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A Review of the Role of Nanomaterials in Asphalt Performance Enhancement

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ABSTRACT

Modified asphalt mixtures are increasingly used in high trafficked flexible pavement to improve performance and durability. Many laboratory studies have been conducted to compare the effectiveness of these mixtures with traditional HMA (hot mix asphalt). In mixes for asphalt concrete paving, nano modifiers are typically recommended when increased performance and durability are required, common nano modifiers used in asphalt mixtures, including: CNTs (carbon nanotubes), NC (nano clay), and NS (nano silica). This study reviews these nanomaterials used in asphalt modification, describes the techniques used to modify the asphalt binder using these materials, presents the influences of these nano modifiers on the asphalt pavement concrete mixtures' overall performance based on information from past literatures to assess their effects on properties as rutting resistance and moisture susceptibility as well as discusses challenges and advantages of nanomaterials in asphalt modification. The outcomes demonstrate that the utilizing nano modifiers in hot mix asphalt mixtures reduce the rutting depth by 4% to 88%. Additionally, nanomaterials enhance moisture sensitivity and increase tensile strength ratio by 9% to 25%.

1 Introduction

One of the most important measures of a country's development is its highway system. A significant amount of funds is needed for road construction (Shapie and Taher, 2022) , and as traffic numbers rise, there is an increasingly pressing need for high-quality road materials (Li et al., 2017) .Hot mix asphalt (HMA) is one of the most versatile and widely used materials for pavements and it typically consists of a mixture of aggregates and asphalt binder (Garcia and Hansen, 2002). Many factors govern the performance of asphalt pavement such as: the HMA's temperature, the kind and quality of aggregates, the quantity and kind of asphalt binder, the process of compacting and climatic condition (Abd Taih, 2011) .The asphalt binder provides waterproofing properties, binds aggregate together, and gives asphalt pavement its flexibility (Masri et al., 2022) . However, asphalt binder with its complex chemical composition, shows both viscous and elastic behavior (Viscos-elastic). This behavior affected by temperature and time of loading. Dense traffic and extreme weather can cause road cracks and other problems.

Rutting is a major cause of pavement failure in asphalt, affecting pavement efficiency and safety. It is mainly caused by accumulated strain from traffic loading, which accumulates in the surface layer of asphalt (Hajikarimi et al., 2015) . The gradation and mixed properties of the pavement, significantly impact rutting resistance. To control these effects, the adapting of high-performance asphalt mixtures with modifiers is crucial (Joni and Zghair, 2020) .Enhancing asphalt mixes with different modifiers has been a long-standing practice, with researches continuously looking for alternative materials to modify asphalt mixes and improve their performance. Even though, factors like harsh weather, increased cost, and traffic loads and volumes necessitate further study (Amin et al., 2016) .Nanotechnology has been widely used by pavement experts to develop novel modifiers to enhance performance characteristics of road materials. Nanoparticles have gained recognition in engineering and are being explores for their use in civil engineering, particularly in enhancing

asphalt properties (Sanchez and Sobolev, 2010).

This review provides an analysis of nanomaterial's application in asphalt modification including nano silica, carbon nanotubes as well as nano clay, in addition their impact on asphalt binder performance. It also analyzes the mechanical performance of the asphalt mixture, discusses challenges and limitations, and offers recommendations for future researches.

2 Nanomaterials Incorporated in Asphalt Modification

In asphalt modification field, nanomaterials are utilized to increase durability, enhance performance, and maximize rutting and moisture damage resistance, thereby enhancing the overall performance. Nanomaterials, often denoted by symbol (N), are materials with nanoscale dimensions ranging from 1nm to 100 nm, representing a submultiple of 10^{-9} (Crucho et al., 2019) .The most popular nanomaterials that used for enhancing asphalt performance are: NS, NC and CNTs.

2.1 Nano silica (NS)

One of the most crucial nanomaterials for altering the characteristics of asphalt binders and their mixtures is NS. It is produces mostly from silica precursors, it is an inorganic substance with a high specific area, high stability, strong absorption, appropriate dispersion capacity, and a high purity percentage (Yao et al., 2013) . Industries employ NS extensively to produce fumed silica, colloidal silica, and silica gels (Yang and Tighe, 2013) . NS particles have been utilized to strengthen Portland cement concrete mixes (Quercia and Brouwers, 2010) and polymers in industry (Chrissafis et al., 2008). It is a desirable addition for asphalt due to its high-performance qualities and inexpensive manufacturing cost. These qualities include strong adsorption, good dispersing ability, large specific surface area, high chemical purity, and great stability (Lazzara and Milioto, 2010;Yao et al., 2013).

When NS is used as an additive in asphalt modification, the performance of asphalt pavement is improved by enhancing fatigue life and rutting resistance that leads to lessen the maintenance frequency. However, according to (Sackey et al., 2019) its production is energy-

intensive, requiring 15-24 MJ of natural gas per kilogram, and contributes to greenhouse gas emissions, with a slight 0.4% increase in global warming potential. Furthermore, while nitrogen oxide emissions contribute to eutrophication, the use of sulfuric acid during production raises the possibility for acidification. Notwithstanding these effects, the long-term advantages of asphalt treated with NS can eventually outweigh its environmental cost. **Table 1** illustrates the NS's properties based on some studies (Khan et al., 2023;Mashaan et al., 2022;Obaid, 2021;Mirabdolazimi et al., 2021;Zghair et al.,

2019;Bala et al., 2018;Abed and Oudah, 2018;Bhat and Mir, 2019;Cai et al., 2018). It has been demonstrated that adding 2-4% of nano-silica powder to asphalt binder weight can reduce rut depth by almost half, improving anti-aging, fatigue cracking resistance, and anti-stripping properties (Yang and Tighe, 2013). As a result, asphalt binder and asphalt mixture performance as well as the adherence of asphalt binder to aggregates are enhanced by the application of nano-silica (Yao et al., 2013) .

Table 1: Nano-Silica Characteristics used by Some Researchers

Particle Size (nm)	Specific Surface Area (m ² /g)	True Density (g/cm ³)	Bulk Density (g/cm ³)	SiO ₂ %	Authors	Country
14-36	580	-	0.1-0.15	>98	Khan et al., 2023	Pakistan
15	600	2.4	<0.056	97.3	Mashaan et al.,2022	Australia
10-25	110	-	-	97.8	Obaid,2021	Iraq
20-30	130-600	2.4	-	≥99	Mirabdolazimi et al., 2021	Iran
11-12	200	2.4	<0.1	99.8	Zghair et al.,2019	Iraq
10-25	100±25	-	-	99.8	Bala et al., 2018	Malaysia
15-20	170-200	2.4	<0.1	>99.5	Abed & Oudah, 2018	Iraq
30-50	200-250	-	0.1	99.5	Bhat & Mir, 2019	India
30	200±35	-	-	99.8	Cai et al.,2018	China

2.2 Nano clay (NC)

Another most often used types of nanomaterials available on the market is nano clay. Layered silicates, or nano clay, are naturally occurring minerals with a naturally variable composition. The ultimate qualities of the nanocomposite can be influenced by the clay's purity. The layered structure of alumina-silicates is mostly made up of silica SiO₄ tetrahedron that are bonded to alumina AlO₆ octahedron in various ways, are the building blocks of clay. Montmorillonite (MMT) is one of the most popular layered silicates with a two-to-one layered structure consisting of two silica tetrahedrons enclosing an alumina octahedron. MMT layers are 1 nm thick and feature a large active surface area. Depending on the type of material combined, this might result in an intense interaction between the asphalt. MMT is also widely employed due to its availability,

environmental friendliness, and well-researched chemistry and structure (Abdullah et al., 2015).

During mixing and application operations, less energy is required. Besides, the use of nano clay helps to minimize temperature sensitivity that reduces greenhouse gas emissions. There are still issues, like possible impacts of nano clay during manufacture, handling and eventual release into environment, which call for thorough lifecycle analyses and environmentally friendly production methods (Zangena, 2019). **Table 2** demonstrates the nano clay characteristics that are used by some researchers (Amini et al., 2021;Ameri et al., 2018;Abdel-Raheem et al., 2023;Ghanoon et al., 2020;Mousavinezhad et al., 2019) . According to (Santagata et al., 2012) , the inclusion of NC will both raise the softening point and maximize resistance to aging. By raising asphalt binder stiffness, and lowering phase angle (which increase elasticity), NC modification improves the asphalt binder's

rheological properties (Jahromi et al., 2009) . Adding more NC to the asphalt binder simultaneously reduces its penetration and ductility. In addition, adding 2% of NC to asphalt binder can raise its shear (complex) modulus by

up to 184% (You et al., 2011) .This suggests that such binder has probably enhanced its resistance to rutting.

Table 2: Nano clay Characteristics Used by Some Researcher

Particle Size nm	Surface Area (m ² /g)	Density (g/m ³)	Authors	Country
1-2	220-270	0.8	Amini et al.,2021	Iran
-	-	1.66	Ameri et al.,2018	Iran
<40	-	2.6	Abdel-Raheem et al., 2023	Egypt
2.5	220-270	1.8	Ghanoon et al.,2020	Iran
1-2	500-750	5.7	Mousavinehad et al.,2019	Iran

2.3 Carbon Nanotubes (CNTs)

When compared to conventional building materials, CNTs have better mechanical qualities (Santagata et al., 2012) .According to (De Heer, 2004) , the tensile strength of CNTs can reach 150 GPa and based on (Treacy et al., 1996) its Young's modulus can reach 1000 GPa. Compared to other modifiers, the use of CNTs improves the substrate characteristics because of their tiny size and vast surface area. (MWCNTs) Multi-walled carbon nanotubes and (SWCNTs) Single-walled carbon nanotubes are the two primary categories into which CNTs fall, based on the graphene sheet number. Multi-walled CNTs are favored as modifiers because they can be produced more easily, cheaply, and with more stiffness than single walled CNTs (Steyn et al., 2013) .CNTs are most frequently used in order to improve mechanical

characteristics of other materials by dispersing them throughout them. The mechanical reinforcement, load distribution, and deformation resistance of asphalt have been improved as a result of their integration.

In spite of high performance of modified asphalt which leads to decrease maintenance cost, the production of CNTs using catalytic chemical vapor deposition has significant environmental effects. Methane and benzene are among the volatile organic compounds and polycyclic hydrocarbons released during the process. These substances are dangerous pollutants and greenhouse gases (DI Plata, 2009). **Table 3** shows the characteristics of the carbon nanotubes that are used in some researches (Saltan et al., 2018;Haq et al., 2018;Goli et al., 2017;Amin et al., 2016;Faramarzi et al., 2015).

Table 3: Carbon Nanotubes Characteristics Used by Some Researchers

Outer Diameter nm	Inner Diameter nm	Length μ m	Surface Area (m ² /g)	Density (g/m ³)	Purity %	References	Country
10-20	5-10	10-30	>200	2.1	-	Saltan et al.,2018	Turkey
30-50	5-12	0.5-2	60	2.1	>90	Haq et al., 2018	Pakistan
-	-	30	200	2.1	>95	Goli et al.,2017	Iran
10-30	5-10	-	>200	2.1	>90	Amin et al., 2016	Egypt
10-20	5-10	10-30	>200	2.1	>95	Faramarzi et al., 2015	Iran

3. Blending Asphalt Binder with Nano Modifications

It was commonly thought that because of their high viscosity and superior solubility, nanoparticles would cluster together when mixed with asphalt binder. The primary causes of

agglomeration, which degraded the mechanical and rheological properties of the modified asphalt binder, where thought to be the Ostwald ripening phenomena and van der Waals attraction force (Yao et al., 2013). According to (Faramarzi et al., 2015) , improper mixing can lead to the

destruction of nanoparticles and a significant degradation in the characteristics of materials. In order to guarantee uniform diffusion of nanomaterials, it is imperative to utilize an appropriate mixing technique and condition.

3.1 Mixing Method

The majority of investigations start by modifying the asphalt binders with nanomaterials, then use the modified binder to get the asphalt mixture. The ideal amount of nanomaterial in the asphalt binder varies depending on the type of nanomaterials, the asphalt binder, and the testing procedure; it usually ranges from 2 to 6% of the asphalt binder's mass (Martinho and Farinha, 2019). According to (Crucho et al., 2019), there are two main techniques for combining nanomaterials with asphalt binder: dry blending and solvent blending.

3.1.1 Dry Blending method

The technology that produces nanomodified composites is the most extensively utilized and well-established due to its simplicity and efficiency. There are two main steps in this method. First, nanomaterials are added to asphalt binder and then the nanomaterials as well as the asphalt binder are combined uniformly. To facilitating the dispersion of nanomaterials, the asphalt binder is heated above its softening point, which is usually (160-180) °C and for achieving the homogeneity, a high-shear mixer is performed. For example, (Abdel-Raheem et al., 2023) heated the asphalt to 180 °C, mixed the composites for 60 minutes at a fixed speed of 4000 rpm, and obtained homogeneous blends. To find the ideal rotation speed and mixing time, trials may be required.

3.1.2 Solvent Blending method

Which is sometimes referred to as “mother liquor melting”, entails utilizing a low shear mixer to combine a solvent, nanoparticle, and asphalt binder at temperatures ranging from medium to high until the solvent evaporates. The solvent acts as a mediator between the asphalt binder and the nanoparticles to provide even dispersion. Selecting an organic “mother liquor” is crucial and consideration should be given to factors including solubility, viscosity and evaporation rates. Acetone, turpentine, varsol and kerosene are typical solvents due to their affordability and ease of availability (Li et al., 2017). The solvent disperses the nanoparticles, lowering the viscosity of asphalt binder as well as promoting even dispersion. (Faramarzi et al., 2015) utilized the methods of sonication and high shear mixing to ensure homogeneous dispersion of nanofibers into asphalt binder to obtain the uniform nanomaterials-solvent mixtures. They chose two different sonication durations: eight minutes with two minutes of high shear mixing at 3000 rpm and twenty-five with two minutes of high shear mixing at 2500 rpm. They decided to take a 25-minute break in between each cycle. It was thought that combining those two techniques would supply sufficient energy to stop the nanoparticles from aggregating and damaging their size and structure. Additionally, basic asphalt was combined with nanomaterials-solvent combinations at an appropriate temperature until the solvent had evaporated completely. Solvent blending method produce better dispersion. However, it is more costly, energy-intensive as well as environmentally harmful. **Table 4** provides a summary of the benefits and drawbacks of the solvent blending technique and dry blending technique (Li et al., 2017).

Table 4: Advantages and Disadvantages of Both Mixing Methods

	Dry blending method	Solvent blending method
Advantages	1.Easier to apply in the industrial scale 2.Economic & environmentally friendly	1.Better dispersion 2.Better performance in terms of penetration and ductility
Disadvantages	1.Less homogenous	1.Expensive and complicated 2.Using a high amount of solvent to disperse a small amount particles

3.2 Mixing Conditions

It's difficult to choose the right mixing conditions. High temperatures promote the speed of nanoparticles but may hasten the aging process of asphalt. It is crucial to regulate the temperature to guarantee consistent dispersion without causing substantial aging. For uniform diffusion, a comparatively long mixing time is needed, which raises manufacturing costs and energy consumption. A suitable mixing speed is essential to guarantee adequate dispersion; nevertheless, an excessive speed could lead to damage to the structure of the nanomaterial (Li et al., 2017). The temperature, time, and speed

used by the researchers to create nanomodified asphalts are summed up in **Table 5** (Mashaan, 2024;Abdel-Raheem et al., 2023;Khan et al., 2023;Eisa et al., 2022;Mashaan et al., 2022;Aboelmagd et al., 2021;Obaid, 2021;Amini et al., 2021;Mirabdolazimi et al., 2021;Ghanoon and Tanzadeh, 2019;Bhat and Mir, 2019;Ghanoon et al., 2020;Bala et al., 2018;Saltan et al., 2018;Haq et al., 2018;Abed and Oudah, 2018;Cai et al., 2018;Enieb and Diab, 2017;Goli et al., 2017;Amin et al., 2016;Ezzat et al., 2016;Alhamali et al., 2016;Yusoff et al., 2014;Faramarzi et al., 2015).

Table 5: Temperature, Time and Speed Used by Various Authors

Asphalt Binder Type	Modifiers	Temp. (°C)	Duration (min)	Speed (rpm)	Authors	Country
C320	NS/HDPE ^a	170	90	2200	Mashaan,2024	Australia
Pen (60/70)	NC/HDPE	180	60	4000	Abdel-Raheem et al.,2023	Egypt
Pen (60/70)	NS/SBS ^b	163	-	3000	Khan et al., 2023	Pakistan
Pen (60/70)	CNTs	150	60	-	Eisa et al., 2022	Egypt
C320	NS/PET ^c	160±5	120	4000	Mashaan et al.,2022	Australia
Pen (70/80)	NS	160	60	2000	Aboelmaged et al., 2021	Egypt
Pen (40/50)	NS/PP ^d	150	-	3500	Obaid,2021	Iraq
PG (58-22)	NC/CR ^e	180	60	4000	Amini et al.,2021	Iran
Pen (60/70) Pen (85/100)	NS	150	30	4000	Mirabdolazimi et al., 2021	Iran
PG (64-22)	NS	140	80	2500	Ghanoon &Tanzadeh,2019	Iran
Pen (80/100)	NS	150±5	120	3500	Bhat and Mir, 2019	India
PG (64-22)	NC/NL ^f /SBS	150-160	60-80	3500	Ghanoon et al.,2020	Iran
Pen (80/100)	NS/PP	150±10	-	4000	Bala et al., 2018	Malaysia
PG (64-22)	NS/CNTs	160	120	4000	Saltan et al.,2018	Turkey
Pen (70/80)	CNTs	158±5	45	3000	Haq et al. , 2018	Pakistan
PG (64-16)	NS/SBS	180	240	2000	Abed and Oudah,2018	Iraq
Pen (60/70)	NS/RA ^g /SBS	170	120	5000	Cai et al.,2018	China
Pen (60/70)	NS	160	60	2000	Enieb and Diab, 2017	Egypt
PG (58-16)	CNTs/SBS	180	30	4000	Goli et al.,2017	Iran
Pen (60/70)	CNTs	120	30	2500	Amin et al., 2016	Iran
Pen (50/60)	NC/NS	145±5	60	1500	Ezzat et al., 2016	Egypt
PG (76-xx)	NS/SBS	163	60	3000	Alhamali et al.,2016	Malaysia
PG (76-xx)	NS/Ph ^h	160	60	1500	Yusoff et al., 2014	Malaysia
Pen (60/70)	CNTs	160	40	1550	Framarzi et al., 2015	Iran

a=waste high density polyethylene; b=styrene butadine styrene; c=waste polyethene terephthalate

d=polypropylene polymer; e=crumb rubber; f=nano lime; g=rock asphalt; h= polymer

4 The Role of Nanomaterials in the Asphalt Binder

Asphalt binders have been modified more and more often with the use of nanomaterials in an effort to improve their rheological characteristics, increase their resistance to aging, and boosting their performance under different environmental conditions. This section focuses on analyzing data from several investigation to comprehend how different nanomaterials affect the properties of asphalt binders such as complex modulus (G^*), viscosity and aging resistance.

Data from several investigation on nanomaterial, such as NS, CNTs, and NC, has been compiled. The investigation clarify how fundamental properties of asphalt binders are affected by these nano modifiers, which are critical to pavement performance over time. Nano-modified asphalt binders showed a decrease in penetration, increase in viscosity, and increase in softening point. The modified binders exhibit reduced phase angle (δ) and greater complex modulus (G^*) in terms of rheological behavior as measured by the dynamic shear rheometer (DSR).

The addition of NS remarkably alters the rheological characteristics of asphalt binders, according to (Ezzat et al., 2016). At higher temperatures, softening point rose suggesting more resistance to deformation; nevertheless, the penetration value fell, suggesting improved hardness and stiffness. Despite declining unevenly, the penetration index was within acceptable boundaries, suggesting a slight increase in temperature sensitivity. Reduced ductility indicated a loss of flexibility brought on by aggregation of particles and increased stiffness. Ultimately, the action of the NS particles within the binder is responsible for the increase in rotational viscosity, which thickened and increased the binder's resistance to flow.

The ideal workability of asphalt binder material at high temperatures (during mixing and compaction) is determined through a rotational viscometer test. The Viscosity of the NS modified asphalt binder increases with adding NS, leading to stiffer asphalt binder and increased NS adsorption and diffusion. High viscosity asphalt

binder is suitable for high traffic volumes roads (Zghair et al., 2019).

Asphalt binder's cohesion and adhesion properties are demonstrated by the ductility test. The ductility value decreases with an increase in NS percentage, attributed to light volatile absorption in the maltene portion of asphalt binder. Asphalt binder stiffens up due to NS alteration, and longer mixing times result in less ductility (Zghair et al., 2019). The NS concentration increases the flash point (Mirabdolazimi et al., 2021).

The viscous and elastic behavior of asphalt binder at medium and high temperatures is described by the DSR. DSR is used to measure phase angle (δ) and shear modulus (G^*). According to (Saltan et al., 2018), the experiment was conducted on unaged, RTFO aged, and PAV aged asphalt binder. SiO₂ doped CNTs modified with 5% decreased asphalt binder (δ) and increased (G^*) at 64°C.

5 Influence of Nanomaterials on the Mechanical Properties of Asphalt Mixtures

In addition to improving the asphalt binder's characteristics, nanomaterials also remarkably maximize the mechanical performance of asphalt mixtures. The influence of various nanomaterials on the mixture's key mechanical characteristics is examined in this section. When evaluating the performance of asphalt mixes, the mechanical tests that were most commonly found in the literature were rutting and water sensitivity (using tensile strength ratio).

5.1 Rutting Resistance

Permanent deformation or rutting is a significant failure issue that affects the performance of asphalt pavements, especially in areas with high traffic volumes and hot temperatures. According to (Ameri et al., 2018), rutting is the consequence of repetitive loads that cause the pavement to gradually distort.

(Khan et al., 2023) stated that combining NS and SBS in HMA improves rutting resistance at 6% NS. While, (Cai et al., 2018) discovered that a composite asphalt binder of 1% NS, 6% rock asphalt (RA) and 2% SBS have greater resistance to deformation under high traffic loads. It can be seen that warm mix asphalt

(WMA) treated with NS and PP performed better, with greatest reduction in rut depth at higher NS content (Obaid, 2021). **Table 6** shows the % reduction in rutting depth (RD) between the unmodified and modified mixtures from various experiments with different nanomaterials at their optimum content, based on researches by

$$\% \text{Reduction of rutting depth (RD)} = \frac{A1-A2}{A1} \times 100 \quad (1)$$

Where:

A1 is rutting depth for unmodified sample; and

A2 is rutting depth for modified sample

Table 6: Summary of Data on Rutting Resistance of Asphalt Mixtures with Nanomaterials

Type of Modifiers	Optimum % of Modifiers	% Reduction of RD	Authors	Country
NS/PET	6%PET+6%NS	88%	Mashaan et al.,2022	Australia
NS/PP	3%PP+4%NS	27%	Obaid,2021	Iraq
CNTs/NS NS/CNTs	SiO ₂ doped CNTs 5%	10%	Saltan et al.,2018	Turkey
NS/HDPE	45HDPE+6%NS	4%	Mashaan,2024	Australia
NS/SBS	4.5%SBS+6%NS	50%	Khan et al., 2023	Pakistan
NS/RA/SBS	1%NS+6%RA+3%SBS	49%	Cai et al.,2018	China
CNTs	3%CNTs	37%	Haq et al., 2018	Pakistan
CNTs	0.5%CNTs	13%	Eisa et al., 2022	Egypt
CNTs	1.6%CNTs	73%	Ziari et al., 2014	Iran
NC/SBR ^a	2%NC+4%SBR	69%	Ameri et al., 2018	Iran
NHDPE ^b	5%NHDPE	71%	Abed and Bahia, 2020	Iraq

a=styrene butadiene rubber, b= nano high-density polyethylene.

Based on Table 6, numerous investigations show that the percentage decrease in rutting depth caused by various nano additions exceeds 1%, indicating that modified mixtures containing nanomaterials have greater rutting resistance values compared to control mixtures. This showed that nanomaterials play a significant role in enhancing the rutting resistance of asphalt mixtures. It can be clear that adding nanomaterials can reduce rutting depth by 4% to 88%. The results indicate the positive effect of nano modifiers on rutting

(Mashaan et al., 2022;Obaid, 2021;Saltan et al., 2018;Mashaan, 2024;Khan et al., 2023;Cai et al., 2018;Haq et al., 2018;Eisa et al., 2022;Ziari et al., 2014;Ameri et al., 2018;Abed and Bahia, 2020) . Eq. (1) is used to compute the percentage reduction in rutting depth

resistance. These studies collectively attribute the enhancements to improve adhesion between the binder and aggregate, which prevents the aggregate from slithering under the influence of compressive pressures. Consequently, there was less rutting deformation. Fig. 1 visually compares the percentages reduction in rutting depth across various nanomaterials, highlighting the effectiveness of each in reducing rutting depth in asphalt mixtures.



Fig. 1: Rutting Depth Reduction in Nanomaterial Modified Asphalt Mixtures

5.2 Moisture Susceptibility

Moisture susceptibility is assessed in term of tensile strength ratio (TSR) which is the function of indirect tensile strength (ITS). ITS is one of the best methods that measures asphalt mixtures strength when subjected to tension for all specimens (unconditioned and moisture conditioned). As an important design parameter, the asphalt mixtures should not deteriorate substantially due to the presence or intrusion of moisture into the mixture. The mixture may be identified as a moisture susceptible mixture if cohesive and/or adhesive failures occur within the asphalt-aggregate system.

(Bala et al., 2018) found that adding NS to asphalt binder (Penetration (80/100)) improved their tensile strength (ITS) compared to control mixtures. The NS composite mixtures had higher ITS values, suggesting improved tensile resistance. However, conditioned samples have lowered ITS values due to decreased adhesion or loss of cohesiveness due to prolonged

$$\% \text{ Increase of TSR} = \frac{B2 - B1}{B1} \times 100$$

(2)

Where:

B1 is TSR for unmodified sample; and

B2 is TSR for modified sample

Table 7: Summary of Data on Moisture Susceptibility of Asphalt Mixtures with Nanomaterials

Type of Modifiers	Optimum % of Modifiers	% TSR Increase	Authors	Country
NS/PP	3%PP+5%NS	20%	Obaid,2021	Iraq
NS/PET	6%PET+4%NS	96%	Mashaan et al.,2022	Australia
NS/CNTs	SiO ₂ doped CNTs 3%	17%	Saltan et al.,2018	Turkey
NS	6%NS	22%	Enieb & Diab, 2017	Egypt

NS/SBS	4.5%SBS+6%NS	22%	Khan et al., 2023	Pakistan
NS/RA/SBS	1%NS+6%RA+2%SBS	17%	Cai et al.,2018	China
NS/P	SiO ₂ NP 0.3%	25%	Saltan et al.,2017	Turkey
NS	4%NS	21%	Yusoff et al., 2014	Malaysia
NS	5%NHDPE	9%	Abed &Bahia, 2020	Iraq

According to Table 7, various studies demonstrate that the percentage increase in TSR due to different nano modifiers exceed 1%, indicating that modified mixtures with nanomaterials exhibit higher ITS values compared to control mixtures. This showed that nanomaterials play a significant role in enhancing the tensile resistance of asphalt mixtures. The data also shows that conditioned samples generally have slightly lower ITS values than unconditioned samples, which can be attributed

to adhesion loss in the mixture or a reduction in cohesion within the modified binder due to prolonged moisture exposure. Notably, the inclusion of nanomaterials has been shown to increase TSR by 9% to 25%, making them highly effective in strengthening the bond between asphalt binder and aggregate. Fig. 2 visually compares the percentage increase in TSR across various nanomaterials, highlighting the effectiveness of each in preventing moisture-related damage in asphalt mixtures.

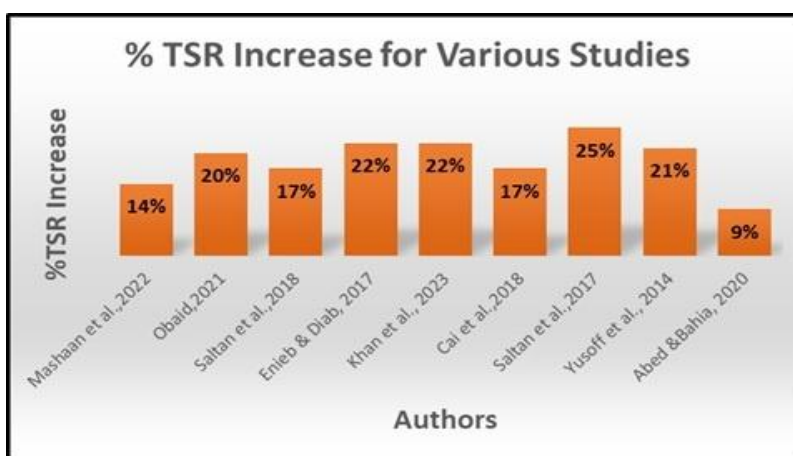


Fig. 2: Tensile Strength Ratio Increase in Nanomaterial Modified Asphalt Mixtures

6 Critical Analysis and Discussion of Conflicting Findings and limitations for Future Directions

The incorporating asphalt binders into HMA mixtures has revealed encouraging outcomes. Nanomaterials may greatly improve the asphalt mixture's properties, especially its resistance to rutting and indirect tensile strength. However, the literature also shows a number of contradictory conclusions and limits which calls for more investigation.

(Eisa et al., 2022) studied the influences of CNTs at concentration of %0.1, %0.5 and %1 into (60/70) asphalt binder. According to their study, the modified asphalt mixture's performance was enhanced at low temperatures,

and it became more resistant to low temperature cracking, with 0.5% CNTs lowering temperature from 24.8 to 26.4 °C and raising the fracture strength from 4.3 to 4.55 Mpa. Additionally, the study evaluated the economic implications, showing a 57% increase in the initial cost of HMA even when 0.5% CNTs was added.

(Haq et al., 2018) added 0.5%, 1%, 1.5% and 3% CNTs into (60/70) asphalt binder and they used both dry and wet mixing strategies to investigate the dispersion of CNTs in asphalt binder. They found that the homogenous dispersion of CNTs in asphalt binder is more easily achieved using wet mixing techniques than with dry mixing. On the other side, (Ziari et al., 2014) investigated the effect of CNTs at

concentration of 0.3, 0.6, 0.9, 1.2, and 1.5 wt% into (60/70). While, (Saltan et al., 2018) added (1%, 3% and 5%) of CNTs and CNTs doped with %50 weight percent SiO₂ nano powder (SiO₂ doped CNTs) to improve asphalt binder. They found that 3% SiO₂ doped CNTs has the excellent performance.

(Mashaan et al., 2022) combined waste polyethene terephthalate PET and NS with the C320 binder to create stone mastic asphalt mixtures. While, (Mashaan, 2024) combined waste high density polyethylene (HDPE) and NS with the C320 asphalt binder to create SMA. The C320 asphalt binder was supplemented with 2%, 4%, 6% and 8% NS for both studies.

(Cai et al., 2018) have investigated a unique combination of styrene-butadiene-styrene (SBS), rock asphalt (RA), and nano silica (NS), the pavement performance of composite modified asphalt. Although a lot of study has been done on individual modifiers, less is known about their combined effects, especially NS/RA/SBS. Furthermore, economic research demonstrates that NS/RA/SBS modifications result in better cost performance. Although there isn't a noticeable price increase, 1%NS+6%RA+3%SBS asphalt mixture performs better than 5% SBS modified asphalt mixture.

(Abed and Bahia, 2020) compared the effect of SBS and nano high-density polyethylene (NHDPE) on asphalt binder and mixture. Since the NHDPE is derived from waste material, so it considered to be eco-friendly and cost-effect alternative. They investigated that NHDPE need less energy during mixing and compaction, which leads to decrease emission during producing.

While many investigations have been done in modifications of asphalt with nanomaterials, and current studies advanced our understanding of nanomaterial modification in asphalt binder and mixture, several limitations need further exploration such as:

1. Although the cost of adding nanomaterial was investigated and initially showed no cost benefit in some research, the asphalt sector needs to see long-term cost benefits. A comprehensive model is necessary to be developed to explore the economic impact of nanomaterials in the asphalt industry,

considering both direct costs and savings due to changes in maintenance and traffic.

2. For rutting resistance and moisture susceptibility, additional testing at various temperatures and pressures is advised.

3. Future investigation could discover the utilize of locally available 40/50 asphalt binder for nanomaterial modification, as it is largely used but underexplored very often in nanomaterial modification.

4. The environmental influences of adding nanomaterials to asphalt binders are not well studied.

5. The majority of research is carried out in controlled laboratory settings, which are not representative of the traffic loading and environmental variables encountered in the field.

7 Advantages and Challenges of Nanomaterials in Asphalt

Since nanomaterials can improve material qualities, they have drawn a lot of attention in a variety of sectors, including civil engineering, where they are used in asphalt for road construction. The benefits and drawbacks of adding nano-modifiers in asphalt are discussed in this section.

Nanomaterials substantially improve the mechanical properties of asphalt, including elasticity and strength. They also enhance its durability, enhancing fatigue life, resistance to rutting, and temperature susceptibility. By lowering production temperatures and emissions, nanomaterials also lessen their negative effects on the environment. Because of their high surface area and catalytic activity, they can also alter the quality of the air in the urban areas. Since nanoparticles are more evenly distributed in asphalt than microparticles, they also improve stability and dispersion (Yang and Tighe, 2013).

High prices, compatibility problems, health and safety considerations, and technological difficulties are among challenges in asphalt modification sector. Nanoparticle's expensive cost restricts their use to cutting-edge technologies, and their incompatibility can cause particle aggregation and degrade the mechanical properties of asphalt. Concerns about health and safety are especially crucial since research indicates that nanoparticles may be harmful to

humans. Achieving the proper dispersion of nanoparticles is one of the technical challenges since they have a tendency to cluster together, making uniform distribution challenging. Reduced performance advantages and non-homogeneous material properties might arise from inconsistent dispersion (Korniejenko et al., 2023).

8 Conclusion

In material science, nanocomposites are a major development that creates novel multifunctional materials and enhances features for sophisticated applications. For sectors like asphalt binder and their mixtures, they are essential. Researchers have looked into how the mechanical characteristics of asphalt mixtures are affected by nanomaterials such as CNTs, NS, and NC. Properties like rutting and moisture sensitivity can be enhanced by properly dispersing nanoparticles. Based on the review that has been presented, the following conclusions can be drawn:

1. Dry blending and solvent blending are the two primary methods used to combine nanomaterials with asphalt binder. The dry approach is more economical and ecologically benign, it is simpler to use on an industrial scale and it is less homogeneous. Nonetheless, the solvent approach performs better in terms of penetration and ductility as well as dispersion and it is more expensive and complicated.
2. Any nanomaterial may be used as a modifier to enhance the rheological and physical characteristics of virgin asphalt binders. Physically, nanoparticles can raise the softening point value while decreasing ductility and penetration. At the same time, rheological characteristics like rutting resistance and performance grade also demonstrated improved gains. Furthermore, the engineering characteristics of mixes including asphalt binders modified with nanoparticles were greatly enhanced, especially in the areas of moisture resistance as well as rutting resistance.
3. Nanomaterials significantly enhance rutting resistance in asphalt mixtures,

reducing rutting depth by 4% to 88%. This is due to improved adhesion between binder and aggregate, preventing aggregate slithering under compressive pressures.

4. Modified asphalt mixtures with nanomaterials have higher ITS than unmodified asphalt mixtures, indicating their substantial role in enhancing tensile resistance. In addition to increasing TSR by 9% to 25%, making them effective in strengthening the bond between modified asphalt binder and aggregate.
5. One major obstacle to broader usage is the absence of international standards, especially laws pertaining to nano-dispersion modifiers. Furthermore, safety, long-term characteristics, durability, and appropriate dispersion of nano-modifiers for asphalt binder and their mixtures are challenges in the usage of nanomaterials.
6. The temperature, time, speed, type of origin binder and nanomaterials all affect how well the nanomaterial disperses throughout the asphalt-producing process. Further studies should examine how mixing conditions impact on uniform nanomaterial modified binder.
7. Studies based on nanomodified binders were more evident than those based on mixtures, thus more research should focus on the behaviors of nanomodified mixes, particularly the low-temperature characteristics.
8. A large-scale implementation in practical engineering requires careful consideration of the economic, ecological, and environmental assessments of nano-modified asphalt.

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