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# A Review On The Impact Of Nanomaterials Modification On The Performance Of Asphalt Mixtures

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***ABSTRACT:*** *Nanomaterials are emerging as potential modifiers to enhance the performance of asphalt binders and mixtures to address the growing needs for sustainable and long-lasting road infrastructure. This review presents a critical evaluation of the development of nanomaterial-modified asphalt technology, citing papers between 2015-2025. A variety of nanomaterials, such as nano-silica, carbon nanotubes, nano-clay, graphene oxide, and nano-zinc oxide, are evaluated for performance on mechanical characteristics, rutting resistance, fatigue life, and moisture sensitivity. The article also details common mixing protocols, dosage rates, and test procedures used in laboratory studies. Although these nanomaterials have shown significant performance gains, practical application is hindered by issues such as constraints in dispersion, material cost, lacking field validation, and potential environmental and health issues. The review also highlights the growing role of bio-based and waste-derived nanomaterials as more sustainable alternatives. It finally summarizes key research gaps and proposed future research areas focusing on field-scale testing, lifecycle assessment, and development of standard protocols to enable broader adoption of nanotechnology in flexible pavement systems.*
***Keywords:*** *Nanomaterials, asphalt mixes, rutting, fatigue, moisture susceptibility, environmental impact*

## INTRODUCTION:

Flexible pavements are a critical aspect of modern infrastructure and are widely adopted because of their ease of construction and adaptable nature. Bitumen, being the primary material, is a by-product of petroleum refining. Due to a wide range of challenges, such as heavy traffic loads, extreme environmental conditions, various distresses like rutting, fatigue, and moisture damage occur in asphalt mixtures, resulting in early failures of pavements [1]. This requirement accentuates the necessity for rehabilitation of flexible pavements within shorter durations, resulting in higher life cycle costs and ineffective pavement designs. Therefore, it has become necessary to develop a solution to these issues and create a sustainable solution. The bitumen modification is a feasible solution, as it improves the mechanical characteristics of pavements [2].

Different modifiers have been studied over the years to be applied in asphalt mixtures, such as polymers, chemical stabilizers, industrial byproducts, glass, plastic, rubber, etc. In recent years, however, nanomaterials have been of interest as a material that can potentially be used as a modifier based on their high surface-to-volume ratios, which allow them to interact with binder particles in the nanorange. The use of nanomaterials improves aggregate-binder adhesion by minimizing the risk of stripping and increasing adhesion [3]. Additionally, mechanical properties like rutting and cracking resistance can be improved through the addition of nanomaterials to asphalt mixtures [4], [5]. Some nanomaterials are also known to help slow down the oxidation and degradation of bitumen, hence reduce its aging process [6]. Nano materials fill voids in the bitumen matrix, making it denser and more stable [7]. In addition, their unique physicochemical properties—high thermal conductivity, large surface area, and nanoscale reactivity—make them efficient in boosting high- and low-temperature performance. Carbon nanomaterials like CNTs and graphene, for example, possess high tensile strength and elasticity, resulting in improved fatigue life and load transfer. Inorganic nanomaterials like nano-silica, nano-alumina, and nano-titanium dioxide have wide documentation to enhance stiffness, moisture resistance, and overall binder performance through improved dispersion and physical interlocking. In addition, advances in dispersion processes, such as high-shear mixing, ultrasonication, and chemical functionalization, have further improved the compatibility and stability of these nanomaterials with the asphalt matrix. These benefits have witnessed a deluge of experimental research into a range of nanomaterials and combinations thereof, aiming at particular performance improvements under varied climatic and loading conditions. This paper attempts to provide a critical review of various nanomaterials and their application in improving asphalt mixtures. Current advancements in the application of nanomaterials in flexible pavements are addressed, including the techniques used in their integration into the asphalt binder. The performance of various nanomaterials is then compared on the basis of three basic criteria: rutting resistance, fatigue resistance, and moisture susceptibility. The study synthesises findings from literature published between 2015 and 2025. A comprehensive literature review was conducted using databases such as Scopus, Web of Science, and Google Scholar using keywords such as "nanomaterials," "asphalt mixtures," "fatigue and rutting," "moisture damage," and specific nanomaterials. Realistic limitations, including scalability issues, environmental concerns, cost constraints, and lack of field implementation, are considered. The review concludes by suggesting possible future research considerations to bridge these gaps.

## CLASSIFICATION OF NANOMATERIALS USED IN BITUMEN:

Nanomaterials for asphalt modification can be classified into zero-dimensional, one-dimensional, and two-dimensional, each offering unique benefits. Each type contributes distinct properties to the bitumen, improving its mechanical, rheological, and thermal performances.

### *Zero-Dimensional Nanomaterials:*

Zero-dimensional (0D) nanomaterials are nanomaterials where the three dimensions of space, length, width, and height are limited to the nanoscale, typically lower than 100 nanometers. These are spherical, cubic or irregularal shaped particles. Nanoparticles such as nano-silica, nano-titanium dioxide, and nano-iron oxide are classified as 0D; they significantly enhance asphalt performance by improving its mechanical properties, durability, and resistance to environmental degradation [7], [8]. Incorporation of such materials enhances asphalt viscosity by forming spatial network structures via van der Waals interactions and chemical bonding, increasing resistance to rutting at high temperatures and cracking at low temperatures [7]. For example, the incorporation of nano-silica at a concentration of 8% can result in an approximate increase of 138% in binder viscosity while, concurrently, lowering penetration by 40.8%, enhancing hardness and consistency [9]. Moreover, nanomaterials such as nano-titanium dioxide and nano-aluminum oxide enhance aging resistance by lowering mass loss and increasing thermal stability, while nano-$Fe_3O_4$ enables self-healing characteristics, in effect fixing microcracks and prolonging pavement life [10], [11]. However, challenges such as poor compatibility, uneven dispersion, high production cost, and possible environmental and health hazards necessitate comprehensive economic and ecological research, in addition to standardized tests, to guarantee cost-effectiveness and long-term performance in field use for broader implementation [7], [12], [13].

### *One-Dimensional Nanomaterials:*

One-dimensional (1D) nanomaterials are nanostructures in which two dimensions, i.e., width and thickness, are confined to the nanoscale, i.e., below 100 nanometers, whereas the third dimension, length, is significantly larger, extending to the microscale or beyond. To put it more simply, these materials are long nanoscale fibers, rods, wires, or tubes. Nanomaterials such as carbon nanotubes (CNTs) and nanofibers enhance asphalt performance significantly by engaging with non-polar asphalt molecules through $\pi$–$\pi$ stacking, mechanical entanglement, and van der Waals interactions to form bonds that increase adhesion, stability, and resistance to cyclic loading [7], [14]. The interactions enhance the asphalt matrix to allow effective stress transfer and to retard or slow crack propagation [15]. CNT addition increases asphalt viscosity, enhancing rut resistance at high temperature and cracking resistance at low temperature, while at the same time improving durability through the prevention of water damage and permanent deformation under changing environmental conditions [16], [17]. Poor dispersion and compatibility in the asphalt matrix, high production costs, and environmental and health concerns deter widespread use [7]. The challenges must be addressed through optimized dispersion means and comprehensive economic and ecological assessment to allow the sustainable application of one-dimensional nanomaterials in asphalt technology.

***Two-Dimensional Nanomaterials:***

Two-dimensional (2D) nanomaterials are defined by their nanoscale thickness (≤100 nm) but with broad surface areas in width and length, thus possessing a sheet-like or layered structure. The ultra-thin materials are usually a single layer or a few atomic layers and have been extremely in demand due to their high mechanical strength, barrier capacity, and surface reactivity. Materials like graphene and graphene oxide nanoparticles greatly improve asphalt performance through chemical interactions that form hydrogen bonds and aromatic deposits that improve surface roughness and affect aggregate mobility [7], [10]. The interactions improve asphalt viscosity and form a cross-linked network that traps light components, minimizing thermal mobility and improving resistance to high-temperature rutting and low-temperature cracking. The high adsorption capability of graphene-based materials facilitates improved mechanical properties, such as stiffness and high-temperature stability, while minimizing permanent deformation (Guo et al., 2019). The nanomaterials also enhance aging resistance through the formation of a surface barrier within the asphalt, protecting against oxidation and UV radiation, thereby extending pavement life under heavy traffic loads and harsh environmental conditions [18]. Low compatibility, non-uniform dispersion, high production cost, and potential health and ecological constraints, however, constrain large-scale application (Huang et al., 2024). In-depth economic and ecological analysis, as well as standardized testing, must be conducted to guarantee long-term field performance and enable sustainable application of two-dimensional nanomaterials into asphalt technology [7], [13].

Table 1 indicates the physical properties of commonly used nanomaterials for asphalt modification, including morphology, particle size, surface area, and density. These are some key properties which plays a critical role in the control of dispersions as well as the mechanism of interaction with bitumen.

**Table 1:** Physical characteristics of commonly used nanomaterials in asphalt modification:

| Nano Material | Shape/ Appearance | Avg. particle size (nm) | SSA (m2/g) | Density (g/cm3) | Purity | Melting Pt. (°C) | Reference |
|---|---|---|---|---|---|---|---|
| NS | White Powder | 25-35 | 190-250 | 0.08 | 99.8 | 1730 | [19] |
| CNT | Tubular | 23.86 | >200 | 0.06 | - | - | [20] |
| NZ | Hexagonal | 40 | - | 5.6 | 98 | 1975 | [21] |
| | Cubic | 20 | 40 | 5.5-5.6 | - | - | [22] |
| NHL | Pearl white powder | 10-30 | 120-200 | 420 | 99 | 580 | [23] |
| NGO | Earthy brown powder | 0.6-1 | 1000-1217 | - | - | - | [24] |
| | Black Powder | 10-50 | 300-450 | - | >95 | - | [25] |
| | Gray- black powder | 10 | 182 | 0.78 | 98 | 142 | [26] |
| NA | White powder | 10-20 | 120-160 | 0.2 | 99.9 | 2030 | [27] |
| | Spherical | 30-50 | 130-150 | - | 99.9 | 2055 | [28] |
| NT | Off-white powder | 20-30 | 120-160 | 0.51 | 99.9 | 1860 | [27] |
| | Rhombohedral | 21 | 50 | 4.26 | 99.5 | - | [29] |
| | White powder | 21 | - | 4.26 | 99.9 | 1843 | [30] |
| NC | Yellow | 1-2 | 500-750 | 5.7 | - | - | [31] |
| | Off-white | <10 | - | 0.13 | - | - | [32] |
| N-CaCO3 | Cubic/ white | 20 | 40 | 2.93 | 99.9 | - | [33] |

**Note:** SSA- Specific Surface Area; NS- Nano-Silica; CNT- Carbon Nanotubes; NZ-; NHL-Nano Hydrated Lime; NGO- Nano Graphene Oxide; NA- Nano-Aluminium Oxide; NT-Nano Titanium Dioxide; NC-Nano Clay, N-CaCO3- Nano-Calcium Carbonate. **"-"** indicates data not mentioned in the cited reference.

**MIXING AND DISPERSION TECHNIQUES:**

***Dry Mixing:*** It involves the direct mixing of the nanomaterials and asphalt without the use of solvents, and it is a simple and cost-effective process. The process tends to produce a non-uniform dispersion of the nanomaterials because the nanomaterials do not wet the asphalt much. Dry mixing works effectively if the nanomaterials inherently contain compatibility with asphalt in a way that mechanical mixing is enough to achieve proper dispersion [34], [35].

***Wet Mixing:*** This method involves the pre-dispersion of nanomaterials in a solvent, like methanol or kerosene, before adding them to asphalt. This allows for a much more uniform distribution of particles. For example, carbon nanotubes (CNTs) in methanol have been reported to have better bitumen compatibility [34]. Solvent evaporation after mixing, usually confirmed using methods like Fourier Transform Infrared Spectroscopy (FTIR), adds to the complexity of the process but improves the overall dispersion [35].

The key to releasing their ultimate performance potential lies in achieving a homogeneous dispersion of nanoparticles within asphalt binders. ***High-shear mixing*** is likely one of the most used and effective methods utilized to disperse the particles uniformly and prevent them from aggregating together. The process typically involves agitation at between 3,000 and 6,000 RPM while, at the same time, heating the blend to 135–160°C for 30–60 minutes, depending on the particular nanomaterial and binder in use [36], [37]. Nano-metakaolin, for example, exhibited greater dispersion and more consistent flow behavior when blended at 4,000 RPM for 60 minutes [38]. ***Sonication***, in the majority of cases, is utilized beforehand to further break up clusters, greatly enhancing uniformity, especially in the case of materials like carbon nanotubes (CNTs) and nano-clay [39]. ***Pre-blending*** in controlled laboratory conditions is also a good method, particularly for composite nanomaterials, where microstructure control of the blend can be finely adjusted [8]. Ultimately, the optimal mixing strategy, tailored to the type of nanomaterial, the grade of binder, and the desired performance goals, is necessary to optimize the durability and performance of nano-modified asphalt.

Table 2 discusses various mixing methods used for dispersing nanomaterials into asphalt binders, highlighting key factors such as mixing speed, temperature, mixing time, and other dispersion steps. The blending has to be done correctly to avoid agglomeration and obtain a uniform distribution throughout the binder matrix

**Table 2:** Summary of nanomaterials mixing techniques results from recent literature:

| Nano Material | Binder Type | Mixing technique | Mixing Speed (RPM) | Temp (°C) | Time (min) | Remarks | Reference |
|---|---|---|---|---|---|---|---|
| CNT | PG 40/50, PG 60/70 | Flash mixer | 1500 | 163 | 45 | Initially manual mixing, then mechanical stirring | [20] |
| NS | PG 64-16 | High shear mixer | 4000 | 150-160 | 45 | Manual stirring for 20 mins | [40] |
| N-CaCO3 | PG 64-16 | High shear mixer | 6000 | 150-160 | 45 | Manual stirring for 20 mins | [40] |
| NT | PG 64-16 | High shear mixer | 6000 | 150-160 | 45 | Dry blending was done initially | [41] |
| NT | PG 64-22 | High shear mixer | 2000 | 160 | 60 | Binder was heated to 160 °C | [42] |
| NZ | - | High shear mixer | 6000 | 150 | 30 | Wet mixing method; kerosene used as solvent | [21] |
| NS,NA,NT | PG 40/50 | High speed | 4000 | 140 | 20 | High speed shear mixer allows uniform dispersion | [27] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | shear mixer | | | | | |
| NC, CNT | PG 60/70 | High shear mixer | 3000 | 160 | 45 | Dry mix method used | [43] |
| NGO | PG 64-22 | High speed shear mixer | 5000 | 120 | 45 | First binder samples were heated at 160°C for 30 mins | [44] |
| nGO | PG 60/70 | High shear mixer | 4000 | 160 | 45 | Pure bitumen Heated up to 160 C | [45] |

**Note:** CNT- Carbon Nanotubes; NS- Nanosilica; N-CaCO3- Nano-Calcium Carbonate; NT- Nano-Titanium Dioxide; NZ- Nano-Zinc Oxide; NA- Nano-Alumina; NC- Nanoclay; NGO- Graphene Oxide; PG -Performance Grade. **"-"** indicates data not mentioned in the cited reference.

Table 2 provides an overview of methodologies used for incorporating nanomaterials into asphalt binders, with a focus on the superiority of high-shear mixing (2000–6000 RPM, 120–160°C, 20–60 minutes) for ensuring homogeneous dispersion of different nanomaterials (e.g., NS, CNT, NT, NGO). The results indicate that increased mixing velocities and temperatures, as seen with N-CaCO3 and NT, not only ensure improved dispersion but also increase energy demands. Strategies like wet mixing for NZ and pre-heating for NGO improve compatibility, but at the cost of increased procedural complexity. These findings underscore the need for standard mixing protocols tailor-made for different nanomaterial and binder pairings for optimized performance while ensuring accompanying economic and scalability concerns.

## PERFORMANCE ENHANCEMENT ASPECTS:

### *Mechanical Properties:*

The incorporation of nanomaterials in asphalt significantly alters its physical properties, including penetration, softening point, and viscosity, and the performance that results under thermal and mechanical stresses. The addition of nanomaterials decreases the penetration of asphalt, hence making the binder harder. For example, nano zinc oxide decreases penetration, improving the thermal stability of the asphalt binder [46]. Similarly, nano silica and nano aluminum oxide significantly decrease the penetration values, making the binder stronger and more durable [47], [48]. In addition, nano titanium dioxide decreases penetration, which improves rutting resistance and binder stiffness [49]. Nanomaterials tend to increase asphalt's softening point, thereby enhancing its performance under heat. For instance, nano zinc oxide and nano silica increase the softening point, thereby decreasing the amount by which asphalt softens under heat [46], [48]. Likewise, nano calcium carbonate and nano hydrated lime increase the softening point, allowing asphalt to withstand heat with little softening [9].The addition of nanomaterials enhances asphalt viscosity, which provides improved resistance to flow and deformation. Nano silica and nano zinc oxide enhance viscosity, which improves the binder load-carrying capacity [46], [48]. Nano titanium dioxide and nano aluminum oxide improve viscosity, which improves the high-temperature performance and reduces the temperature susceptibility of asphalt [47], [49].

### *Rutting resistance:*

Rutting is one of the most important distresses in flexible pavements, usually occurring due to the sustained effect of heavy loads and high temperatures. Nanomaterials like nano-silica and nano-calcium carbonate significantly enhance the rutting resistance of asphalt mixtures. Nano-silica improves stiffness and lowers permanent deformation, as evidenced through enhanced flow number values and wheel tracking test results [50], [51], [52]. Up to 15% nano-silica by weight of bitumen optimizes rutting resistance and shape retention, especially at high temperatures [53]. Nano-alumina also increases dynamic stability and lowers cumulative permanent strain, further enhancing rutting resistance [54].

Table 3 shows the rutting resistance gains through the application of nanomaterials, as measured by tests like the Hamburg Wheel Tracking Test (HWTT) and Multiple Stress Creep Recovery (MSCR). The reduction in rut depth and the improvement in dynamic stability indicate improved structural performance under high loads.

**Table 3:** Summary of rutting performance of nanomaterials in asphalt mixtures:

| Nano Material | Binder type | Dosages used | Optimum dosage | Test method | Performance metrics | % change in rutting depth/resistance | Reference |
|---|---|---|---|---|---|---|---|
| NS | C320 | 2%, 4%, 6%, 8% | 6% | DSR, MSCR | Stiffness ↑, softenijng point ↑, rutting res ↑ | 45% ↑ in rutting resistance | [55] |
| | AC 40-50 | 2%, 4%, 6% | 6% | Wheel Tracking test | Rut depth ↓, Marshall stability ↑ | 2.4 mm at 45° C and 3.1 mm at 55° C | [50] |
| | PG 60/70 CR 10% | 1%, 2%, 3%, 4%, 5% | 5% | Cooper wheel tracker test | Stiffness ↑, rut depth ↓ | 26% ↓in rut depth | [56] |
| NC | PG 40/50 | 1%, 3%, 5% | NC 5% CR 30% | Wheel Tracking Test | Greater dynamic stability values | 40.85% ↓ in rut depth | [57] |
| CNT | - | 0.1%, 0.5%, 1% | 1% | ABAQUS finite element modeling | Vertical compressive strain reduced | 250% ↑ in rutting resistance | [58] |
| CNT | PG 40/50, 60/70 | 0%, 0.5%, 1%, 1.5%, ad 2% | 1.5 | Wheel Tracking Test | Rutting resistance ↑, best with 40/50 | 61% ↑ in rutting resistance | [20] |
| NC, CNT | PG 60/70 | CNT 0.5%, 1.5%, 2.5% NC 2%, 4%, 6%, 8% | 1.5% CNT and 6% NC | Wheel Tracking Test | Dynamic stability ↑, resilient modulus ↑ | 64.7% ↓ in rut depth | [43] |
| NT | PG 64-22 | 1.5%, 3.5%, 5.5%, 9% | 9% | Hamburg wheel tracking device | Rutting resistance ↑ | 25.5%↑ in rutting resistance | [42] |
| NGO | PG 64-22 | 0.05% and 0.2% | 0.05% | DSR | Above 0.05, performance ↓ | - | [44] |
| NGO | PG 60/70 | 0.2%, 0.5%, 0.8% | 0.5% | Hamburg wheel tracking test | Adhesion ↑, rutting resistance ↑ | 25% ↓ in rut depth | [45] |

Note: NS- Nanosilica; NC- Nanoclay; CNT- Carbon Nanotubes; NT- Nano-Titanium Dioxide; NGO-Nano-Graphene Oxide; PG- Performance Grade; DSR- Dynamic Shear Rheometer; MSCR- Multiple Stress Creep Recovery; CR- Crumb Rubber. "-" indicates data not mentioned in the cited reference.

***Fatigue life:***

Under cyclic loading, fatigue cracking takes place, causing surface degradation and structural failure with time. Nanomaterials, such as nano-calcium carbonate, enhance the fatigue performance of asphalt mixtures by enhancing cyclic loading resistance, hence reducing fatigue cracking occurrence [59]. Additionally, the addition of nano-silica enhances fatigue performance, with studies showing enhanced tensile strength and reduced susceptibility to cracking due to repeated stress [54], [60].

Table 4 shows the effect of various nanomaterials on the fatigue properties of asphalt mixtures and binders. Beam fatigue test and four-point bending beam test were some of the techniques used to measure the increase in fatigue life, with most of the studies recording significant improvements at optimum concentrations.

**Table 4:** Summary of fatigue performance of nanomaterials in asphalt mixtures:

| **Nano Material** | **Binder type** | **Dosages used** | **Optimum dosage** | **Test method** | **Performance metrics** | **% change in fatigue life** | **Reference** |
|---|---|---|---|---|---|---|---|
| NS | PG 60/70 Crumb rubber 10% | 1%, 2%, 3%, 4%, 5% | 5% | Four-point bending beam test | Rheological properties ↑, fatigue life ↑ | 21% ↑ | [56] |
| N-CaCO3 | PG 60-70 | 0.3%, 0.6%, 0.9%, 1.2% | 0.9% | Linear Amplitude Sweep | Fatigue life ↑, >0.9% decrease fatigue life | 22.4 ↑ | [33] |
| GNP | AC 70-60 | 0.1%, 0.3%, 0.5% | 0.5% | Indirect Tensile Fatigue Test (ITF) | Fatigue life ↑, tensile strength ↑ | 55 ↑ | [61] |
| NZ | PG 60/70 | 2%, 4%, 6%, 8% | 6% | Beam Fatigue test | Fatigue life ↑ | 283.33 ↑ | [21] |
| NZ | PG 50/70 | 3%, 5%, 7% | 7% | Linear Amplitude sweep | consistency, viscosity, and stiffness ↑; Fatigue life ↑ | - | [62] |
| CNT | - | 0.1%, 0.5%, 1% | 1% | Finite Element Analysis | Resistance to fatigue damage life ↓ at 0.1% and 0.5% | 10% ↑ | [58] |
| NGO | PG 60/70 | 0.5%, 1%, 1.5%, 2%, 2.5% | 2% | Four-point bending beam fatigue test | Enhanced Fracture resistance and fatigue life | | [25] |
| NT | PG Grade 60/70 | 1.5%, 3.5%, 5.5%, 9%. | 5.5% | Bending Beam Rheometer | Better low-temp cracking resistance | | [42] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| NT | PG 85-10 | NT: 2%, 4%<br>SBR: 3%, 6% | 4% NT + 6% SBR | Linear Amplitude Sweep | Improved fatigue life with higher proportions | | [29] |

Note: NS- Nanosilica; N-$CaCO_3$- Nano-Calcium Carbonate; GNP- Graphene Nanoplatelets; NZ- Nano-Zinc Oxide; CNT- Carbon Nanotubes; NGO- Nano Graphene Oxide; NT- Nano-Titanium Dioxide; PG-Performance Grade; SBR- Styrene Butadiene Rubber. "-" indicates data not mentioned in the cited reference.

***Moisture Susceptibility:***

Moisture susceptibility reduces the durability of pavement through weakening of the asphalt-aggregate bond, resulting in stripping and early failure. Nanomaterials improve the moisture damage resistance of asphalt mixes through increased adhesion between binder and aggregate and reduced water sensitivity at the same time. Modified binders have increased resistance to stripping and moisture damage, a behavior often attributed to the increased surface area and higher microstructural coherence promoted by nanoparticle [63]. Empirical evidence suggests that the use of nanomaterials results in improved tensile strength ratios and improved wet conditions performance compared to unmodified mixtures [64].

In Table 5, the outcomes of the test such as Indirect Tensile Strength (ITS), Tensile Strength Ratio (TSR) were compiled in order to assess the moisture resistance of asphalt mixtures containing nanomaterials. Enhanced aggregate and binder adhesion indicates enhanced lifespan performance under water damage.

**Table 5:** Summary of moisture resistance performance of nanomaterials in asphalt mixtures:

| **Nano Material** | **Binder type** | **Dosages used** | **Optimum dosage** | **Test method** | **Performance metrics** | **% change in moisture resistance** | **Reference** |
|---|---|---|---|---|---|---|---|
| NS, NA, NT | PG 40/50 | 2%, 4%, 6%, 8% | 4%, 6%, 6% | ITS | TSR ↑for all 3. NS performed best | 91%↑, 88%↑, 84.1% ↑ resp. | [27] |
| NC, CNT | PG 60/70 | CNT 0.5%, 1.5%, 2.5%<br>NC 2%, 4%, 6%, 8% | 1.5% CNT and 4% NC | TSR | TSR ↑ | 22.35% ↑ | [43] |
| NS | PG 60-70<br>PG 85-100 | 0.2%, 0.4%, 0.7%, 0.9% | 0.7% | Modified Lottman test | Viscosity ↑, ITS ↑, NS more effective on PG 60-70 | - | [65] |
| CNT | PG 60/70 | 0.05%, 0.1%, 0.5% | 0.5% | ITS | Moisture susceptibility ratio ↑, TSR ↑ | 16% ↑ in TSR, 5-15% ↑ in MSR | [66] |
| NS, NC | PG 60/70 | 1%, 2%, 3%, 4% | 3% NC<br>4% NS | ITS | NC performed better than NS | 67% ↑<br>43% ↑ | [67] |
| GNP | AC 70-60 | 0.1%, 0.3%, 0.5% | 0.5% | ITS | ITS for dry and wet condition↑ | 23% ↑ dry<br>38% ↑ wet | [61] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| N-Bentonite | PG50/70 | 2%, 4 %, 6% | 4% | Modified Lottman test | TSR ↑ | 14% ↑ | [68] |

Note: NS- Nanosilica; NA- Nano-Alumina; NT- Nano-Titanium Dioxide; NC- Nanoclay; CNT- Carbon Nanotubes; GNP- Graphene Nanoplatelets; N-Bentonite- Nano-Bentonite; AC- Asphalt Concrete; TSR- Tensile Strength Ratio; ITS- Indirect Tensile Strength; MSR- Moisture Susceptibility Ratio; PG- Performance Grade. "-" indicates data not mentioned in the cited reference.

Tables 3, 4, and 5 collectively show the interesting improvements in rutting resistance, fatigue life, and moisture susceptibility of nano-modified asphalt mixtures with nanomaterials such as nanosilica (NS), nano-calcium carbonate (N-$CaCO_3$), nano-titanium dioxide (NT), carbon nanotubes (CNTs), nanoclay (NC), and graphene derivatives (GNP, NGO). For rutting resistance (Table 3), nanomaterials such as NS and NC at 5–6% dosages decrease rut depth by 26–64.7% and improve dynamic stability, with up to 45% improved rutting resistance due to increased binder stiffness. CNTs and NT at 1.5% and 9% dosages improve by 61% and 25.5%, respectively, but dosages too high pose a risk of agglomeration or brittleness. For fatigue performance (Table 4), nano-zinc oxide (NZ) at 6–7% improves by up to 283.33% in fatigue life, while NS, N-$CaCO_3$, and GNP at 0.5–5% dosages improve fatigue life by 21–55% due to increased tensile strength and cracking resistance. High dosages (e.g., >0.9% N-$CaCO_3$) lower fatigue life due to over-stiffening. For moisture susceptibility (Table 5), NS, NA, and NT at 4–6% dosages increase tensile strength ratio (TSR) by 84.1–91%, with NS showing superior performance due to improved binder-aggregate adhesion. GNP and NC at 0.5% and 4% increase TSR by 22.35–38%, improving wet conditioning durability. These findings show the promise of nanomaterials to improve asphalt performance through multiple distress mechanisms by creating reinforcing networks and attaining maximum interfacial bonding. However, optimum dosages (0.05–9%) differ significantly, and issues such as agglomeration, cost, and unreliable test methods (e.g., DSR, Hamburg Wheel Tracking, ITS) highlight the necessity of standardized protocols and field validation for practical, cost-effective application.

## ENVIRONMENTAL IMPACTS:

The use of nanomaterials in asphalt modification raises important environmental considerations that must be carefully addressed to ensure sustainable application. On one hand, nanomaterials can contribute positively by extending pavement life, reducing maintenance frequency, and enhancing resistance to common distresses- factors that ultimately lower the environmental footprint of road infrastructure over its lifecycle. Certain nanomaterials, especially those derived from industrial by-products or natural sources such as nano-clay or nano-calcium carbonate, offer additional sustainability benefits due to their lower production energy and carbon intensity. However, concerns persist regarding the environmental and health risks associated with the manufacturing, handling, and application of engineered nanomaterials [69]. Their extremely small particle size and high reactivity may pose hazards to workers through inhalation or dermal exposure, and the long-term ecological effects of nanoparticle leaching into soil and water systems remain largely unexplored. Moreover, the high energy requirements and chemical processes involved in producing some nanomaterials, such as carbon nanotubes and graphene derivatives, can offset the environmental benefits if not properly managed. Although nanomaterials increase pavement life and maintenance intervals, therefore providing indirect sustainability benefits [13], [70], it is important to conduct a whole lifecycle assessment (LCA) to see trade-offs between performance gains and environmental consequences. Therefore, future research must incorporate cradle-to-grave environmental assessments and establish safe handling guidelines to ensure that nanotechnology in pavements contributes positively to sustainable development goals.

## CHALLENGES AND LIMITATIONS:

Despite promising improvements in the mechanical and rheological performance of asphalt materials, the widespread adoption of nanomaterials in pavement engineering is restrained by several challenges and practical limitations. These can be categorized into technical, economic, environmental, and standardization-related issues.

- ***Agglomeration of nanomaterials:*** Even distribution of the nanomaterials within the asphalt binder is a major technical challenge. Due to their high surface energy, nanomaterials, especially carbon nanotubes (CNTs) and graphene, agglomerate and, therefore, do not distribute evenly in the binder matrix. Agglomeration makes the binder non-uniform, reduces expected performance benefits, and negatively affects workability. Methods like high-shear mixing and ultrasonication can improve dispersion but require special equipment and add to processing costs. Most available studies are limited to laboratory-scale testing. Full-scale field trials and long-term monitoring under varying traffic and climatic conditions are essential to validate the laboratory-proven benefits of nanomaterials in real-world scenarios.

- ***Optimal Dosage and Stability of Binders:*** Optimal dosage of nanomaterials is extremely critical to improve performance and reduce side effects. High dosages will lead to increased viscosity, brittleness, and decreased fatigue life. Long-term stability of nano-modified binders under storage and operating conditions has not been thoroughly investigated in most of the studies, thus creating concerns regarding consistency and durability.
- ***High Costs and Economic Viability:*** The manufacture and processing of high-performance nanomaterials like CNTs, graphene derivatives, and nano-$TiO_2$ are economically infeasible for mass-level pavement applications. Although low-cost or naturally occurring alternatives like nano-clay and nano-lime are under investigation, their reliability of performance and mass-scale supply chains are not yet developed. Additionally, life cycle cost analyses of nano-modified pavements are not commonly reported in the literature.
- ***Lack of Standardization:*** One of the primary barriers to wider use of nanomaterials in asphalt is the absence of standard procedure protocols to implement them. There is no codes available to select dosage levels, process of mixing, compatibility tests, or performance tests under simulated conditions related to real-life use. Lack of uniformity between studies makes comparison or setting uniform specifications difficult.
- ***Limited Field Implementation:*** Most of the literature available pertains to laboratory testing, and few field trials have been reported. It is difficult to determine the field performance of the nano-modified asphalt mixtures without long-term testing under actual traffic loading and changing climatic conditions.

There needs to be more interaction between the research community and industry stakeholders in order to bridge this gap and enable successful field application.

## FUTURE RESEARCH:

While nanomaterials have shown potential to improve the mechanical and durability characteristics of asphalt binders and mixtures, their actual field performance is still a subject of further in-depth research. Future work must emphasize large-scale field testing to confirm laboratory findings under real traffic loading and climatic conditions. Life cycle analysis and cost–benefit studies are required to investigate the long-term economic and environmental impacts of nano-modified pavements. Exploration of synergistic effects through the blending of various nanomaterials or their application with polymers and recycled modifiers can accomplish enhanced performance improvement. Standardization of test procedures, especially for dosage determination, dispersion methods, and performance testing, is essential to ensure reproducibility, consistency, and quality control. The growing emphasis on green and bio-based nanomaterials, e.g., nano-cellulose, waste materials nanoparticles and eggshell-derived $CaCO_3$, offers a cost-effective, sustainable alternative that must be explored methodically. Furthermore, use of advanced modeling tools such as molecular dynamics simulations and machine learning can lead to optimal mix designs, forecast performance, and minimize dependence on large-scale physical testing. Advances in these research areas will be instrumental in transferring the benefits of nanotechnology from the laboratory to widespread field application in pavement engineering.

## CONCLUSION:

This review has comprehensively examined the influence of various nanomaterials on the performance of bituminous binders and asphalt mixtures, with a focus on rheology, rutting resistance, fatigue behavior, moisture susceptibility, and physical properties. These are due to their nanograde interactions with the binder matrix, which improve adhesion, stiffness, and structural stability. However, extensive application of nanotechnology is currently hampered by limitations such as high material cost, agglomeration upon mixing, environmental and health concerns, and lack of standard methodologies and field verification. In order to close the gap between laboratory achievement and real-world use, future research will require to give high priority to long-term field testing, test protocol standardization, and life cycle assessment. Examination of plant-based or waste-derived nanomaterials provides an avenue to greener and cheaper solutions. Development of these technologies will be critical in realizing the full potential of nanotechnology in providing more durable, cheaper, and greener road infrastructure.

**REFERENCES:**

[1] V. Bansal and B. K. Shukla, "Effects of Modifiers on the Properties of Asphalt for Sustainable and Improved construction of Flexible Pavements," *J. Phys. Conf. Ser.*, vol. 2267, no. 1, p. 012062, May 2022, doi: 10.1088/1742-6596/2267/1/012062.

[2] A. Roberto, A. Montepara, E. Romeo, and S. Tatalović, "The Use of a Polyethylene-Based Modifier to Produce Modified Asphalt Binders on Site," in *Springer, Cham*, 2020, pp. 346–355. doi: 10.1007/978-3-030-29779-4_34.

[3] A. S. Mohammed, A. Kavussi, and M. Manteghian, "The role of nanomaterials in enhancing adhesion properties between bitumen and aggregate particles," *Results Eng.*, vol. 24, no. August, p. 103193, 2024, doi: 10.1016/j.rineng.2024.103193.

[4] M. Saltan, S. Terzi, and S. Karahancer, "Performance analysis of nano modified bitumen and hot mix asphalt," *Constr. Build. Mater.*, vol. 173, pp. 228–237, 2018, doi: 10.1016/j.conbuildmat.2018.04.014.

[5] M. M. Mannar, "A Review on Modification of Bitumen for Flexible Pavement," *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 6, no. 3, pp. 2594–2599, 2018, doi: 10.22214/ijraset.2018.3582.

[6] R. S. Alam, O. F. Maynul, and S. Hossain, "Nano-modified Bitumen Enhancing Properties with Nano-materials Nano-modified Bitumen Enhancing Properties with Nano- materials," no. June, 2025, doi: 10.59247/sjer.v1i2.26.

[7] H. Huang, Y. Wang, X. Wu, J. Zhang, and X. Huang, "Nanomaterials for Modified Asphalt and Their Effects on Viscosity Characteristics: A Comprehensive Review," *Nanomaterials*, vol. 14, no. 18, p. 1503, Sep. 2024, doi: 10.3390/nano14181503.

[8] A. H. Albayati, R. H. Latief, H. Al-Mosawe, and Y. Wang, "Nano-Additives in Asphalt Binder: Bridging the Gap between Traditional Materials and Modern Requirements," *Appl. Sci.*, vol. 14, no. 10, 2024, doi: 10.3390/app14103998.

[9] A. H. Albayati, N. K. Oukaili, M. M. Moudhafar, A. A. Allawi, A. I. Said, and T. H. Ibrahim, "Experimental Study to Investigate the Performance-Related Properties of Modified Asphalt Concrete Using Nanomaterials Al2O3, SiO2, and TiO2," *Materials (Basel).*, vol. 17, no. 17, p. 4279, Aug. 2024, doi: 10.3390/ma17174279.

[10] J. Crucho, L. Picado-Santos, J. Neves, and S. Capitão, "A Review of Nanomaterials' Effect on Mechanical Performance and Aging of Asphalt Mixtures," *Appl. Sci.*, vol. 9, no. 18, p. 3657, Sep. 2019, doi: 10.3390/app9183657.

[11] X. Chen, Y. Zhang, K. Liu, and Q. Dong, "Study on the properties of nano-Fe3O4 modified asphalt materials based on molecular dynamics," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1332, no. 1, p. 012036, May 2024, doi: 10.1088/1755-1315/1332/1/012036.

[12] S. Imoni, M. T. Tiza, M. Onyebuchi, and E. O. Akande, "The Use of Nanomaterials for Road Construction," *Bincang Sains dan Teknol.*, vol. 2, no. 03, pp. 108–117, Oct. 2023, doi: 10.56741/bst.v2i03.435.

[13] S. Wu, "Nanomaterials in roadway asphalt materials," in *Handbook of Nanomaterials, Volume 1*, Elsevier, 2024, pp. 649–662. doi: 10.1016/B978-0-323-95511-9.00010-X.

[14] C. Yu and Q. Yang, "Multiscale Interfacial Interactions in Carbon Nanotube–Asphalt Nanocomposites: Implications for Asphalt Pavement Materials," *ACS Appl. Nano Mater.*, vol. 6, no. 9, pp. 7715–7730, May 2023, doi: 10.1021/acsanm.3c00856.

[15] P. J. Ramadhansyah *et al.*, "Nanoparticle in Asphalt Binder: A State-of-The-Art Review," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 712, no. 1, p. 012023, Jan. 2020, doi: 10.1088/1757-899X/712/1/012023.

[16] T. Abdel-wahed, A. Salah, and A. Abdel-Raheem, "Performance Evaluation of Asphalt Mixtures Modified with Medical Plastic Waste," *Mansoura Eng. Journa*, vol. 47, no. 1, pp. 178–188, 2022, doi: 10.21608/sej.2024.312852.1063.

[17] R. Q. Aljbouri and A. H. Albayati, "Investigating the effect of nanomaterials on the Marshall properties and durability of warm mix asphalt," *Cogent Eng.*, vol. 10, no. 2, 2023, doi: 10.1080/23311916.2023.2269640.

[18] S. P. Muñoz Pérez, L. A. Salazar Horna, and D. Luna Pastor, "Resistance to Aging of Asphalt Modified with Multidimensional Nanomaterials: A literary Review," *Period. Polytech. Civ. Eng.*, Jun. 2022, doi: 10.3311/PPci.19768.

[19] A. H. Albayati, M. J. Al-kheetan, M. M. Moudhafar, and A. M. Mohammed, "Nanomaterials in asphalt cement : Exploring their single and combined effects on the physical and rheological properties Results in Engineering Nanomaterials in asphalt cement : Exploring their single and combined effects on the physical and rheological p," *Results Eng.*, vol. 24, no. December, p. 103225, 2024, doi: 10.1016/j.rineng.2024.103225.

[20] M. Q. Ismael, M. Y. Fattah, and A. F. Jasim, "Improving the rutting resistance of asphalt pavement modified with the carbon nanotubes additive," *Ain Shams Eng. J.*, vol. 12, no. 4, pp. 3619–3627, 2021, doi: 10.1016/j.asej.2021.02.038.

[21] S. Mousavi Rad, N. Kamboozia, K. Anupam, and S. A. Saed, "Experimental Evaluation of the Fatigue Performance and Self-Healing Behavior of Nanomodified Porous Asphalt Mixtures Containing RAP Materials under the Aging Condition and Freeze–Thaw Cycle," *J. Mater. Civ. Eng.*, vol. 34, no. 12, 2022, doi: 10.1061/(asce)mt.1943-5533.0004488.

[22] G. H. Hamedi, F. M. Nejad, and K. Oveisi, "Estimating the moisture damage of asphalt mixture modified with nano zinc oxide," *Mater. Struct. Constr.*, vol. 49, no. 4, pp. 1165–1174, 2016, doi: 10.1617/s11527-015-0566-x.

[23] A. H. Albayati, F. S. Mustafa, A. F. Al-ani, M. Sukhija, M. M. Moudhafar, and A. M. Maher, "Advancing asphalt binder

performance through nanomaterial and polymer modification: Experimental and statistical insights," *Results Eng.*, vol. 25, no. January, p. 104458, 2025, doi: 10.1016/j.rineng.2025.104458.

[24] D. Wang, F. Zhang, K. Huang, and L. Zhang, "Study on preparation and performance of advanced nano-modified epoxy asphalt," *J. Appl. Polym. Sci.*, vol. 140, no. 14, 2023, doi: 10.1002/app.53688.

[25] A. M. Adnan, X. Luo, C. Lü, J. Wang, and Z. Huang, "Improving mechanics behavior of hot mix asphalt using graphene-oxide," *Constr. Build. Mater.*, vol. 254, p. 119261, 2020, doi: 10.1016/j.conbuildmat.2020.119261.

[26] P. Yong, J. Tang, F. Zhou, R. Guo, J. Yan, and T. Yang, "Performance analysis of graphene modified asphalt and pavement performance of SMA mixture," *PLoS One*, vol. 17, no. 5, p. e0267225, May 2022, doi: 10.1371/journal.pone.0267225.

[27] A. H. Albayati, N. K. Oukaili, M. M. Moudhafar, A. A. Allawi, A. I. Said, and T. H. Ibrahim, "Experimental Study to Investigate the Performance-Related Properties of Modified Asphalt Concrete Using Nanomaterials Al2O3, SiO2, and TiO2," *Materials (Basel).*, vol. 17, no. 17, 2024, doi: 10.3390/ma17174279.

[28] F. S. Bhat and M. S. Mir, "Study Investigating the Influence of Warm-Mix Asphalt Additives on Rutting and Fatigue Performance of Nano-Modified Asphalt Binders," *Transp. Res. Rec.*, vol. 2676, no. 4, pp. 719–731, 2022, doi: 10.1177/03611981211064995.

[29] R. Babagoli, D. Nasr, A. Ameli, and M. R. Moradi, "Rutting and fatigue properties of modified binders with polymer and titanium dioxide nanoparticles," *Constr. Build. Mater.*, vol. 345, no. March, p. 128423, 2022, doi: 10.1016/j.conbuildmat.2022.128423.

[30] N. S. S. M. Zali *et al.*, "Properties of stone mastic asphalt incorporating nano titanium as binder's modifier," *Arch. Civ. Eng.*, vol. 68, no. 1, pp. 653–666, 2022, doi: 10.24425/ace.2022.140192.

[31] S. H. Mousavinezhad, G. H. Shafabakhsh, and O. J. Ani, "Nano-clay and styrene-butadiene-styrene modified bitumen for improvement of rutting performance in asphalt mixtures containing steel slag aggregates," *Constr. Build. Mater.*, vol. 226, pp. 793–801, 2019, doi: 10.1016/j.conbuildmat.2019.07.252.

[32] N. Saboo, M. Sukhija, and G. Singh, "Effect of Nanoclay on Physical and Rheological Properties of Waste Cooking Oil–Modified Asphalt Binder," *J. Mater. Civ. Eng.*, vol. 33, no. 3, pp. 1–13, 2021, doi: 10.1061/(asce)mt.1943-5533.0003598.

[33] A. M. Yarahmadi, G. Shafabakhsh, and A. Asakereh, "Laboratory Evaluation of Fatigue and Rutting Performance of Nano CaCO3 Modified Asphalt Binders," *J. Rehabil. Civ. Eng.*, vol. 11, no. 3, pp. 144–157, 2023, doi: 10.22075/JRCE.2022.27095.1651.

[34] Muhammad Ali Raza, Zanib Khurshid, Sajid Hussain, Saad Hafeez, Shahid Hameed, and Waqas Anwar, "A comparative study of mixing nano particles in the bitumen by dry and wet method," *Int. J. Sci. Res. Arch.*, vol. 14, no. 1, pp. 459–466, Jan. 2025, doi: 10.30574/ijsra.2025.14.1.0024.

[35] M. F. ul Haq *et al.*, "Carbon Nanotubes (CNTs) in Asphalt Binder: Homogeneous Dispersion and Performance Enhancement," *Appl. Sci.*, vol. 8, no. 12, p. 2651, Dec. 2018, doi: 10.3390/app8122651.

[36] Y. Liu *et al.*, "Effect of Carbon Nanomaterials on the Rheological Characteristics of Crumb Rubber – Modified Asphalt," vol. 151, no. 2018, pp. 1–10, 2025, doi: 10.1061/JPEODX.PVENG-1119.

[37] H. H. Mohammed and H. H. Joni, "Influence of Waste Rubber Nano-Material Utilization on the Engineering Properties of Asphalt Matrix," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1374, no. 1, 2024, doi: 10.1088/1755-1315/1374/1/012015.

[38] H. H. Zghair, H. H. Joni, and A. A. Mohammed, "Assessment of the Influence of Nano Metakaolin filler on Asphalt Binder Rheological Properties," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 671, no. 1, 2020, doi: 10.1088/1757-899X/671/1/012122.

[39] A. A. Qarni and I. Hafeez, "Characterization of Nano Clay Modified Asphalt Cement," *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 10, no. 4, pp. 2360–2367, 2022, doi: 10.22214/ijraset.2022.41709.

[40] A. M. Mohammed and A. H. Abed, "Enhancing asphalt binder performance through nano-SiO2 and nano-CaCO3 additives: Rheological and physical insights," *Case Stud. Constr. Mater.*, vol. 19, p. e02492, Dec. 2023, doi: 10.1016/j.cscm.2023.e02492.

[41] A. M. Mohammed and A. H. Abed, "Rutting and fatigue behavior of neat and nanomodified asphalt mixture with SiO2 and TiO2," *Alexandria Eng. J.*, vol. 109, no. October, pp. 994–1009, 2024, doi: 10.1016/j.aej.2024.09.083.

[42] M. Enieb, A. Cengizhan, S. Karahancer, and A. Eltwati, "Evaluation Of Physical-Rheological Properties of Nano Titanium Dioxide Modified Asphalt Binder and Rutting Resistance of Modified Mixture," *Int. J. Pavement Res. Technol.*, vol. 16, no. 2, pp. 285–303, 2023, doi: 10.1007/s42947-021-00131-0.

[43] A. Zahid, S. Ahmed, and M. Irfan, "Experimental investigation of nano materials applicability in Hot Mix Asphalt (HMA)," *Constr. Build. Mater.*, vol. 350, no. May, p. 128882, 2022, doi: 10.1016/j.conbuildmat.2022.128882.

[44] C. T. Senseney and J. L. Tucker, "Life-Cycle Cost Analysis of Graphene Oxide Modification of a Neat Asphalt Binder for Flexible Pavement," *J. Mater. Civ. Eng.*, vol. 37, no. 5, pp. 1–9, 2025, doi: 10.1061/jmcee7.mteng-19097.

[45] M. Akbari, E. Shahryari, A. M. Hamedipour, and G. Shafabakhsh, "Laboratory Investigation on the Rutting and Fracture Resistance of Hot-Mix Asphalt Containing Nanographene Oxide," vol. 35, no. 3, pp. 1–15, 2023, doi: 10.1061/(ASCE)MT.1943-5533.0004660.

[46] K. N. M. Yunus, A. Zainorabidin, N. H. M. Kamaruddin, M. K. Ahmad, N. F. N. Anuar, and S. N. K. Yaakop, "Physical and Chemical Properties of Nano Zinc Oxide Modified Asphalt Binder," *Int. J. Integr. Eng.*, vol. 14, no. 9, pp. 133–139, 2022, doi: 10.30880/ijie.2022.14.09.017.

[47] A. M. Emmaima, S. I. A. Ali, and K. S. Gallouz, "Experimental Investigation of Polymer and Nanomaterial modified Asphalt Binder," *Eng. Technol. Appl. Sci. Res.*, vol. 14, no. 1, pp. 12869–12874, Feb. 2024, doi: 10.48084/etasr.6607.

[48] M. S. Samsudin, K. A. Masri, A. K. Arshad, and J. Ahmad, "Physical Properties of Nanomodified Asphalt Binder," in

*Springer, Singapore*, Singapore: Springer Singapore, 2016, pp. 935–946. doi: 10.1007/978-981-10-0155-0_78.
[49] A. M. Mohammed and A. H. Abed, "Effect of nano-TiO2 on physical and rheological properties of asphalt cement," 2024.
[50] Z. K. Taher and M. Q. Ismael, "Rutting Prediction of Hot Mix Asphalt Mixtures Modified by Nano silica and Subjected to Aging Process," *Civ. Eng. J.*, vol. 9, pp. 1–14, Dec. 2022, doi: 10.28991/CEJ-SP2023-09-01.
[51] H. Yao and Z. You, "Performance of Micro- and Nano-Modified Asphalt Mixtures Through Flow Number and Moisture Susceptibility Evaluations," *J. Test. Eval.*, vol. 45, no. 6, pp. 2009–2019, Nov. 2017, doi: 10.1520/JTE20150434.
[52] I. Khan, A. W. Khattak, A. Bahrami, S. Khattak, and A. Ejaz, "Engineering Characteristics of SBS/Nano-Silica-Modified Hot Mix Asphalt Mixtures and Modeling Techniques for Rutting," *Buildings*, vol. 13, no. 9, p. 2352, Sep. 2023, doi: 10.3390/buildings13092352.
[53] A. A. Mohammed *et al.*, "Nano-Silica modifier asphalt concrete under rutting resistance and shape memory component," in *IOP Conference Series: Earth and Environmental Science*, Feb. 2021, p. 012041. doi: 10.1088/1755-1315/682/1/012041.
[54] Y. Cao, Z. Liu, and W. Song, "Performance and overall evaluation of nano-alumina-modified asphalt mixture," *Nanotechnol. Rev.*, vol. 11, no. 1, pp. 2891–2902, Oct. 2022, doi: 10.1515/ntrev-2022-0485.
[55] N. Mashaan, "Rutting Performance of Nano-Silica Modified C320 Bitumen: A Case study," Oct. 10, 2022. doi: 10.20944/preprints202210.0121.v1.
[56] W. Haroon and N. Ahmad, "Effect of nano silica on the performance of modified crumb rubber bitumen and asphalt mixtures," 2024.
[57] F. S. Hassan and M. Q. Ismael, "Enhancement of the Rutting Resistance of Asphalt Mixtures Modified by Nano Clay and Crumb Rubber," *Eng. Technol. Appl. Sci. Res.*, vol. 14, no. 5, pp. 17438–17444, 2024, doi: 10.48084/etasr.8531.
[58] Z. A. Alkaissi, E. A. Alghalibi, W. K. Leabi, and L. Najim, "Experimental and theoretical investigation on the effect of carbon nanotubes on flexible pavement," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 870, no. 1, 2020, doi: 10.1088/1757-899X/870/1/012105.
[59] A. M. Yarahmadi, G. Shafabakhsh, and A. Asakereh, "Laboratory investigation of the effect of nano Caco3 on rutting and fatigue of stone mastic asphalt mixtures," *Constr. Build. Mater.*, vol. 317, no. December 2021, p. 126127, 2022, doi: 10.1016/j.conbuildmat.2021.126127.
[60] G. Shafabakhsh, M. Motamedi, M. Firouznia, and M. Isazadeh, "Experimental investigation of the effect of asphalt binder modified with nanosilica on the rutting, fatigue and performance grade," *Pet. Sci. Technol.*, vol. 37, no. 13, pp. 1495–1500, Jul. 2019, doi: 10.1080/10916466.2018.1476534.
[61] K. Ghalandari Shamami, M. Effati, and S. M. Mirabdolazimi, "Evaluation of the Effects of Graphene-Nanoplatelets on the Rutting, Fatigue Performance, and Moisture Sensitivity of Hot-Mix Asphalt," *Int. J. Pavement Res. Technol.*, vol. 18, no. 1, pp. 199–212, Jan. 2025, doi: 10.1007/s42947-023-00337-4.
[62] V. F. de S. Neto, L. C. de F. L. Lucena, A. G. de Barros, A. E. de F. L. Lucena, and P. G. T. M. Filho, "Rheological evaluation of asphalt binder modified with zinc oxide nanoparticles," *Case Stud. Constr. Mater.*, vol. 17, 2022, doi: 10.1016/j.cscm.2022.e01224.
[63] A. Afshin and A. Behnood, "Nanomaterials in asphalt pavements: A state-of-the-art review," *Clean. Waste Syst.*, vol. 10, no. January, p. 100214, 2025, doi: 10.1016/j.clwas.2025.100214.
[64] H. Yao and Z. You, "Effectiveness of Micro- and Nanomaterials in Asphalt Mixtures through Dynamic Modulus and Rutting Tests," vol. 2016, 2016, doi: 10.1155/2016/2645250.
[65] S. M. Mirabdolazimi, A. H. Kargari, and M. M. Pakenari, "New achievement in moisture sensitivity of nano-silica modified asphalt mixture with a combined effect of bitumen type and traffic condition," *Int. J. Pavement Res. Tec[1] S. M. Mirabdolazimi, A. H. Kargari, M. M. Pakenari, "New Achiev. moisture Sensit. nano-silica Modif. Asph. Mix. with a Comb. Eff. Bitum. type traffic Cond. I*, vol. 14, no. 1, pp. 105–115, 2020, doi: 10.1007/s42947-020-0043-y.
[66] V. B. Le, H. B. Tran, and V. P. Le, "Laboratory evaluation of resistance to moisture damage in carbon nanotubes modified hot mix asphalt mixtures," *Transp. Res. Procedia*, vol. 85, pp. 185–190, 2025, doi: 10.1016/j.trpro.2025.03.150.
[67] T. Abdel-Wahed, A. Abdel-Raheem, and G. Moussa, "Performance Evaluation of Asphalt Mixtures Modified with Nanomaterials.," *Mansoura Eng. J.*, vol. 47, no. 1, pp. 1–15, Feb. 2022, doi: 10.21608/bfemu.2022.221670.
[68] H. Raufi, A. Topal, B. Sengoz, and D. Kaya, "Assessment of asphalt binders and hot mix asphalt modified with nanomaterials," *Period. Polytech. Civ. Eng.*, vol. 64, no. 1, pp. 1–13, 2020, doi: 10.3311/PPci.14487.
[69] S. Sackey, D.-E. Lee, and B.-S. Kim, "Life Cycle Assessment for the Production Phase of Nano-Silica-Modified Asphalt Mixtures," *Appl. Sci.*, vol. 9, no. 7, p. 1315, Mar. 2019, doi: 10.3390/app9071315.
[70] G. Ali Shafabakhsh, M. Sadeghneja, and S. Alizadeh, "Engineering the Effect of Nanomaterials on Bitumen and Asphalt Mixture Properties. A Review," *Balt. J. Road Bridg. Eng.*, vol. 18, no. 2, pp. 1–31, Jun. 2023, doi: 10.7250/bjrbe.2023-18.596.