical properties of nanomaterials.

| NM | Reference | Form | Particle Size (nm) | Density ($g/cm^3$) | SSA* ($m^2/g$) | Purity(%) |
|---|---|---|---|---|---|---|
| Silica | (Taherkhani et al., 2017) | White Powder | 11-13 | 2.4 (<0.1 Bulk) | 200 | 99 |
| | (Shi et al., 2018) | | 30 | n/a | 225 | 99.8 |
| | (Taherkhani et al., 2019) | | 20 | 2.85(<0.1 Bulk) | 10-40 | >99 |
| | (Shafabakhsh et al.,2020) | | 80 | 2.4 | 160 | 99.9 |
| | (Al-mousawi et al., 2020) | | 11-12 | 2.4 | 200 | 99.8 |
| | (Mohammed et al., 2021) | | 10-20 | 2.4 | 180-600 | 99.8 |
| | (Qasim et al., 2022) | | 15 | 2 | 100±25 | >99.9 |
| | (Khan et al., 2023) | | 14-36 | n/a | 580 | >98 |
| Alumina | (Ali et al., 2016) | White Powder | 13-20 | n/a | 100-200 | >99 |
| | (Karahancer, 2020) | | n/a | 2.9 (0.2 Bulk) | ≥550 | >99.1 |
| | (Hussein et al., 2021) | | 20 | 3.89 | >138 | <99 |
| | (Bhat et al., 2021) | | 30-50 | n/a | 130-150 | 99.9 |
| | (Cao et al., 2022) | | ≤80 | 0.9 | n/a | n/a |
| | (Kadhim et al., 2024) | | 80 | 3.97 | >15 | +99 |
| | (Albayati et al., 2024) | | 10-20 | (0.2 Bulk) | 120-160 | 99.9 |
| Titanium | (Tanzadeh et al., 2012) | White Powder | 10-25 | n/a | 200-240 | n/a |
| | (Shafabakhsh et al., 2014) | | 20 | (0.08 bulk) | 50 | n/a |
| | (Qian et al., 2019) | | 20 | 3.16 | 50-100 | 8.1 |
| | (Ameli et al., 2020) | | 20 | (0.08 bulk) | 50 | n/a |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **(Masri et al., 2022)** | | 20 | 4.26 | n/a | 7.5 |
| | **(Mohammed et al., 2024)** | | 10-30 | (0.08 bulk) | 50-100 | n/a |
| **Zinc** | **(Hamedi et al., 2015)** | White Powder | 20 | 5.5-5.6 | 40±5 | n/a |
| | **(Xu et al., 2019)** | | 30 | 4.6 | 40 | n/a |
| | **(Saltan et al., 2019)** | | 30 | 5.5 (0.28 bulk) | 50 | 99.9 |
| | **(AlMistarehi et al., 2023)** | | 20-30 | 5.6 | n/a | 99.8 |
| *SSA: Special Surface Area. | | | | | | |

**Table 2**. Typical properties of carbon Nanotubes.

| **Reference** | **Physical Form** | **Outside Diameter (nm)** | **Length (μm)** | **Density ($g/cm^3$)** | **SSA* ($m^2/g$)** | **Purity %** |
|---|---|---|---|---|---|---|
| **(Faramarzi et al., 2015)** | Black Powder | 10-20 | 10-30 | 2.1 (0.22 bulk) | >200 | >95 |
| **(Galooyak et al., 2015)** | | n/a | 30 | 2.1 | 200 | n/a |
| **(Amin et al., 2016)** | | 10-30 | 10-30 | 2.1 | >200 | >90 |
| **(Gong et al., 2017)** | | >50 | 10-20 | n/a | >40 | >90 |
| **(Ashish et al., 2018)** | | 30-32 | 20 | n/a | 190 | n/a |
| **(Yang et al., 2019)** | | 9.5 | 1.5 | 0.1 | 250-300 | 90 |
| **(Ismael et al., 2021)** | | 10-30 | 10-30 | (0.06 bulk) | >200 | n/a |
| *SSA: Special Surface Area. | | | | | | |

## 2.6 Preparation and Mixing Method

The incorporation of Nanomaterials into asphalt is a crucial step in achieving their benefits. Ensuring proper mixing is vital for the uniform dispersion of Nanomaterials within the asphalt matrix, which is necessary for consistent performance enhancements. A key challenge is preventing Nanoparticles from agglomerating, as this can reduce their effectiveness. Advanced mixing methods and the use of dispersing agents might be needed to achieve a uniform distribution of nanomaterials. Different types of addition methods are reviewed; **(Shafabakhsh et al., 2020)** prepared several samples of Kerosene-Nanomaterial solution (wet blend) mixed at different times, as well as in different mixing periods. In the end, the results were that the mix for 30 min at 2500 rpm had the best results for initial mixing, and then continued mixing after the evaporation of the dispersion agent (kerosene) with high shear mixing (HSM) at 4000 rpm, 150 °C for 30 min. **(Mohammed et al., 2023)** used a (dry blending) method with PG (64-16) for the 1, 3, 5, and 7% dosages, with initial heating of (500g) of asphalt at 140°C for 20min. After that, 2-4 grams /min at 2500 rpm and then at 4000rpm for 45min at 150-160°C. Modified asphalt cement properties (penetration, softening point, ductility, and penetration index) are presented in **Table 3**.

**Table 3**. Characteristics of nanomaterial modified asphalt.

| **NM** | **Researcher** | **Dosage %** | **Penetration (ASTM D5) 25°C(0.1mm)** | **Soft. Point (ASTM D36) (°C)** | **Ductility ASTM D113 25°C (cm)** | **Pen. Index** |
|---|---|---|---|---|---|---|
| **Silica** | **(Saltan et al., 2017)** | 0 | 62 | 50 | >100 | n/a |
| | | 0.1 | 54 | 50 | | |
| | | 0.3 | 54 | 48 | | |
| | | 0.5 | 55 | 51 | | |
| | **(Taherkhani et al., 2019)** | 0 | 69 | 49 | 100 | -0.69 |
| | | 1 | 68 | 49 | 94 | -0.7 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 3 | 63 | 50 | 87 | -0.56 |
| | | 5 | 55 | 55 | 70 | 0.14 |
| | (Abdel Wahed et al., 2022) | 0 | 62 | 45 | n/a | -2 |
| | | 1 | 43 | 53 | | -1 |
| | | 2 | 39 | 54 | | -0.5 |
| | | 4 | 41 | 57 | | 0.1 |
| Alumina | (Ali et al., 2016) | 0 | 70 | 46 | >100 | -1.48 |
| | | 5 | 25 | 53 | 62 | -1.84 |
| | | 7 | 38 | 51 | 91 | -1.54 |
| | (Karahancer, 2020) | 0 | 62 | 50 | >100 | -0.705 |
| | | 3 | 54 | 49 | >100 | -1.25 |
| | | 7 | 57 | 48 | >100 | -1.39 |
| | (Hussein et al., 2021) | 0 | 42 | 55 | 120 | -0.31 |
| | | 3 | 31 | 59 | 90 | -0.25 |
| | | 5 | 25 | 62 | 50 | -0.195 |
| | | 7 | 28 | 60 | 75 | -0.34 |
| Titanium | (Neto et al.,2020) | 0 | 52 | 54 | n/a | |
| | | 3 | 45 | 57 | | |
| | (Ameli et al., 2020) | 0 | 67 | 49 | 102 | -1.25 |
| | | 4 | 61 | 52 | 107 | 0.5 |
| | | 6 | 60 | 53 | 109 | 1.1 |
| | | 8 | - | 55 | 112 | 1.4 |
| | (Mohammed and Abed, 2024) | 0 | 42 | 49 | 112 | -1.53 |
| | | 3 | 39 | 56 | 115 | -0.4 |
| | | 5 | 37 | 60 | 120 | 0.2 |
| | | 7 | 40 | 58 | 123 | -0.2 |
| Zinc | (Zhang et al., 2018) | 0 | 64 | 47 | 240 | n/a |
| | | 2 | 63 | 48 | 225 | |
| | | 3 | 56 | 49 | 200 | |
| | | 4 | 58 | 50 | 190 | |
| | (Saltan et al., 2019) | 0 | 62 | 50 | > 100 | -0.70 |
| | | 1 | 48 | 50 | > 100 | -1.29 |
| | | 3 | 54 | 50 | > 100 | -0.89 |
| | | 5 | 52 | 53 | > 100 | -0.38 |
| | (Zhu et al., 2024) | 0 | 65 | 48 | n/a | -0.96 |
| | | 1 | 70 | 48 | | -0.84 |
| | | 5 | 74 | 50 | | -0.73 |
| Carbon Nanotubes | (Faramarzi et al., 2015) | 0 | 61 | 49 | 123 | n/a |
| | | 0.1 | 58 | 48 | 116 | |
| | | 0.5 | 55 | 50 | 101 | |
| | | 1 | 52 | 52 | 81 | |
| | (Galooyak et al., 2015) | 0 | 65 | 52 | n/a | 0.062 |
| | | 0.9 | 55 | 56 | | 0.433 |
| | | 1.5 | 49 | 61 | | 1.175 |
| | (Ismael et al., 2021) | 0 | 42 | 51 | n/a | |
| | | 0.5 | 41 | 54 | | |
| | | 1 | 38 | 56 | | |
| | | 1.5 | 35 | 59 | | |

Different mixing techniques including low shear mixer (LSM), mechanical mixing (MM), sonication process (SP), and ultrasonic mixing (USM) a to integrate different Nanomaterials into asphalt are shown in **Table 4.**

**Table 4**. Integration of Nanomaterials.

<table>
<tr><th>NM</th><th>Researcher</th><th>Binder</th><th>Blend Method</th><th>Mixer</th><th>Temp (°C)</th><th>Speed (rpm)</th><th>Time (min)</th><th>Scan Method</th></tr>
<tr><td rowspan="7">Silica</td><td>(Taherkhani et al., 2017)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>160</td><td>3000</td><td>60</td><td>SEM</td></tr>
<tr><td>(Shafabakhsh et al., 2020)</td><td>60-70</td><td>Wet</td><td>HSM</td><td>150</td><td>4000</td><td>30</td><td>n/a</td></tr>
<tr><td>(Mohammed et al., 2021)</td><td>80-100</td><td>n/a</td><td colspan="4">n/a</td><td>SEM</td></tr>
<tr><td>(Abdel Wahed et al., 2022)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>145</td><td>4000</td><td>60</td><td>XRD/TEM/FTIR</td></tr>
<tr><td>(Taher et al., 2023)</td><td>40-50</td><td>Dry</td><td>HSM</td><td>163</td><td>3000</td><td>60</td><td>SEM</td></tr>
<tr><td>(Mohammed et al., 2023)</td><td>40-50</td><td>Dry</td><td>HSM</td><td>160</td><td>4000</td><td>45</td><td>SEM</td></tr>
<tr><td>(Albayati et al., 2024)</td><td>PG 64-16</td><td>Dry</td><td>HSM</td><td>140</td><td>4000</td><td>20</td><td>SEM</td></tr>
<tr><td rowspan="6">Alumina</td><td>(Ali et al., 2016)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>170</td><td>5000</td><td>90</td><td>FTIR/XRD</td></tr>
<tr><td>(Ali et al., 2016)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>170</td><td>5000</td><td>90</td><td>n/a</td></tr>
<tr><td>(Karahancer, 2020)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>160</td><td>3000</td><td>60</td><td>SEM</td></tr>
<tr><td>(Hussein et al., 2021)</td><td>40-50</td><td>Dry</td><td>MM</td><td>145</td><td>1500</td><td>60</td><td>n/a</td></tr>
<tr><td>(Song, 2022)</td><td>#70 Asph.</td><td>Wet</td><td>HSM</td><td>150</td><td>4000</td><td>n/a</td><td>n/a</td></tr>
<tr><td>(Albayati et al., 2024)</td><td>PG 64-16</td><td>Dry</td><td>HSM</td><td>140</td><td>4000</td><td>20</td><td>SEM</td></tr>
<tr><td rowspan="7">Titanium</td><td>(Tanzadeh et al., 2012)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>n/a</td><td>7000</td><td>45</td><td>SEM</td></tr>
<tr><td>(Neto et al., 2014)</td><td>50-70</td><td>Dry</td><td>MM</td><td>150</td><td>2000</td><td>90</td><td>n/a</td></tr>
<tr><td>(Buhari et al., 2018)</td><td>80-100</td><td>Dry</td><td>HSM</td><td>155</td><td>3500</td><td>45</td><td>EDS/FTIR</td></tr>
<tr><td>(Qian et al., 2019)</td><td>50-60</td><td>Dry</td><td>HSM</td><td>170</td><td>8000</td><td>30±5</td><td>SEM</td></tr>
<tr><td>(Filho et al., 2020)</td><td>50-60</td><td>Dry</td><td>MM</td><td>150</td><td>2000</td><td>90</td><td>SEM / XRD</td></tr>
<tr><td>(Mohammed et al., 2024)</td><td>40-50</td><td>Dry</td><td>HSM</td><td>160</td><td>6000</td><td>40</td><td>SEM</td></tr>
<tr><td>(Albayati et al., 2024)</td><td>40-50</td><td>Dry</td><td>HSM</td><td>140</td><td>4000</td><td>20</td><td>SEM</td></tr>
<tr><td rowspan="9">Zinc</td><td>(Zhang et al., 2015)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>150</td><td>4000</td><td>60</td><td>n/a</td></tr>
<tr><td>(Yunus et al., 2018)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>145</td><td>2000</td><td>30</td><td>SEM</td></tr>
<tr><td>(Saltan et al., 2019)</td><td>PG 64-22</td><td>Dry</td><td>HSM</td><td>160</td><td>4000</td><td>120</td><td>SEM</td></tr>
<tr><td>(Xu et al., 2019)</td><td>60-70</td><td>Dry</td><td>HSM</td><td>150</td><td>5000</td><td>60</td><td>SEM /UVS</td></tr>
<tr><td>(Kleizienė et al., 2020)</td><td>70-100</td><td>Dry</td><td>n/a</td><td>150</td><td>5000</td><td>30</td><td>n/a</td></tr>
<tr><td>(Neto et al., 2022)</td><td>50-70</td><td>Dry</td><td>LSM</td><td>150</td><td>2000</td><td>90</td><td>XRD</td></tr>
<tr><td rowspan="2">(Al Mistarehi et al., 2023)</td><td rowspan="2">60-70</td><td rowspan="2">Dry</td><td rowspan="2">HSM</td><td>160</td><td>2000</td><td>20</td><td rowspan="2">n/a</td></tr>
<tr><td>170</td><td>4500</td><td>40</td></tr>
<tr><td>(Zhu et al., 2024)</td><td>PG 64-22</td><td>Dry</td><td>HSM</td><td>163</td><td>5000</td><td>45</td><td>SEM/AFM/FTIR</td></tr>
<tr><td rowspan="7">Carbon Nanotubes</td><td rowspan="2">(Faramarzi et al., 2015)</td><td rowspan="2">60-70</td><td rowspan="2">Dry/ Wet</td><td>SP</td><td colspan="3">240watt 25min</td><td rowspan="2">SEM</td></tr>
<tr><td>HSM</td><td>160</td><td>2500</td><td>2</td></tr>
<tr><td>(Galooyak et al., 2015)</td><td>60-70</td><td>n/a</td><td>USM</td><td colspan="3">65watt 15min</td><td>SEM / XRD</td></tr>
<tr><td>(Gong et al., 2017)</td><td>60-80</td><td>Dry</td><td>HSM</td><td>120</td><td>2000<br>5000</td><td>10<br>30</td><td>TEM / FTIR / AFM</td></tr>
<tr><td>(Ashish et al., 2018)</td><td>AC-10</td><td>Dry</td><td>HSM</td><td>155</td><td>5000</td><td>60</td><td>n/a</td></tr>
<tr><td>(Yang et al., 2019)</td><td>PG 64-22</td><td>Dry</td><td>HSM</td><td>170</td><td>5000</td><td>30</td><td>SEM / DSC</td></tr>
<tr><td>(Ismael et al., 2021)</td><td>40-50<br>60-70</td><td>Dry</td><td>MM</td><td>163</td><td>1500</td><td>45</td><td>SEM / AFM</td></tr>
</table>

### 2.7 Testing Methods

A comprehensive suite of standardized tests was used to evaluate the performance of asphalt binders and mixtures. Binder morphological tests include Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Transmission Electron Microscopy (TEM), Energy Dispersive X-ray Spectroscopy (EDS), Atomic Force Microscopy (AFM), and Differential Scanning Calorimetry (DSC). Chemical analysis includes Fourier Transform Infrared Spectroscopy (FTIR), UV-Vis-infrared Spectrophotometer (UVS). Behavior on rheological and deformation, including the Rotational Viscometer **(ASTM D4402/D4402M-15, 2015)** to assess stiffness (viscosity), the Dynamic Shear Rheometer **(AASHTO T315-12, 2011)** to evaluate high-temperature rutting resistance, and the Multiple Stress Creep Recovery (MSCR) test **(AASHTO T350-14, 2013)** at 0.1 and 3.2 kPa to quantify non-recoverable compliance. Mixture performance tests comprise Resilient Modulus (MR) **(AASHTO T307-99, 2010)** for stiffness evaluation, Indirect Tensile Strength (ITS), and uniaxial dynamic creep **(AASHTO TP79, 2013)** for permanent deformation, repeated loading Permanent Deformation (PD) under repeated loading. Marshall Stability (MS) and Flow (MF) **(ASTM D6927-15, 2015)**, while the Wheel Tracking Test (WTT) **(AASHTO T324-19, 2018)** simulated rutting under controlled temperature and loading. Additional performance indicators included the Asphalt Pavement Analyzer (APA), Flow Number (FN) **(AASHTO T378-17, 2014)** for rutting resistance, , Rutting Test (RT), Dynamic Stability (DS) Static Creep Test (SCT), Double Punch Test (DPT), Dynamic Creep Test (DCT) and Shape Memory (SM), providing insight into the resistance to load-induced deformation and structural integrity.

## 3. RESULTS AND DISCUSSION

### 3.1 Binder Rheological Tests

3.1.1 Rotational Viscometer

Rotational viscosity of unaged Nano-modified binder for different modifiers is shown in **Figs. 2 to 5**.

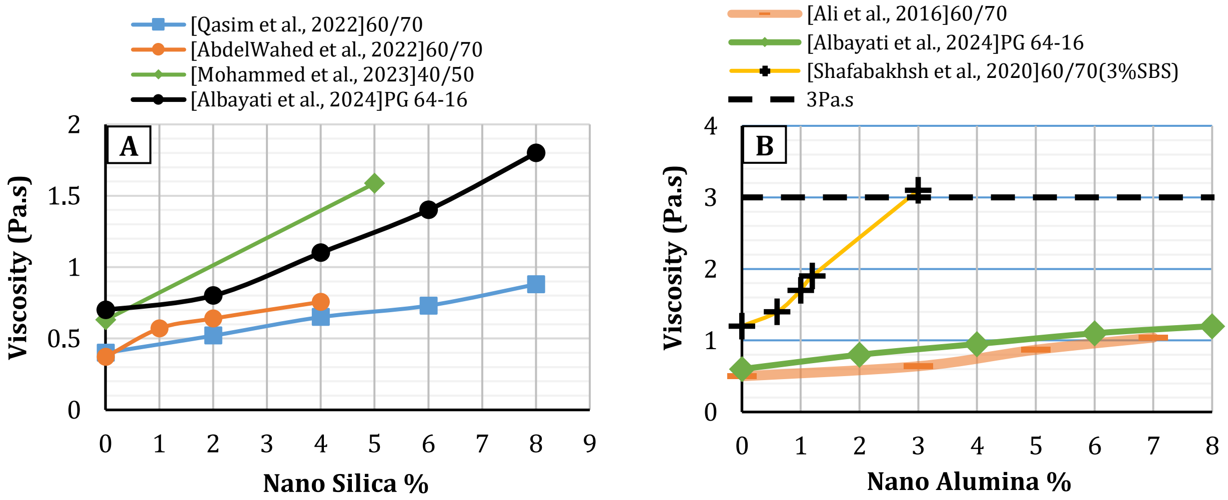


**Figure 2.** Rotational viscosity at 135 °C for A) nano silica B) nano alumina modified asphalt.

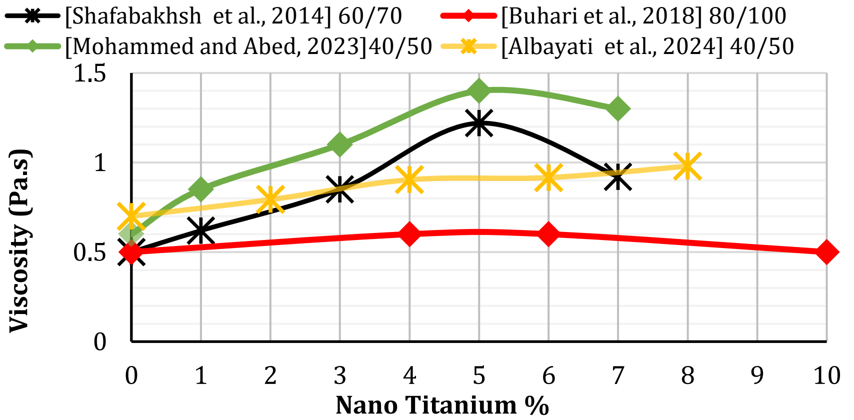


**Figure 3.** Rotational viscosity at 135 °C for nano titanium modified asphalt.

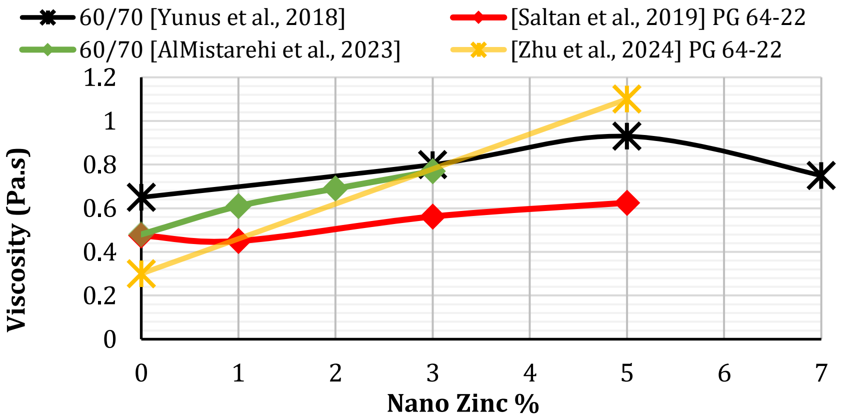


**Figure 4.** Rotational viscosity at 135 °C for nano zinc modified asphalt.

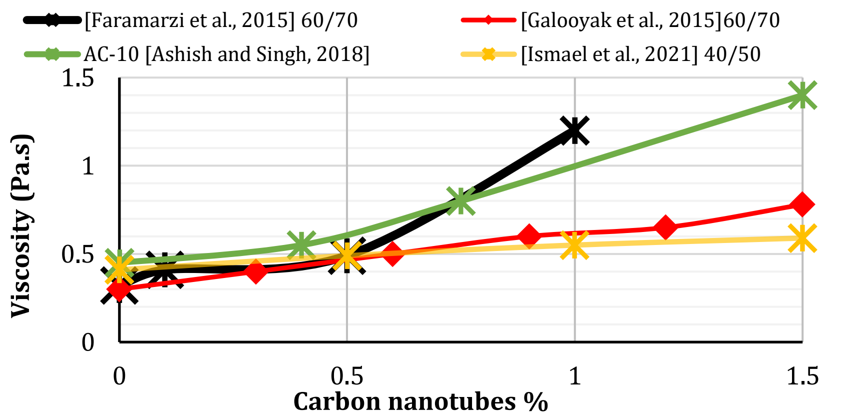


**Figure 5.** Rotational viscosity at 135 °C for carbon Nanotubes modified

3.1.2 Dynamic Shear Rheometer (Rutting Parameter)

Rutting parameters of different Nano-modified asphalt are shown in **Figs. 6 to 10**

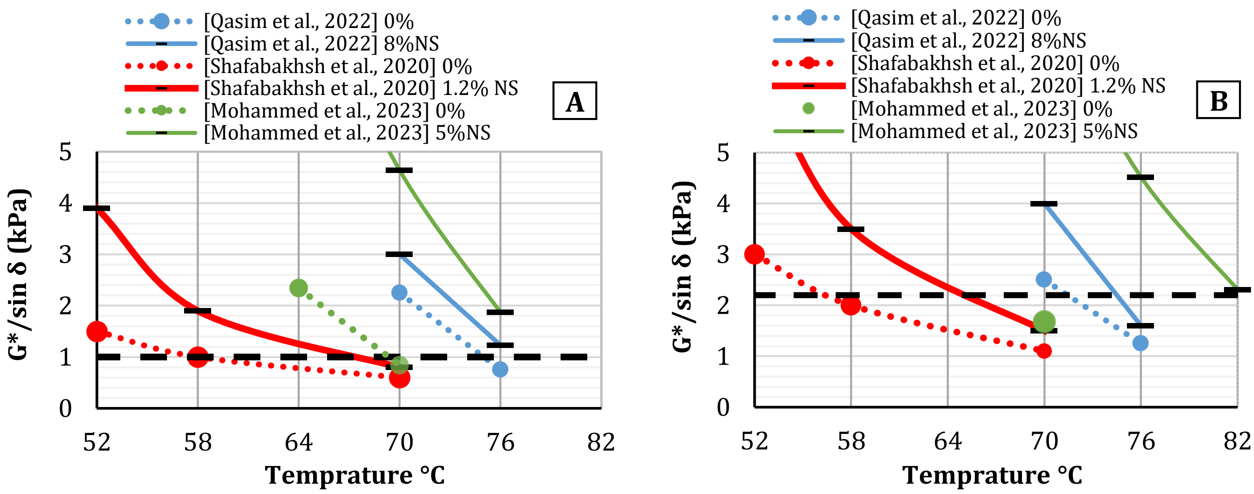


**Figure 6.** Rutting parameter of nano silica: A) unaged, B) RTFO aged binder.

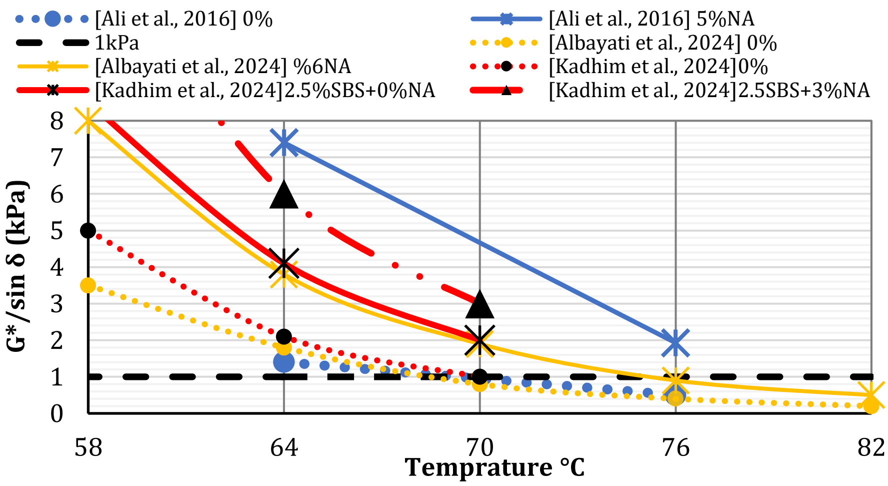


**Figure 7.** Rutting parameter of nano alumina unaged binder.

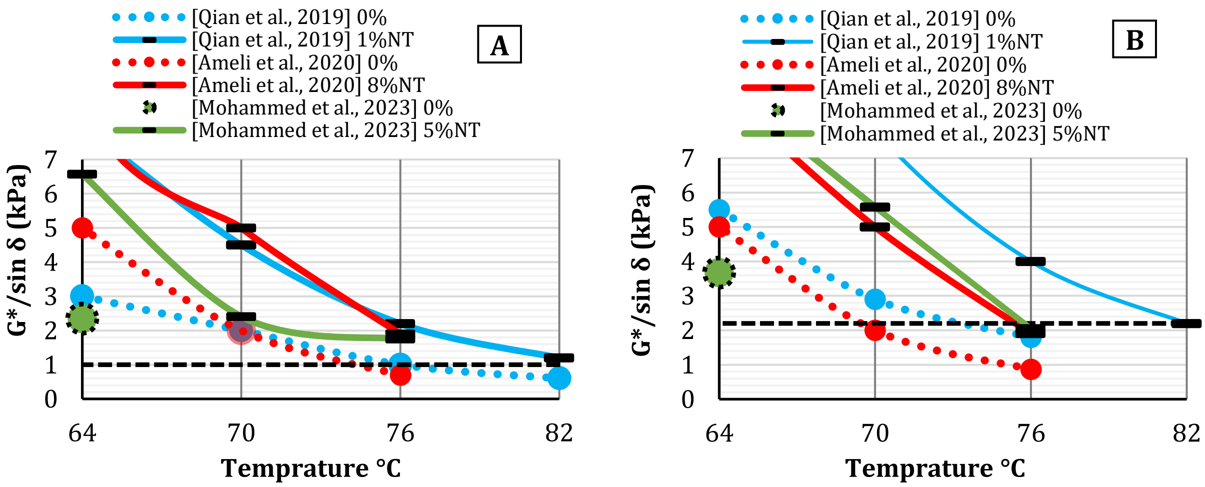


**Figure 8.** Rutting parameter of nano titanium A) unaged, B) RTFO aged binder.

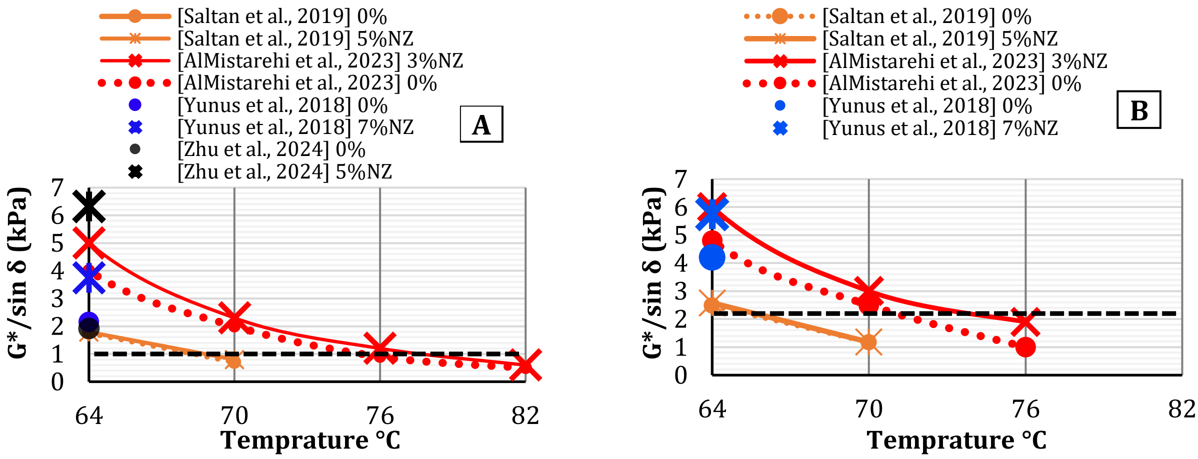


**Figure 9.** Rutting parameter of nano zinc A) unaged, B) RTFO aged binder.

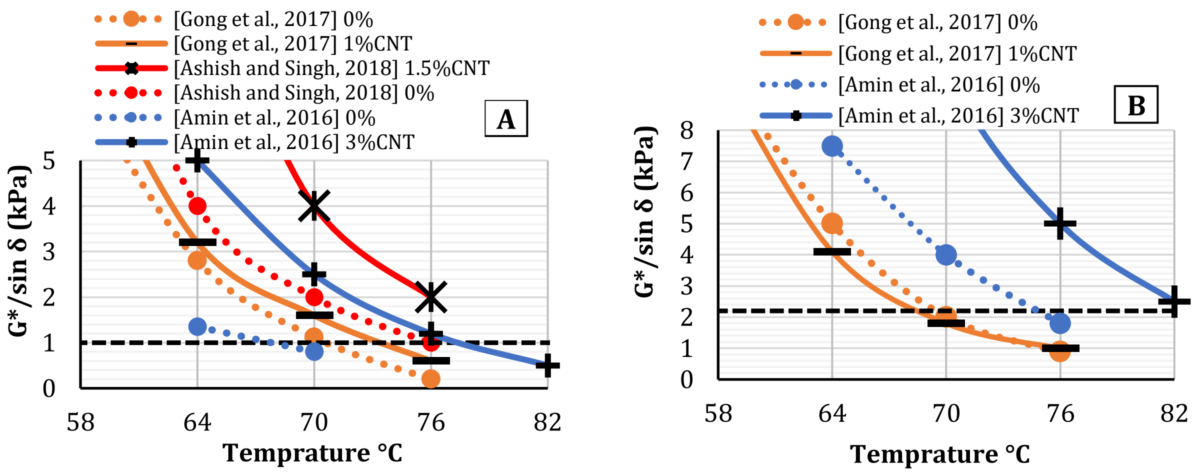


**Figure 10.** Rutting parameter of carbon nanotubes A) unaged, B) RTFO aged binder.

3.1.3 Multiple Stress Creep Recovery (Jnr)

Multiple stress creep recovery (Jnr) at 0.1 and 3.2kPa of unaged Nano-modified asphalt for different materials is shown in **Figs. 11-14**.

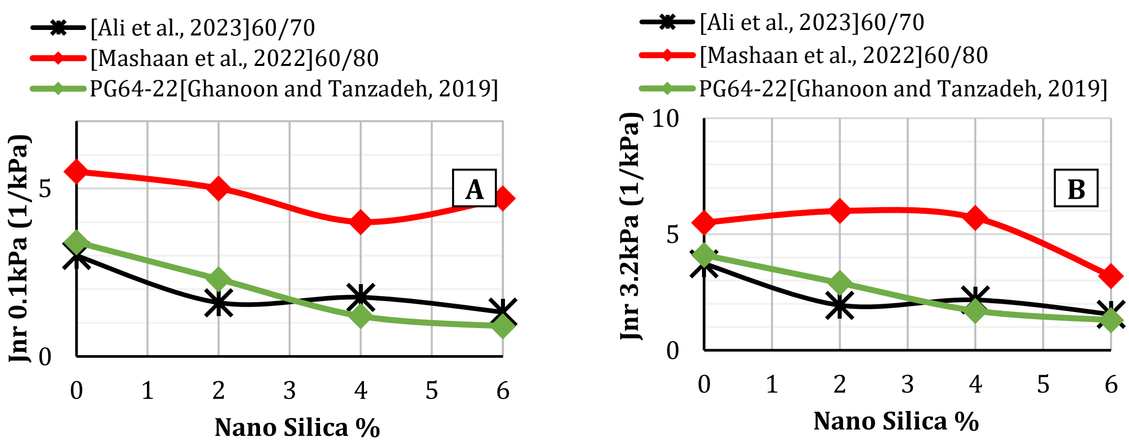


**Figure 11.** Jnr of nano silica modified asphalt cement.

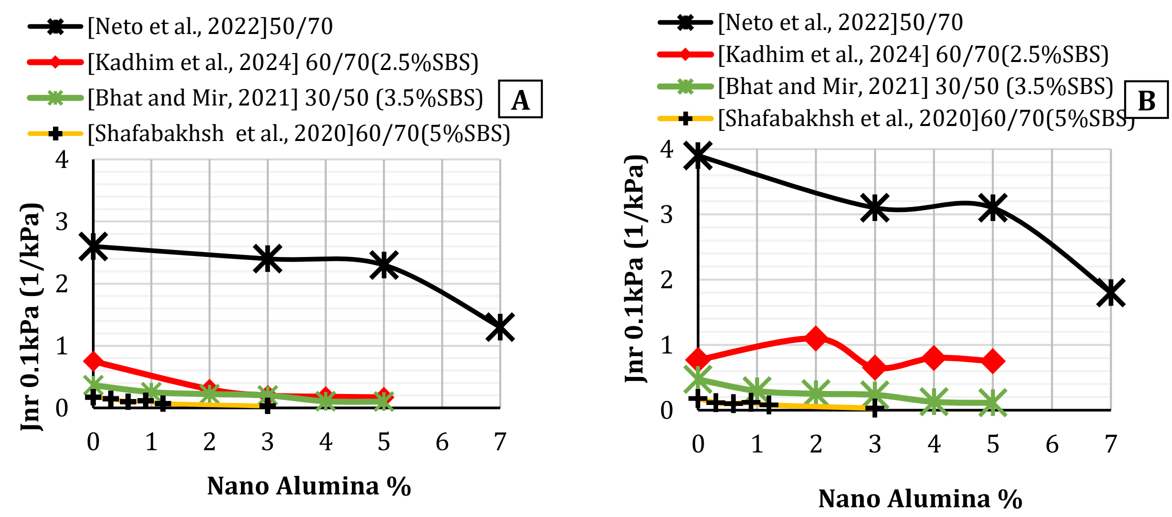


**Figure 12.** Jnr of Nano alumina modified asphalt cement.

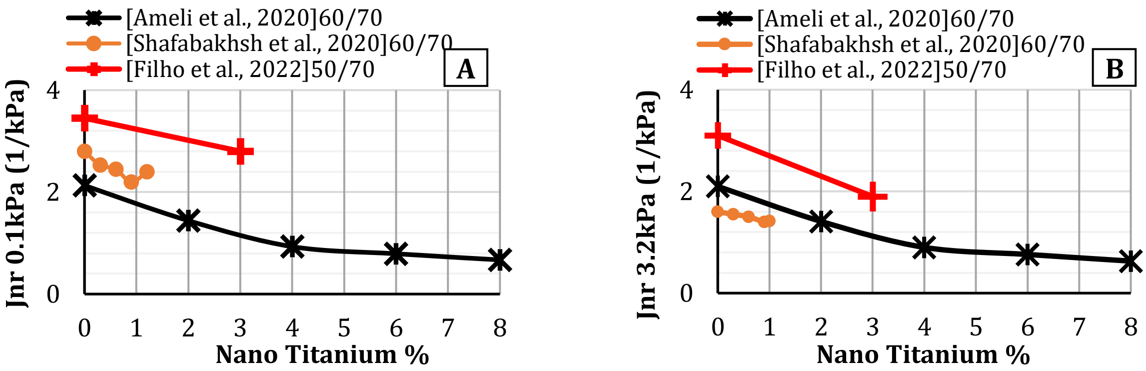


**Figure 13.** Jnr of Nano titanium modified asphalt cement.

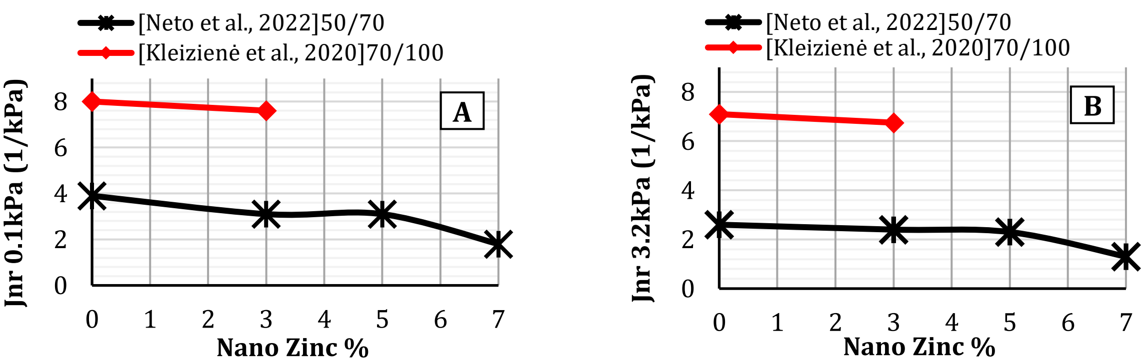


**Figure 14.** Jnr of Nano zinc modified asphalt cement.

## 3.2 Asphalt Mixture Properties

### 3.2.1 Volumetric Properties of Mixtures

Volumetric properties of Nano-modified asphalt mixtures are shown in **Table 5**.

**Table 5.** Volumetric properties of modified mixtures.

| NM | Reference | Asphalt Content % | Dosages (%) | Air Voids (%) | Voids in Mineral Aggregate (%) | Voids Filled with Asphalt (%) |
|---|---|---|---|---|---|---|
| Silica | (Taherkhani et al., 2017) | 5.3 | 0 | 4.15 | 16.3 | 74.65 |
| | | | 1 | 4.38 | 15.95 | 72.95 |
| | | | 3 | 4.64 | 15.74 | 70.38 |
| | | | 5 | 4.93 | 15.43 | 66.58 |
| | (Albayati et al., 2024) | 5 | 0 | 4 | 14.5 | 72.5 |
| | | | 2 | 3.8 | 14.2 | 73 |
| | | | 4 | 3.4 | 14.2 | 76.5 |
| | | | 6 | 3.2 | 14.6 | 77.5 |
| | | | 8 | 3.1 | 15 | 78.5 |
| Alumina | (Karahancer, 2020) | 4.55 | 0 | 4 | 14.75 | 72 |
| | | 5.96 | 3 | 4 | 16.5 | 75 |
| | | 5.25 | 5 | 4 | 16.48 | 75 |
| | | 4.85 | 7 | 4 | 15.6 | 72 |
| Alumina | (Albayati et al., 2024) | 5 | 0 | 4 | 14.5 | 72.5 |
| | | | 2 | 3.95 | 14.6 | 73.5 |
| | | | 4 | 3.8 | 15 | 75 |
| | | | 6 | 3.65 | 15.1 | 76 |
| | | | 8 | 3.5 | 15.3 | 77 |
| Titanium | (Albayati et al., 2024) | 5 | 0 | 4 | 14.5 | 72.5 |
| | | | 2 | 3.8 | 14.6 | 73.5 |
| | | | 4 | 3.4 | 15.2 | 76 |
| | | | 6 | 3.2 | 15.7 | 74.9 |
| | | | 8 | 3.1 | 16 | 73.5 |
| Zinc | (Ashish et al., 2018) | 4.5 | 0 | 4 | 14.2 | 74 |
| | | 4.5 | 1 | 4 | 16.1 | 75 |
| | | 5.1 | 3 | 4 | 15.2 | 75 |
| | | 5.3 | 5 | 4 | 16.1 | 76 |
| CNT | (Ismael et al., 2021) | 5 | 0 | 4 | 15.5 | 74.19 |
| | | | 0.5 | 3.76 | 15.37 | 75.54 |
| | | | 1 | 3.56 | 15.2 | 76.58 |
| | | | 1.5 | 3.3 | 14.64 | 77.46 |
| | | | 2 | 3.4 | 14.8 | 77.03 |

3.2.2 Testing of Asphalt Mixtures

Asphalt mixture tests of Nano-modified asphalt mixtures are shown in **Table 6.**

**Table 6.** Modified asphalt mixtures tests.

| NM | Researcher | Binder /NMS Dosages | Test | Results |
|---|---|---|---|---|
| Silica | (Taherkhani et al., 2017) | 60-70 /12.5mm 1, 3, 5 % | MS | 12% higher Marshall Stability at 5% NS. |
| | | | MF | Flow decreases with increasing NS content. |
| | | | MR | At 5% NS, a 49% increase in resilient modulus. |
| | | | DCT | Accumulated vertical strain decreases with increasing NS. |
| | | 80-100 | SM | Best NS content is 15 % (at 40°C). |

| | | | | |
|---|---|---|---|---|
| | **(Mohammed et al., 2021)** | /14mm<br>4, 6, 15 % | DCT | At 10,000 cycles, the minimum displacement at 6% NS. |
| | **(Abdel Wahed et al., 2022)** | 60-70<br>/12.5mm<br>1, 2, 3, 4 % | MS &MF | 16.16% increase in Marshall Stiffness at 4% NS. |
| | | | DPT | NS content (4%) leads to increased DP values. |
| | | | SCT | Adding NS leads to decreased strain values. |
| | **(Qasim et al., 2022)** | 60-70<br>2, 4, 6, 8 % | MF | Min flow (3.1mm) at 2% NS. |
| | | | MS | Max stability 15.5kN at 6% NS, 12.75kN at 8% NS, OAC 4.9%. |
| | | | WTT | 58% decrease in rut depth after 10,000 cycles at 8% NS. |
| **Alumina** | **(Gedafa et al., 2019)** | PG 64-28<br>1, 5, 7% | APA | 5% NA resulted in the best reduction of rut depth.<br>1% NA had negative effects on the rut depth above 2000 cycles. |
| | **(Karahancer, 2020)** | 60-70<br>3, 5, 7 % | ITS | Increase in ITS value (dry and wet) as the NA dosage increases. |
| | **(Song, 2022)** | #70Asphat<br>0.3-1.2% | DCT | 0.3–1.2% can reduce the strain by 2–49%. |
| | **(Cao et al., 2022)** | #70 Matrix Asphalt<br>/13.2mm<br>3, 6, 9, 12 % | MS | 12% NA, MS of dry and wet samples (15.9kN, 14.4 kN), which are (72-90%) higher than the control sample. |
| | | | RT | 3–12% NA, the rut depth (60°C) decreases by 12–36% respectively, and dynamic stability increases by 17–39%. |
| | | | DCT | 9% NA results in 49% lower final strain at 60°C. |
| | **(Albayati et al., 2024)** | 40 -50<br>/12.5mm<br>2, 4, 6, 8% | MS | 19% increase in Marshall Stability at 8% NA. |
| | | | MF | 29% decrease in Marshall Flow at 8% NA. |
| | | | PD | 16% ($M_r$) improvement of at 8% NA. |
| **Titanium** | **(Tanzadeh et al., 2012)** | 60-70/ 4% | WTT | 4% NT reduced rutting depth at 10,000 cycles. |
| | **(Shafabakhsh et al., 2014)** | 60-80<br>1, 3, 5, 7% | PD | 5% NT resulted in the best reduction in final strain. |
| | **(Ameli et al., 2020)** | 60-70<br>/12.5mm<br>2, 4, 6, 8 % | MR | 8% NT made a 34% enhancement to MR. |
| | | | FN | 79% improvement in FN 8% NT mixture with lime. |
| | | | WTT | 29% reduction in rutting depth at 8% NT. |
| | **(Albayati et al., 2024)** | 40-50<br>/12.5mm<br>2, 4, 6, 8% | MS | 11% increase in Marshall Stability at 8% NT. |
| | | | MF | 31% decrease in Marshall Flow at 8% NT. |
| | | | MR | Slight improvement of 8% improvement at 8% NT. |
| | | | PD | At 10,000 loading cycles, a 64% reduction in permanent strain (8% NT). |
| **Zinc** | **(Hamedi et al., 2015)** | 60-70<br>1, 3, 5 % | ITS | NZ significantly improved ITS values for (unconditioned & conditioned samples). |
| | **(Zhang et al., 2018)** | PG 64–16 4% | DS | 22.3% improvement in dynamic stability. |

| | | | | |
|---|---|---|---|---|
| | **(Saltan et al., 2019)** | PG 64-22<br>1, 3, 5 % | ITS | 3-5% NZ increased ITS 5.3-30.87% respectively. However, ITS decreased by 1% NZ. |
| **Carbon Nanotubes** | **(Mostafa et al., 2016)** | 70-80<br>0.01, 0.1, 0.5, 1% | MS | 58% increase in stability at 0.5% CNT. |
| | | | MF | 8% decrease in Flow at 0.5% CNT. |
| | **(Saltan et al., 2018)** | PG 64-22<br>1, 3, 5 % | ITS | 3-5% CNT increased ITS by 22-39 respectively.<br>1% CNT reduced ITS by 6%. |
| | **(Ismael et al., 2021)** | 40-50 /12.5mm<br>0.5, 1, 1.5, 2% | MS | 35% increase in MS at 1.5% CNT. |
| | | | MF | 14% decrease in MF at 1.5% CNT. |
| | | | WTT | 1.5% CNT yields 61% improvement in rutting resistance at 10,000 cycles. |

At high temperatures, Nanomaterials incorporated into asphalt mixtures significantly influence the performance of asphalt mixture by enhancing the rheological and structural properties of the binder **(Albayati et al., 2024)**. The addition of Nanomaterials increases the viscosity and complex modulus of the asphalt binder at elevated temperatures **(Neto et al., 2022)**, resulting in a binder that is less prone to flow and permanent deformation. This characteristic is particularly beneficial in hot climatic regions and under heavy traffic loading, where conventional binders tend to soften and deform. The improvement in rutting resistance arises from the formation of a stiffer and more elastic binder due to Nanomaterial addition **(Ameli et al., 2020)**. This modified binder often exhibits a lower creep rate under repeated traffic loading, which directly translates to reduced rut depths in asphalt pavements. Furthermore, Nanomaterials function as active fillers, enhancing the filler–binder interaction and forming a densely packed microstructural network within the asphalt matrix **(Nazari et al., 2018)**. This microstructural reinforcement limits binder mobility at high temperatures, effectively strengthening the aggregate–binder interface and reducing the risk of stripping, shoving, and plastic flow. In addition to mechanical benefits, certain Nanomaterials, such as Nano titanium, provide enhanced thermal and ultraviolet (UV) stability **(Liu et al., 2014)**. These properties slow down binder softening and oxidative aging under prolonged heat exposure, thereby preserving the mixture's structural integrity and extending its service life. Another critical effect arises from the interfacial bonding improvement, as Nanomaterials may have surfaces that can interact with polar components of asphalt, such as asphaltenes. This enhanced adhesion improves the aggregate–binder bond strength, making it more resistant to shear deformation and stripping **(Long et al., 2020)**. Collectively, these mechanisms contribute to a durable, rut-resistant asphalt mixture that can better withstand the challenges of high-temperature service conditions.

### 3.3 Results of Previous Research

Findings of previous research are gathered and shown in **Table 7**.

**Table 7.** The effect of Nanomaterials on asphalt mixtures.

| NM | Researcher | Country | Binder | Dosage % | Findings |
|---|---|---|---|---|---|
| **Silica** | **(Taherkhani et al., 2017)** | Iran | 60-70 | 1, 3, 5 | – NM of 5 % resulted in a 49% higher resilient modulus.<br>– Fatigue life (5% NM) is approximately 160% higher. |

| | | | | | |
|---|---|---|---|---|---|
| | **(Shafabakhsh et al., 2020)** | Iran | 60-70 | 0.3, 0.6, 0.9, 1.2 | – 1.2% addition increases rutting resistance by around 100% (at 40 °C).<br>– Increase in fatigue life of samples by 50%. |
| | **(Mohammed et al., 2021)** | Malaysia | 80-100 | 4 , 6 , 15 | – 15% Nano-silica leads to the best rutting resistance at 40°C. |
| | **(Qasim et al., 2022)** | Iraq | 60-70 | 2 , 4 , 6 , 8 | – The optimal dosage (8%) decreased the rut depth.<br>– Higher tensile strength, lower rutting depth, higher stability and minimum flow. |
| | **(AbdelWahed et al., 2022)** | Egypt | 60-70 | 1 , 2 , 3 , 4 | – Optimal dosage is 4%.<br>– The binder's storage stability decreases with increasing Nano contents. |
| | **(Taher et al., 2023)** | Iraq | 40-50 | 2 , 4 , 6 | – Enhance pavement performance (stability and volumetric characteristics).<br>– Greatest Marshall Stability and the best reduction in Marshall Flow were achieved in 6% and 4% respectively. |
| | **(Mohammed et al., 2023)** | Iraq | 40-50 | 1 , 3 , 5 , 7 | – Recommended 5% dosage of NS.<br>– 5% showed a 60% increase in RV at 135 °C. |
| | **(Albayati et al., 2024)** | Iraq | PG 64-16 | 2 , 4 , 6 , 8 | – Optimal dosage of 4%, viscosity increase of 33%.<br>– Improved the resistance to rutting. Making it effective for high temperature pavement performance. |
| **Alumina** | **(Ali et al., 2015)** | Malaysia | 60-70 | 3, 5 , 7 | - The optimal performance was at 5% NM.<br>– Increased resistance to rutting and fatigue. |
| | **(Ali et al., 2016)** | Malaysia | 60-70 | 3 , 5 , 7 | - Enhanced elastic behavior of asphalt.<br>- Increase the high temperature rutting resistance, (best at 5% NA).<br>– Decrease in G*.sin δ (up to 5% Nano content) at 25 °C. |
| | **(Karahancer, 2020)** | Turkey | 60-70 | 3 , 5 , 7 | - Economic benefit for NM≤5% (lower compaction and mixing temperatures).<br>- Reduced Rutting Performance and enhanced fatigue parameter.<br>- Only after RTFO, 5% NA made rutting parameter improvement.<br>– Performance grades were determined as PG 64-22. |
| | **(Shafabakhsh et al., 2020)** | Iran | 60-70 (SBS) | 0.3, 0.6, 0.9, 1.2, 3.0 | - 1.2% showed potential to improve the high temperature performance.<br>- Jnr remarkably decreased with dosage increase.<br>– 3% NA showed increased viscosity above (3 Pa.s). |
| | **(Hussein et al., 2021)** | Iraq | 40-50 | 3 , 5 , 7 | - Penetration decreased by about 49% when 5% modifier was added.<br>– Better resistance to oxidation and aging obtained, up to 7% decreased ductility. |

| | | | | | |
|---|---|---|---|---|---|
| | **(Cao et al., 2022)** | China | #70 Asphalt | 3, 6, 9, 12 | - At the optimum content of 9%, dynamic stability of asphalt mixture showed 34% (at 60°C).<br>- Reduced cumulative permanent strain by 36–49%.<br>- Improved fatigue performance, water stability by 3-7% & 8-19% respectively, with 2% reduction in low-temperature tensile strain. |
| | **(Song, 2023)** | China | #70 Asphalt | 0.3 , 0.6 , 0.9 , 1.2 | - Decreased rut depth by 12–36% for 0.3-1.2% dosage, respectively.<br>- The dynamic stability increases by 17–39%.<br>- Fatigue properties improve to some extent (best at 0.6%).<br>- Low temperature performance decreases slightly. |
| **Alumina** | **(Kadhim et al., 2024)** | Iran | 60-70 (SBS) | 2, 3, 4 , 5 | - 5% NA +2.5%SBS resulted in 31% Higher MSCR.<br>- 4% NA + 2.5%SBS improved fatigue resistance by 67%. |
| | **(Albayati et al., 2024)** | Iraq | PG 64-16 | 2 , 4 , 6 , 8 | - 6% NA enhanced rutting resistance, with satisfactory fatigue resistance.<br>- Although a 6% dosage does not offer the highest resistance to fatigue, it provides a balanced improvement in asphalt properties, including penetration, softening point, and mass loss. |
| **Titanium** | **(Tanzadeh et al., 2013)** | Iran | 60-70 | 4 | - Nano $TiO_2$ decreases the rutting depth and increases the softening point, consequently, improving the temperature sensitivity. |
| | **(Shafabakhsh et al., 2014)** | Iran | 60-70 | 1 , 3 , 5 , 7 | - Adding NT lead to improvements in permanent deformation and HMA. With an optimal content of 5%. |
| | **(Qian et al., 2019)** | China | 50-60 | 1 , 2 , 5 , 10 | - Following RTFO aging, there is a substantial increase in the rutting factor after modification.<br>- Rutting parameter progressively rises with increasing the dosage from 1% to 10% [slower rate of growth compared to (0% - 1%)]. |
| | **(Filho et al., 2020)** | Brazil | 50-60 | 1 , 3 , 5 , 7 | - Increased resistance to permanent deformation.<br>- Improve asphalt binder workability at higher temperatures as well as aging resistance.<br>- Optimal content is 5%. |
| | **(Mohammed et al., 2024)** | Iraq | 40-50 | 1 , 3 , 5 , 7 | - At ideal modifier (5%) rutting parameter increased by 64% at 64°C.<br>- Promoted PG by 1 grade at 3% and 2 grades at 5–7%.<br>- At 5% and 7% Nano $TiO_2$, the complex modulus increased. |
| | **(Albayati et al., 2024)** | Iraq | 40-50 | 2 , 4 , 6 , 8 | - Optimal dosage of 6%.<br>- Major increase in the rutting parameter.<br>- Lower concentrations of NT acts as an effective anti-aging agent (12% reduction in mass loss at 2% NT). |

| | | | | | |
|---|---|---|---|---|---|
| **Zinc** | **(Zhang et al., 2016)** | China | 60-70 | 2 , 3 , 4 | – Reducing the 2μm size to 80nm, anti-rutting factors & the dynamic stabilities of asphalt improve by 22.3% & 17.9% respectively.<br>– Flexural tensile strength is improved. |
| | **(Yunus et al., 2018)** | Malaysia | 60-70 | 3 , 5 , 7 | – Greater rutting resistance at 7% NZ (before and after aging). |
| | **(Saltan et al., 2019)** | Turkey | 60-70 | 1 , 3 , 5 | – Best rutting performance was achieved with 5% NM, with a 3.94% increase compared to neat bitumen.<br>– Lower fatigue performance. |
| | **(Xu et al., 2019)** | China | 60-70 | 1 , 2 , 3 , 4 , 5 | – Improvement to the rheological properties of asphalt.<br>– Improve the fatigue properties of asphalt, but excessive dosages lead to decreased fatigue performance. |
| **Zinc** | **(Kleizienė et al., 2020)** | Lithuania | 70-100 | 1 , 3 | – NZ < 3% does not affect bitumen mechanical performance.<br>– Excessive amounts may lower fatigue resistance. |
| | **(Neto et al., 2022)** | Brazil | 50-60 | 3 , 5 , 7 | – Optimum content of 7% leads to an increase in Performance Grade, rutting resistance, and fatigue life. |
| | **(AlMistarehi et al., 2023)** | Saudi Arabia | 60-70 | 1 , 2 , 3 | – Adding 3% NZ exhibited the best improvements for different temperatures (increased stiffness). |
| | **(Zhu et al., 2024)** | China | PG 64-22 | 1 , 3 , 5 | – NZ with a particle size of 10–30 nm at 3-5% was suggested to reduce agglomeration.<br>– Optimum NZ content and particle size distribution demonstrated potentially superior rheology, durability, and morphology. |
| **Carbon Nanotubes** | **(Faramarzi et al., 2015)** | Iran | 60-70 | 0.1, 0.5, 1 | – 17% increase in permanent deformation resistance at 1% CNT.<br>– CNT increased resistance to thermal cracking. |
| | **(Galooyak et al., 2015)** | Iran | 60-70 | 0.3, 0.6, 0.9, 1.2, 1.5 | – Optimal percentage of CNT of 1.2% has the best performance. |
| | **(Mostafa et al., 2016)** | Egypt | 70-80 | 0.01, 0.1, 0.5, 1 | – An optimum CNT dosage of 0.5% increased stability by 58.3% and reduced flow by 8.6%.<br>– High shear mixing proved more effective than conventional mechanical mixing. |
| | **(Gong et al., 2017)** | China | 60-80 | 1, 2, 3 | – As the CNT content increases, binder penetration decreases while the softening point rises. A significant drop in ductility is observed at 0.5% CNT; however, at CNT > 0.5% there is only a minor change.<br>– CNT improved the high temperature performance and aging resistance.<br>– Decreased low temperature performance. |
| | **(Ashish et al., 2018)** | India | AC-10 | 0.4, 0.75, 1.5, 2.25 | – Addition of CNT beyond 1.5% is not recommended due to agglomeration of CNT. |

| | | | | | |
|---|---|---|---|---|---|
| | **(Yang et al., 2018)** | China | PG 64-22 | 0.2, 0.4, 0.6, 0.8, 1, 1.5, 3 | – CNT of 1.5% is the best content to improve the high temperature performance.<br>– At 3% CNT, some agglomerations are observed. |
| | **(Ismael et al., 2021)** | Iraq | 40-50<br>60-70 | 0.5, 1, 1.5, 2 | – At 1.5%, CNT of 40-50 grade resulted in an increase in rutting resistance and stability by 61.0% & 35.0% respectively.<br>– 60-70 grade needed 2.0% of CNT to be near the 40-50 results. |

### 3.4 Conflicted Findings

There is a notable divergence in the reported optimal dosages of Nanomaterials for asphalt modification, as shown in **Table 8**, as discrepancies persist among researchers regarding the most effective content levels. While some studies suggest that lower dosages are sufficient to enhance performance without compromising other properties, others report that higher dosages yield better improvements in rutting resistance or stiffness. These inconsistencies highlight the complexity of determining a universally accepted optimal dosage, which may vary depending on the type of Nanomaterial, binder grade, mixing method, and specific performance criteria evaluated.

**Table 8.** Optimum Nanomaterial dosages.

| NM | Researcher | Optimum Dosage (%) | Comment |
|---|---|---|---|
| Silica | **(Mohammed et al., 2021)** | 15% | Reported dosages from 4% to 15% vary widely due to differences in materials, blending methods, and evaluation targets. |
| | **(Qasim et al. 2022)** | 8% | |
| | **(Albayati et al. 2024)** | 4% | |
| Alumina | **(Ali et al., 2016)** | 5% | Optimum contents from 0.9% to 9% reflect varied binder types and dispersion efficiencies. |
| | **(Cao et al., 2022)** | 9% | |
| | **(Song, 2022)** | 0.9% | |
| Titanium | **(Tanzadeh et al., 2013)** | 4% | Dosage discrepancies (4–8%) likely stem from binder variations. |
| | **(Shafabakhsh et al., 2014)** | 5% | |
| | **(Ameli et al., 2020)** | 8% | |
| Zinc | **(Zhang et al., 2016)** | 4% | Studies reported 3–7% as optimal, influenced by material and method variability. |
| | **(Yunus et al., 2018)** | 7% | |
| | **(AlMistarehi et al., 2023)** | 3% | |
| Carbon Nanotube | **(Galooyak et al., 2015)** | 1.2% | CNT dosage ranged from 0.5% to 2%, highlighting sensitivity to type and dispersion quality. |
| | **(Mostafa et al., 2016)** | 0.5% | |
| | **(Ismael et al., 2021)** | 2% | |

These discrepancies in reported outcomes can be attributed to multiple factors. Key contributors include differences in nanomaterial properties (particle size, morphology, surface treatment, and purity), variation in binder grades and aggregate types, aggregate gradation, and non-uniform mixing or dispersion techniques, which directly influence the degree of particle interaction with the binder matrix. Additionally, differences in testing methodologies and targeted performance metrics can result in non-comparable performance trends across studies. Optimum dosage can be subjective and criterion-dependent, as some consider cost-effectiveness. Testing protocols and performance evaluation criteria vary widely, with some studies conducted in hot climates reporting higher optimum dosages, focusing on rutting resistance. Whereas cold-climate studies may favor lower dosages to avoid embrittlement and cracking on which reduces fatigue life or stiffness, and some try to find balanced performance, leading to non-comparable definitions of (optimum dosage). Also, even when proper initial dispersion is achieved, Nanoparticles may re-agglomerate during storage **(Jenima et al., 2024)**. This effect can reduce the effectiveness of Nanomaterials, causing inconsistencies between immediate laboratory testing and delayed performance evaluation. Aging protocols and oxidative hardening also influence reported results; for instance, a dosage that appears optimal under unaged conditions may behave differently after short or long-term aging. Furthermore, differences in test scale (binder-level DSR versus mixture-level wheel tracking) can produce conflicting interpretations because improvements in binder rheology do not always directly translate to mixture-level rutting resistance. Interaction with other additives, such as polymers, hydrated lime, or fibers, can either enhance or interfere with the Nanomaterial's effects, further contributing to dosage variability. To reconcile these conflicting findings, future research needs to adopt standardized protocols for Nanomaterial preparation and performance evaluation. Establishing unified, consistent mixing procedures, dosage optimization strategies, and performance testing protocols will enhance cross-study comparability and reproducibility, supporting the practical implementation of Nanotechnology in pavement engineering.

## 4. CONCLUSIONS

For the limited studies reviewed, the following conclusions and research implications can be drawn:

1- Most nanomaterials studied tend to increase the binder's stiffness and resistance to rutting when added in controlled dosages.
2- Nanomaterial additives, including nano silica, alumina, titanium dioxide, and carbon nanotubes, improve the stiffness and high-temperature rutting resistance of asphalt binders. However, the effect of nano zinc oxide remains inconclusive.
3- There is a critical dosage threshold for each nanomaterial, beyond which the benefits plateau or reverse, often leading to reduced performance and workability. This underlines the importance of identifying material-specific optimal contents to balance high-temperature performance and long-term durability.
4- Blending techniques and equipment significantly influence nanomaterial dispersion quality and performance outcomes. While high shear mixing at 140–160°C and 3000–8000 rpm was widely used, no standardized mixing protocol exists, limiting reproducibility and field implementation.
5- Agglomeration remains a technical barrier, particularly for carbon nanotubes. Although ultrasonic mixing has shown promise, cost-effective and scalable dispersion techniques are still not clear.
6- There is a need for standardization for processing protocols to ensure repeatability, scale-up potential, and field performance.
7- Field performance studies and life-cycle assessments remain sparse and are needed to bridge the lab-to-field gap.

## Nomenclature

| Symbol | Description | Symbol | Description |
|---|---|---|---|
| AFM | Atomic Force Microscopy | APA | Asphalt Pavement Analyzer |
| DSC | Differential Scanning Calorimetry | DCT | Dynamic Creep Test |
| EDS | Energy Dispersive X-ray Spectroscope | DPT | Double Punch Test |
| FTIR | Fourier Transform Infrared Spectroscopy | DS | Dynamic Stability |
| HSM | High Shear Mixer | FN | Flow Number |
| LSM | Low Shear Mixer | ITS | Indirect Tensile Strength |
| MM | Mechanical Mixer | MF | Marshall Flow |
| SEM | Scanning Electron Microscopy | MS | Marshall Stability |
| SM | Shear Mixer | NMS | Nominal Maximum Aggregate Size |
| SP | Sonication Process | PD | Permanent Deformation |
| TEM | Transmission Electron Microscopy | MR | Resilient Modulus |
| USM | Ultrasonic Mixer | RT | Rutting Test |
| UVS | UV-Vis-infrared Spectrophotometer | SCT | Static Creep Test |
| | | SM | Shape Memory |
| XRD | X-ray Diffraction | WTT | Wheel Tracking Test |

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Yousuf AlHamdou: Original draft writing & editing. Amjad AlBayati: Conception, supervision, methodology & review.

## Declaration of Competing Interest

The authors declare no known financial or personal conflicts of interest that could have influenced the findings presented in this study.

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# تحسين مقاومة التشوه الدائم للخرسانة الاسفلتية عند درجات الحرارة المرفعة بواسطة مواد معدِلة بقياس نانوي – مراجعة

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**الخلاصة**

إضافة المواد النانوية في تعديل الخلطات الاسفلتية يُعد نهجًا واعدًا لتعزيز أداء الخرسانة الاسفلتية ، خاصةً في الظروف ذات درجات الحرارة المرتفعة. المواد النانوية ، بفضل خصائصها الفريدة مثل المساحة السطحية العالية ، والقوة الميكانيكية الاستثنائية، وثباتها الحراري ، توفر تحسينات كبيرة في الخصائص الريولوجية ، المتانة ومقاومة التشوه الدائم. تستعرض هذه الدراسة تطبيق مجموعة متنوعة من المواد النانوية ، بما في ذلك نانو السيليكا ، نانو الألومينا ، نانو تيتانيوم ، نانو زنك وأنابيب الكربون النانوية في تعديل الأسفلت. وقد أظهرت إضافة هذه المواد النانوية إلى الخلطات الاسفلتية قدرة على زيادة الصلابة وتحسين الأداء عند درجات الحرارة العالية ، مما يؤدي إلى تقليل إمكانية حدوث التشوه الدائم (التخدد) ، وتحسين العمر الخدمي الكلي للطرق. كما تناولت الدراسة التحديات المتعلقة بتوزيع هذه المواد وطرق خلطها. وتم استكشاف الآليات التي تعزز من خلالها المواد النانوية الخصائص الحرارية والميكانيكية للأسفلت. وتشير النتائج إلى أن المواد النانوية تَحمِل إمكانيات كبيرة في تحسين أداء الأسفلت في درجات الحرارة العالية ، إلا أن هناك حاجة إلى مزيد من الأبحاث من أجل تحسين استخدامها وتحقيق أقصى استفادة منها في التطبيقات على نطاق واسع.

**الكلمات المفتاحية:** الاسفلت، مواد نانوية، التشوه الدائم.