# The Influence of Nanomaterials on the Permanent Deformation of Hot Mix Asphalt

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## ABSTRACT

**Improving the permanent deformation resistance of asphalt pavements is a vital challenge. Nanomaterials have emerged as promising additives due to their ability to enhance the binder stiffness and elasticity. This study evaluated the influence of five nanomaterials, namely Nano-Silica (NS), Nano-Alumina (NA), Nano-Zinc (NZ), Nano-Titanium (NT), and Carbon Nanotubes (CNTs) incorporated into a base asphalt binder at varying dosages, with up to 10% for NS, NA, and NT, and up to 5% for NZ and CNT. Fifteen modified binders were assessed using the Multiple Stress Creep Recovery (MSCR) test to obtain non-recoverable creep compliance ($J_{nr}$), while the corresponding hot mix asphalt samples underwent repeated load testing and rut depth prediction using the VESYS 5 W model. The results showed that most nanomaterials improved the high-temperature binder properties with a reduced rutting potential. Strong correlations were observed between $J_{nr}$ and the mixture performance for NS and NZ, whereas NA and CNTs enhanced the mixture stiffness and deformation resistance beyond what was indicated by $J_{nr}$ alone. NT showed minimal correlation between the binder and mixture performance. While $J_{nr}$ is a valuable parameter for rutting prediction, it may not always accurately reflect the nano-modified mixture performance, particularly when using higher modification dosages. Therefore, combining the binder with mixture tests provides a reliable performance prediction and optimal nanomaterial selection.**

***Keywords-asphalt; nanomaterials; MSCR; permanent deformation; VESYS***

## I. INTRODUCTION

Rutting remains one of the major challenges in asphalt pavement engineering and is characterized by the accumulation of permanent deformation along the wheel path owing to repeated traffic loading [1]. A rut depth of 1.1 inches can significantly reduce the serviceability of flexible pavements, lowering the pavement serviceability index from 4.2 to 2.5 [2]. This substantial decline underscores the detrimental effect of rutting on the overall pavement functionality and ride quality [3]. Traditionally, the Superpave Performance Grade (PG) system uses the Dynamic Shear Rheometer (DSR) parameter $G^*/\sin\delta$ to designate the high-temperature rutting potential of binders. However, subsequent research has found that $G^*/\sin\delta$ correlates inadequately with the rutting performance of the actual mixture [4, 5]. In response, the MSCR test was established to better characterize the binder behavior under repeated loading and to improve the correlation with the rutting of the asphalt mixtures. The MSCR results offer an improved prediction of the rutting performance under varying traffic stresses compared to the traditional Superpave criteria. The MSCR test estimates parameters, such as the non-recoverable creep compliance ($J_{nr}$) at multiple stress levels and percent recovery that have shown a significantly better correlation to the observed rutting behavior [6, 7]. $J_{nr}$ (measured in 1/kPa) reflects the binder's tendency to accumulate permanent strain under load, a critical parameter for the rut resistance evaluation. Although the asphalt binder can meet the conventional specification limits, MSCR testing has revealed its inadequacy in terms of the rutting resistance [8].

In parallel with advances in binder testing, nanomaterials have emerged as a promising class of asphalt modifiers. Nanoscale additives, such as NS, NA, NZ, NT, and CNTs have been explored to enhance the properties of asphalt binders and mixtures [9-11]. Nanotechnology contributes both by enhancing the performance and efficiency of the current materials and processes, and by enabling the development of innovative new products [12]. In asphalt applications, nanomaterials are usually added in small proportions relative to the binder weight. Because of their extremely fine particle size and large surface area, even low dosages can yield significant improvements, comparable to those achieved with traditional modifiers [13]. Owing to their extremely high surface area and unique physicochemical features, these nanoparticles can significantly alter the rheology of the binder, even at low dosages [14]. Previous research has indicated that incorporating nanomaterials can increase the binder stiffness and viscosity, increase the softening point, and improve the rutting parameter G*/sinδ [15, 16]. CNTs, due to their fibrous shape and high tensile strength, have also shown potential to dramatically reduce the permanent deformation in binders and mixtures [17]. Most existing standards are designed for traditional polymers or unmodified binders. No standardized protocols exist for testing, mixing, dosage, dispersion techniques, or performance evaluation of the nano-modified binders or mixtures [18, 19]. This gap largely stems from the relatively recent emergence of nanotechnology in asphalt research, which has outpaced the development of the corresponding standardization. Additionally, the wide variety of nanomaterials, differing in size, shape, surface chemistry, and behavior, present challenges for creating universally applicable guidelines. The lack of long-term field performance data and the limited scalability of the lab procedures further hindered the inclusion of nanomaterials in formal specifications. Accordingly, further investigation is warranted, as there is a need for a comparative understanding of the different nanomaterial effects and for linking the binder-level MSCR metrics to actual mixture performance outcomes.

This research presents a comparative experimental study that relates the MSCR binder parameters with asphalt mixture performance for 15 different nano-modified asphalt binders. Five types of nanomaterials, namely NS, NA, NT, NZ, and CNTs, were used to modify a neat asphalt binder at various dosages. The binders were tested for their physical properties and MSCR response (at 0.1 and 3.2 kPa stress levels). The mixture tests included axial repeated load permanent deformation tests to derive the rutting parameters, slope and intercept, and resilient modulus. Additionally, rut depth predictions over a 20-year period were conducted using the VESYS 5W probabilistic model. The VESYS 5W (Viscoelastic System) is a software developed by the Federal Highway Administration (FHWA), United States [20], for predicting the performance of flexible pavements. Utilizing the multilayer viscoelastic theory, this software forecasts pavement distresses, such as rutting and fatigue cracking, as well as the Present Serviceability Index (PSI), under defined traffic loads and environmental conditions. The primary mechanical parameters required include the resilient modulus, permanent deformation parameters (α and μ) for each pavement layer, and fatigue coefficients (K1 and K2) specific to the asphalt layers [21, 22]. Analyzing these results enhances the understanding of the nanomaterial interactions within the asphalt mixtures. The findings aim to inform both material selection and the identification of binder tests that best correlate with the field performance. Ultimately, this study presents insights into the practical implications of nano-modified binders, contributing to a more integrated link between the binder rheology and pavement performance outcomes.

## II. MATERIALS

### A. Asphalt Binder

The asphalt binder used in this research was obtained from al Daurah refinery, with its properties shown in Table I.

TABLE I. PHYSICAL PROPERTIES OF ASPHALT BINDER

| Property | Standard | Unit | Result | Limit |
|---|---|---|---|---|
| Penetration (25°C, 100g, 5s) | AASHTO T 49 [23] | 0.1 mm | 44 | 40-50 |
| Retained penetration (TFOT) | ASTM D1754 [24] | % | 59 | >50% |
| Specific gravity (25°C) | ASTM D70 [25] | - | 1.04 | - |
| Ductility (25 °C, 5 cm/min) | AASHTO T 51 [26] | cm | >100 | >100 |
| Flashpoint | AASHTO T 48 [27] | °C | 316 | Min. 232 |
| Softening point | AASHTO T 53 [28] | °C | 48.7 | - |

### B. Aggregate Gradation

Hot-mix asphalt utilized a dense graded aggregate gradation (Type D5) produced in accordance with the gradation and design specifications outlined in ASTM D3515 [29]. The aggregate gradation employed in this mixture is presented in Figure 1.

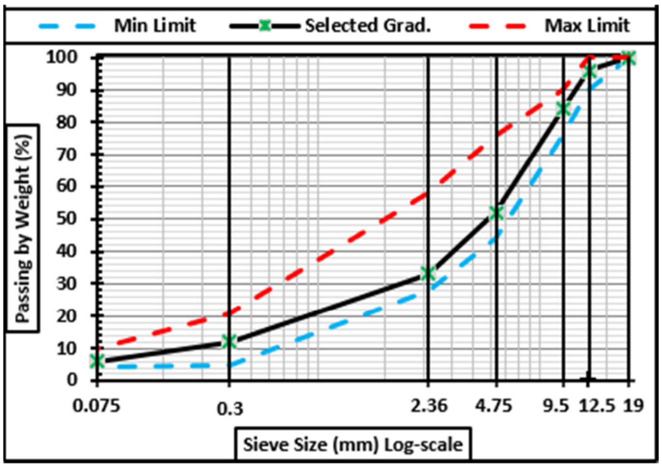


Fig. 1. Aggregate gradation.

### C. Nanomaterials

Each nanomaterial was incorporated into the asphalt binder using a dry blending technique, starting with an initial mixing speed of 400 rpm, while adding the modifier at a rate of 4 g/s. This was followed by high-shear mixing at 3000 rpm for 20 min at 150 ± 5 °C to ensure a uniform dispersion. Table II lists the nanomaterials and their dosages used in this study.

TABLE II. PROPERTIES OF THE NANOMATERIALS

| Nanomaterial | Chemical formula | Dosage | Particle size (nm) | Density (g/mL) | Specific surface area ($m^2/g$) |
|---|---|---|---|---|---|
| NS | $SiO_2$ | 2, 4, 6, 8, 10% | 25-35 | 0.080 | 190-250 |
| NA | $Al_2O_3$ | 2, 4, 6, 8, 10% | 10-20 | 0.200 | 120-160 |
| NT | $TiO_2$ | 2, 4, 6, 8, 10% | 20-30 | 0.510 | 120-160 |
| NZ | ZnO | 1, 2, 3, 4, 5% | 15-20 | 0.331 | 30-60 |
| CNT | MWCNT | 1, 2, 3, 4, 5% | 20 nm diameter, 10 µm length | 0.126 | 100-300 |

## III. EXPERIMENTAL TESTING

### A. Asphalt Binder Physical Properties

The fundamental physical properties of the asphalt binders, including penetration, softening point, and ductility, provide essential insights into their consistency and temperature susceptibility. The penetration (AASHTO T 49) [23] measures the hardness or consistency of the binder at a standard temperature, whereas the softening point (AASHTO T 53) [28] indicates the temperature at which the binder transitions from a semi-solid state to a more fluid state. The ductility (AASHTO T 51) [26] reflects the ability of the binder to deform under tensile stress without breaking, indicating flexibility and resistance to cracking. Additionally, the Rotational Viscosity (RV) (AASHTO T 316) [30] was used to evaluate the flow characteristics of the binder at elevated temperatures, which is critical for assessing the workability during mixing and compaction. Collectively, these parameters are vital for characterizing the binder performance and predicting their behavior under varying service conditions.

### B. Rheological Properties of Asphalt Binder

The MSCR tests (Figure 2) were conducted using an Anton Paar MCR 102 dynamic shear rheometer, in accordance with AASHTO T 350 [31], to evaluate the high-temperature performance of the asphalt binders. It provided key parameters, such as the non-recoverable creep compliance ($J_{nr}$) at 70°C, which reflects the ability of the binder to resist permanent deformation.

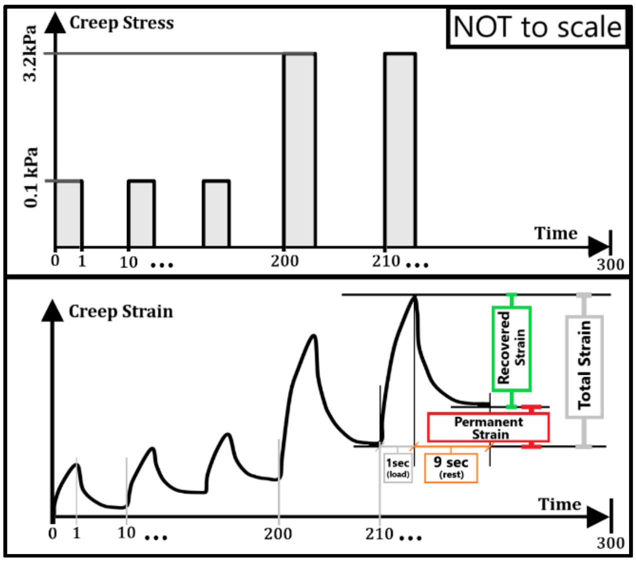


Fig. 2. MSCR test.

### C. Permanent Deformation of Modified Asphalt Mixture

Repeated loading tests were used to evaluate the rutting resistance and deformation behavior of the asphalt mixtures under simulated traffic conditions. The tests involved the application of a cyclic 60 psi stress (0.1 s load and 0.9 s rest periods) at 40 °C on an 8 × 4 in cylindrical specimen (Figure 3) to replicate the effects of the repeated axle loads over time. Two linear variable differential transducers were positioned 180° apart along the specimen's circumference, with a gauge length of 100 mm measured vertically between their mounting points. The specimen was painted white to trace the cracking and deformation. All the samples were prepared using a fixed asphalt binder content of 5% to ensure that any changes in performance could be attributed solely to the added nanomaterials, with the mixtures compacted to a target air void content of 4%. Key parameters, such as the accumulated permanent strain, resilient modulus estimated from (1), and rut depth, were found to gauge their ability to resist permanent deformation.

Fig. 3. 8x4 inch asphalt specimen.

$$Resilient\ Modulus\ (psi) = \frac{Axial\ stress\ (psi)}{Resilient\ microstrain} \quad (1)$$

The pavement section selected for the analysis period is illustrated in Figure 4, with an AASHTO W18 Equivalent Single Axle Load (ESAL) of $7.3 \times 10^6$. The selected pavement structure reflected a sustainable design approach by minimizing the asphalt concrete thickness, and optimizing the layer configurations to balance the performance, cost, and environmental impact over the 20-year analysis period.

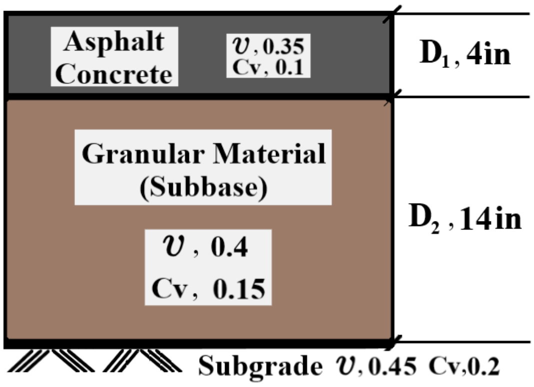


Fig. 4. Pavement structure used in the VESYS 5W analysis.

### *D. Overall Desirability*

Overall Desirability (OD) is a multiple-criteria analysis method used to identify the most favorable nanomaterial dosage for asphalt binder modification by evaluating several properties, such as ductility, softening point, penetration, and viscosity at 135 °C. Each property was normalized on a 0-1 scale, with 1 indicating the most desirable result. Normalization follows either the larger the better method using (2) or the smaller the better method following (3) [32]:

$$x_i^*(w) = \frac{x_i^{(0)}(w) - \min x_i^{(0)}}{\max x_i^{(0)} - \min x_i^{(0)}} \quad (2)$$

$$x_i^*(w) = \frac{\max x_i^{(0)} - x_i^{(0)}(w)}{\max x_i^{(0)} - \min x_i^{(0)}} \quad (3)$$

where $i$ and $w = 1,2,3 \ldots n$, $x_i^{(0)}(w)$ is the *w-th* value of the *i-th* original sequence, $x_i^*(w)$ is the *w-th* value of the *i-th* normalized sequence, $\max x_i^{(0)}$ and $\min x_i^{(0)}$ are the maximum and minimum values of the *i-th* original sequence, respectively. The normalized values were then obtained using the geometric mean to calculate the OD score for each nanomaterial dosage level. This facilitates the determination of the optimal dosage that best enhances the targeted properties of the modified asphalt binder, as described in [32]:

$$y(w) = [x_1^*(w) \times x_2^*(w) \ldots x_n^*(w)]^{\frac{1}{n}} \quad (4)$$

Higher OD values reflect a better overall binder performance, helping to identify the most effective nanomaterial dosage.

## IV. RESULTS

### *A. Selected Dosages*

Table III summarizes the specific dosage levels applied in both the binder and mixture performance tests. The OD results shown in Table IV demonstrate that higher nanomaterial dosages tend to increase the performance of the asphalt under high temperature conditions. This suggests that increasing the dosage level positively contributes to the thermal stability and deformation resistance of the modified asphalt.

TABLE III. SELECTED DOSAGES

| Nanomaterial | Dosage % | Tests |
|---|---|---|
| NS | 6, 8, 10 | MSCR (binder) and Axial repeated loading (mixture) |
| NA | 6, 8, 10 | |
| NT | 6, 8, 10 | |
| NZ | 3, 4, 5 | |
| CNT | 3, 4, 5 | |

### *B. Binder and Mixture Correlation*

Understanding the correspondence between the non-recoverable creep compliance and various asphalt mixture properties is essential for evaluating the binder-mixture compatibility. Parameters, such as the resilient modulus ($M_r$), permanent microstrain (10,000 cycles) from repeated load testing, and rut depth prediction by VESYS 5W under (7.3 x $10^6$ ESAL) traffic loading, offered critical insights into the mixture performance. Exploring how $J_{nr}$ is related to these mixture-level indicators helps establish a more unified approach to the performance prediction and material selection for the rutting resistance.

#### *1) $J_{nr}$ and Permanent Microstrain*

Figure 5 displays the regression models developed between $J_{nr\text{-}3.2}$ and the permanent deformation microstrain ($\varepsilon_p$) for the modified asphalt binders. The modified asphalt binders with NS (Figure 5(a)) and with NZ (Figure 5(e)) both demonstrated strong positive linear relationships, indicating that lower $J_{nr\text{-}3.2}$ values were associated with a decreased mixture deformation, suggesting an enhanced resistance to rutting. However, Figures 5(b) and (d) illustrate negative correlations for NA and CNTs modified asphalt, respectively. These inverse trends suggest that even with high $J_{nr\text{-}3.2}$ values, the mixtures experienced less deformation, likely due to the structural reinforcement or improved internal stability provided by the modifiers. In contrast, Figure 5(c), which presents a transformed relationship for NT containing asphalt of $(J_{nr\text{-}3.2})^2$ versus $1/\varepsilon_p$, yielded a weak correlation, indicating a limited predictive value and possible inconsistencies in the binder-mixture performance behavior. Overall, the results highlighted that while $J_{nr\text{-}3.2}$ generally correlated with rutting performance, the nature and effectiveness of this relationship were highly dependent on the type of nanomaterial used.

#### *2) $J_{nr}$ and Resilient Modulus*

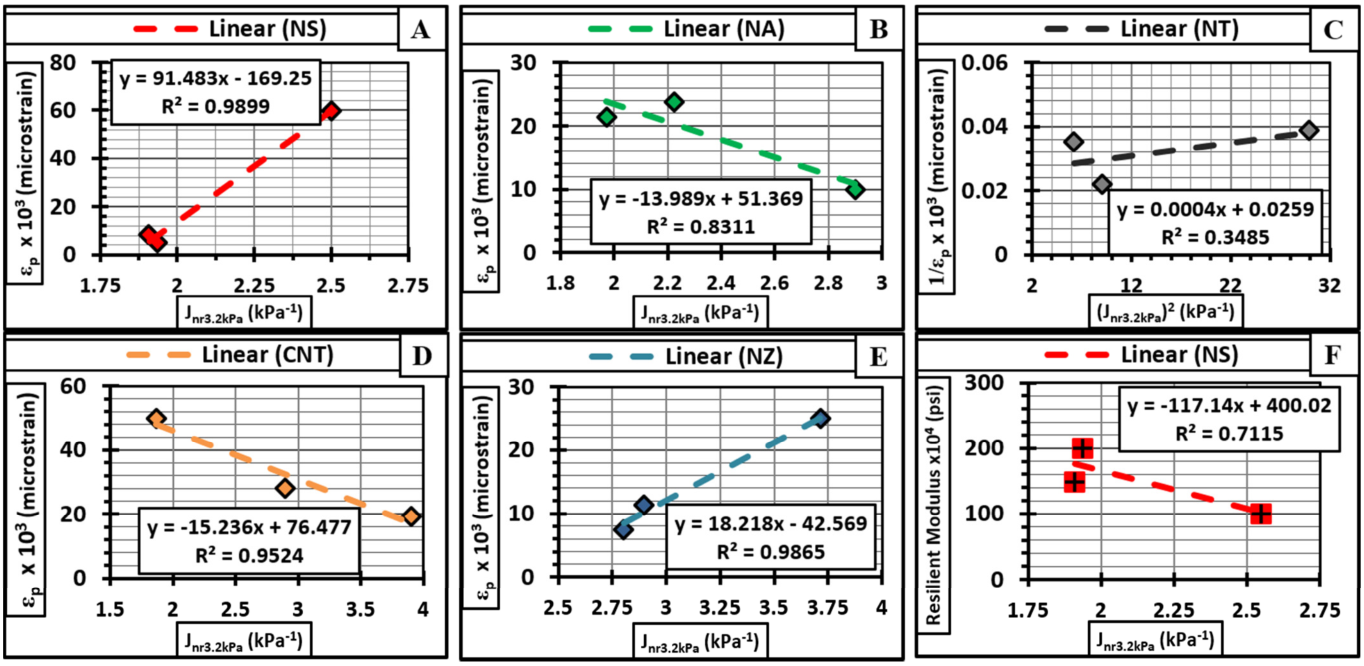
The regression analysis between $J_{nr\text{-}3.2}$ and the resilient modulus $M_r$ of the asphalt mixtures modified with various nanomaterials is also shown in Figure 5. In Figures 5(f) and (h), the NS and NT modified mixtures exhibited moderate to strong negative correlations, indicating that the decreased binder compliance corresponded to an improved mixture stiffness. The NZ modified asphalt exhibited a weak negative trend (Figure 5(g)). In contrast, the NA modified mixture displayed a strong positive correlation, suggesting that a higher $J_{nr\text{-}3.2}$ may be associated with improved stiffness. The CNT-containing mixture demonstrated minimal correlation (Figure 5(i)), indicating a limited predictive value.

#### *3) $J_{nr}$ and Rut Depth*

Figure 5 depicts the regression models between $J_{nr\text{-}3.2}$ and rut depth for the asphalt mixtures incorporating different nanomaterials. The asphalt mixtures containing NS and NZ (Figures 5(k) and (n), respectively) exhibited strong positive correlations, implying that the increased binder compliance led to significantly higher rutting in the mixtures. In contrast, the asphalt mixtures containing NA and CNT (Figures 5(l) and (o)) showed strong negative correlations, suggesting that higher $J_{nr\text{-}3.2}$ or its square is related to lower rut depth, which could be attributed to overdosage. As shown in Figure 5(m), the relationship between $J_{nr\text{-}3.2}$ and rut depth is weak and inconsistent for the asphalt mixture with NT, indicating a poor predictive capability. These trends highlight the influence of $J_{nr}$ in predicting the rutting behavior while also emphasizing the modifier-specific nature of the binder-mixture performance interactions.

TABLE IV. OD RESULTS

| Designation | Penetration | | Softening point | | Ductility | | Rotational viscosity | | y(w) OD |
|---|---|---|---|---|---|---|---|---|---|
| | ***X1***$^{(0)}$ | ***X1***$^{*}$ | ***X2***$^{(0)}$ | ***X2***$^{*}$ | ***X3***$^{(0)}$ | ***X3***$^{*}$ | ***X4***$^{(0)}$ | ***X4***$^{*}$ | |
| NEAT | 44 | 0 | 48.7 | 0 | 100 | 0 | 745 | 0 | 0.00 |
| 2% NS | 42 | 0.091 | 53.6 | 0.4336 | 99.99 | 0.0006 | 1129 | 0.2974 | 0.05 |
| 4% NS | 43 | 0.045 | 52.6 | 0.3451 | 99.99 | 0.0006 | 1183 | 0.3392 | 0.04 |
| 6% NS | 38 | 0.273 | 57.2 | 0.7522 | 95 | 0.3125 | 1368 | 0.4825 | 0.41 |
| 8% NS | 26 | 0.818 | 59.2 | 0.9292 | 87 | 0.8125 | 1777 | 0.7993 | 0.83 |
| 10% NS | 22 | 1 | 60 | 1 | 84 | 1 | 2036 | 1 | 1.00 |
| 2% NA | 22 | 0.846 | 54.2 | 0.5978 | 99.99 | 0.0005 | 1112 | 0.4453 | 0.10 |
| 4% NA | 22 | 0.846 | 54.1 | 0.5869 | 99.99 | 0.0005 | 1214 | 0.5691 | 0.10 |
| 6% NA | 22 | 0.846 | 55.8 | 0.7717 | 99.99 | 0.0005 | 1245 | 0.6068 | 0.11 |
| 8% NA | 18 | 1 | 57.9 | 1 | 86 | 0.6364 | 1295 | 0.6674 | 0.80 |
| 10% NA | 18 | 1 | 56 | 0.7934 | 78 | 1 | 1569 | 1 | 0.94 |
| 2% NT | 35 | 0.500 | 51.5 | 0.4057 | 91 | 0.3913 | 707 | 0.0060 | 0.14 |
| 4% NT | 31 | 0.722 | 53.3 | 0.6666 | 89 | 0.4783 | 704 | 0 | 0.00 |
| 6% NT | 29 | 0.833 | 55.2 | 0.9420 | 87 | 0.5652 | 705 | 0.0020 | 0.17 |
| 8% NT | 26 | 1 | 55.6 | 1 | 82 | 0.7826 | 1200 | 1 | 0.94 |
| 10% NT | 27 | 0.944 | 55.4 | 0.9710 | 77 | 1 | 1074 | 0.74597 | 0.90 |
| 1% NZ | 44 | 0 | 49.15 | 0.0576 | 99.99 | 0.0025 | 840 | 0.1841 | 0.00 |
| 2% NZ | 41 | 0.273 | 50 | 0.1666 | 99.99 | 0.0025 | 852 | 0.2073 | 0.07 |
| 3% NZ | 34 | 0.909 | 50.7 | 0.2564 | 99.99 | 0.0025 | 1150 | 0.7848 | 0.14 |
| 4% NZ | 35 | 0.818 | 53 | 0.5512 | 99.99 | 0.0025 | 1176 | 0.8352 | 0.17 |
| 5% NZ | 33 | 1 | 56.5 | 1 | 96 | 1 | 1261 | 1 | 1.00 |
| 1% CNT | 44 | 0 | 49.8 | 0.1746 | 99.99 | 0.0002 | 1216 | 0.0409 | 0.00 |
| 2% CNT | 42 | 0.125 | 52.2 | 0.5555 | 99.99 | 0.0002 | 1257 | 0.0445 | 0.02 |
| 3% CNT | 38 | 0.375 | 54.7 | 0.9523 | 99.99 | 0.0002 | 1403 | 0.0572 | 0.04 |
| 4% CNT | 31 | 0.813 | 55 | 1 | 95 | 0.1136 | 1602 | 0.0745 | 0.28 |
| 5% CNT | 28 | 1 | 55 | 1 | 56 | 1 | 12249 | 1 | 1.00 |



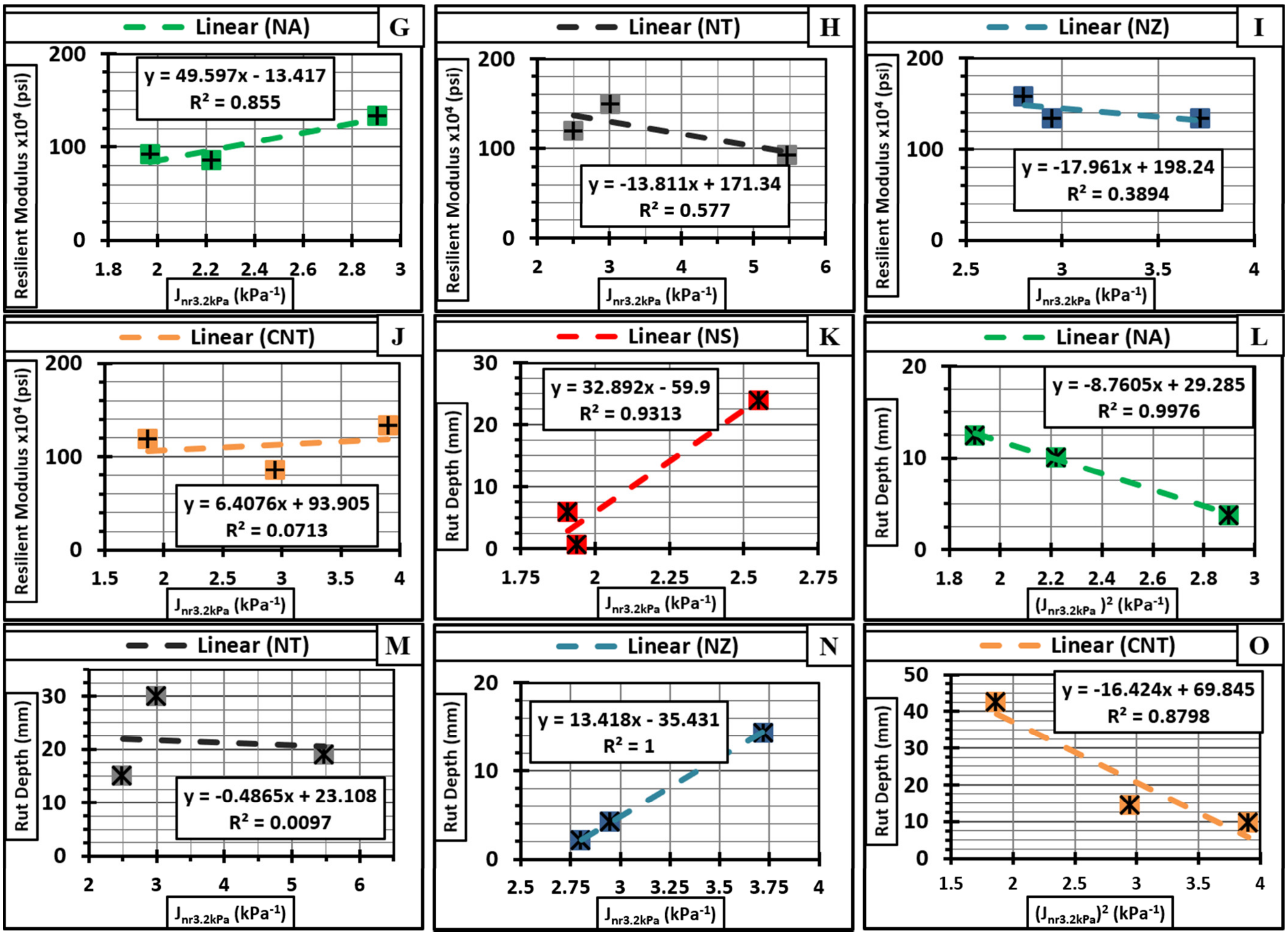


Fig. 5. Regression models of $J_{nr3.2}$ kPa and modified asphalt mixture properties.

## V. CONCLUSIONS

This study explored the potential of nanomaterials in enhancing the properties of asphalt mixtures. To this end, various mechanical tests were performed to evaluate the effect of the nanomaterial dosage on the asphalt mixtures.

Five different nanomaterials were evaluated, including Nano-Silica (NS), Nano-Alumina (NA), Nano-Titanium (NT) oxide, Nano-Zinc (NZ) oxide, and Carbon Nanotubes (CNTs). All nanomaterials showed promising results in enhancing the performance of the asphalt mixtures, particularly in improving their high-temperature properties and reducing rutting. However, the extent of improvement depended on the nanomaterial and the amount added to the mixture, and the optimal dosages which maximized the rutting resistance were found. The optimal dosages for achieving higher rutting resistance were 8% NS, 6% NA, 10% NT, 5% NZ, and 3% CNTs. Additionally, NS and NZ exhibited strong correlations between their binder properties ($J_{nr}$) and mixture rutting parameters. Although the incorporation of NA and CNTs enhanced the rutting resistance and stiffness, these improvements were not fully reflected in their $J_{nr}$ values. NT showed the weakest correlation between the binder and mixture performance among the tested materials. To ensure an accurate performance prediction and appropriate nanomaterial selection, it is proposed to combine binder rheological testing with additional evaluation methods.

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