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The Impact of Nanomaterials on Moisture Resistance in HMA: A Literature Review

Muneeb Salam Imran[1] , Amjad H. Albayati[2], Hassan Mosa Jawed[3]

[1,3] Civil Engineering Department, AI-Nahrain University, Baghdad-Iraq.

[2]Civil Engineering Department, Baghdad University, Baghdad-Iraq.

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ABSTRACT

Moisture damage in asphaltic bituminous mixtures remains a severe challenge. Numerous studies have been conducted to prevent or minimize this issue using conventional anti-stripping agents such as Fly Ash and Hydrated Lime. However, these techniques showed limited affectivity. Therefore, the adoption of new technologies has become inevitable. Nanomaterials NMs have recently attracted significant attention from researchers in this field. Unlike conventional agents, these materials have unique and exceptional properties such as, high surface area and small size which make them more activity against potholes and raveling. This study explores the issue of moisture and the ways in which it infiltrates within the mix layers. Mechanisms of water-induced concern are also explained. An overview of these materials such as nano-silica NS and nano-clay NC and their mixing conditions with bitumen binder is presented. A summarized related literature is also explored. In conclusion, these promising materials although have ability to increase the desirable properties of the asphaltic concrete but they are expensive to produce, difficult to mix and may lead to long-term health conditions.

1. Introduction

Hot mix asphalt (HMA) is the most frequently utilized substance in roadway construction. This is due to its superior ability to offer comfort for both drivers and pedestrians, structural stability, long-term durability and resistance to water. Flexible pavement is preferred due to its ability to withstand repeated traffic loads and environmental [1].

Moisture damage in an HMA mixes refers to the reduction in pavement strength, resistance to deformation, and durability caused by water intrusion. This typically results in adhesive failure at the binder–combined aggregate contact surface and/or internal failure within the asphalt binder or asphaltic cement– fine binder mixture. It is the deterioration of the structural characteristics of the material attributable due to water infiltration within the mix in its microstructure. Alternatively, it can be described as the progressive functional decline of the flexible pavements. It is considered as a one of the major causes of premature failure in asphaltic pavements [2,3]. Durability in hot mix asphalt is considered a key property which is affected by this problem. Moisture damage, commonly referred to as stripping, occurs when water infiltrates the contact surface between asphalt cement and combined aggregate. This infiltration leads leading to failure of bonding and internal cohesion in the pavement structure [4].

Corresponding author E-mail address: manib.pciv23@ced.nahrainuniv.edu.iq

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The harmful effects of this problem (moisture damage in HMA) are increased by various environmental factors like rainfall, temperature variations, and freeze-thaw cycles, making it a chief concern for both transportation engineers and researchers [5]. Trying to mitigate or prevent the water infiltration problem by using traditional methods such as using anti-stripping agents or modifying the combined aggregate properties within the asphaltic mixture HMA showed inadequate effectiveness and frequently failed to offer long-term results. [6]. So there is a great need to innovate recent ways to improve durability of the asphaltic mix to moisture-related problem. Recently, nanomaterials emerged as an effective solution to address the moisture damage in HMA instead of using the conventional approaches. These materials have high surface area, reactivity, and unique mechanical properties making them the promising substances to significantly improve the HMA performance [7]. Nano-Silica (NS) and carbon nanotubes (CN) for example, proved their ability to enhance the adhesion between asphalt cement AC and the combined aggregates within the mix, thus reducing water susceptibility and improving the global durability of the mix [8]. Moreover, other nanomaterials NS like Graphene Oxide (GO) and Nano-clay (NC) can instruct and increase hydrophobic properties to the asphaltic mix, further mitigating the infiltration of water [9].

But a number of challenges remain in the application of theses promising materials in hot mix asphalt is still in its early stages. These challenges comprise in the first place; these materials are very expensive, problems to achieve a homogenous mix when they added to the HMA, and environmental and health effects. Additionally, there is a lack of standard specifications related to those materials for finding the optimal dosage that will be added to HMA [6]. The present research explores a broad overview of Nano sized materials role in enhancing the moisture damage resistance in HMA pavements.

2. Mechanisms of Water Infiltration

The existence of water in bituminous blend is Inevitable. Water can enter the pavement structure from numerous contributing sources. Moisture can Seep into the pavement structure from the top layer cracks in the surface of the pavement or the interconnect air voids. It may also seep in from the Lower layer due to rising water table levels. Additionally, moisture can enter laterally from the edges of the road surface [10].

The major sources of water which influence a road structure consist of rainfall (or melting snow and ice in some areas), ground water, water used in construction, and water induced by roadside maintenance operation. More specifically, sources of water and means of entry are listed below [11]:

- Water exist on verges, shoulders, and pavement surface.
- Pavement cracks and seals can allow more water flow.
- Water flow or water table on the side of the flexible pavements.
- Leakage of water supply and drainage pipes.
- Construction joints, curb edges and the connecting zone between the old and new pavement.
- Capillary action and the vertical movement of water through the subsurface layer.
- Rainfall storms and roadside irrigation during service.
- Longitudinal water flow occurs within flexible pavements especially in sag vertical curves.

3. Mechanisms of Moisture Damage in HMA Pavements

Damage caused by water in asphaltic pavements usually results from either a breakdown of the bond between the binder asphalt and the combined aggregates (adhesion) or a weakening of the asphalt itself (cohesion). In the first mechanism, moisture penetrates the interface between asphalt cement and aggregate particles. This seepage forces out the bituminous layer, revealing the uncoated and exposed aggregate particles. This happens because aggregates exhibit a higher attraction to moisture than to the binder. The second mechanism, this mechanism refers to the effect of water on asphalt cement, leading to a reduction in its cohesive strength. Separation between the bitumen binder and granular materials results in binder stripping. Additionally, stripping may be caused by hydraulic scouring due to the repeated buildup of pore water pressure. Consequently, stripping weakens the pavement structure, making it vulnerable to damage from pore pressure and premature cracking [12]. Several contributing factors have been attributed to causing moisture damage in HMA: detachment, displacement, spontaneous emulsification, pore pressure, hydraulic scour, and environmental effects on the total asphalt system. Moisture infiltration in the asphalt mixture is caused by these mechanisms or factors acting individually or together [13].

Detachment is the process where the asphalt film separates from the granular aggregate surface due to the presence of a thin water film. This separation occurs without a distinct rupture in the asphalt layer. Due to its relatively low polar activity, asphalt's association with debris mainly results from weak dispersion forces. On the other hand, water molecules are highly polar and can displace the asphalt bond from the surface [14].

The mechanism of displacement can begin with changes in the pH of water at the aggregate surface. This moisture enters through points of rupture in the asphalt film. The pH alteration changes the types of polar groups that are adsorbed on the surfaces. This water seeps in through openings in the asphalt film. Changes in pH cause variations in the polar groups attached to the surfaces. As a result, opposing negatively charged electrical double layers build up on both the aggregate and asphalt binder surfaces [15].

Spontaneous emulsification occurs when water and asphalt binder interact to form an inverted emulsion. In this type of emulsion, water droplets are dispersed within the asphalt cement. The asphalt functions as the continuous medium, while the water forms the dispersed phase. This interaction leads to the deterioration of the adhesive bond between the binder and the aggregate [16]. The formation of such emulsions is enhanced by the presence of emulsifying agents, including clays and asphalt additives [17].

Pore pressure develops as the asphalt mixture densifies under repeated traffic loading. This compaction causes interconnected air voids to close off, trapping water inside. When vehicles traverse the pavement, the confined water causes a rise in pore pressure, which decreases upon unloading. These repeated pressure variations impose sustained internal stress on the mixture. Over time, these pressure fluctuations lead to progressive cohesive and/or adhesive failures, accelerating moisture-induced damage in the asphalt mixture [18].

Hydraulic scouring is caused by the movement of vehicle tires across the surface of a wet bituminous layer. Approaching tires compress the wet surface, forcing water into the underlying pavement. As the tires move away, negative pressure behind them extracts the water from the pavement. This continuous action contributes to moisture intrusion and potential damage within the pavement structure [16].

4. Overview of Nanomaterials NMs

Nanomaterials are typically defined as substances that have at least one dimension ranging between 1 and 100 nanometers. In recent years, nano-sized particles have gained significant attention for their potential to address some of the most pressing challenges in pavement engineering, particularly moisture damage. The metric system of units (SI) uses the prefix "nano" to represent one billionth (10^{-9}) of a unit. Nonetheless, setting 100 nm as the maximum size for nanomaterials is still contested and has not been universally accepted. [19]. NMs can be produced using two main methods: the top-down approach and the bottom-up approach. The first approach involves reducing larger structures to the nanoscale. In one method, bulk materials are physically broken down into smaller particles until they reach nanometer dimensions. Another method involves disassembling materials into their fundamental components. In contrast, the bottom-up approach builds nanoparticles from atomic or molecular units through chemical or physical processes. [20]. The use of Nano-sized materials in bituminous pavements has received considerable focus in recent decades due to their ability to enhance the durability and resistance of asphalt mixtures against environmental distresses, particularly moisture-induced damage.

The large surface area of nanomaterials enhances their interaction with both the asphalt binder and aggregates. This increased interaction results in improved adhesion and cohesion within the mixture. [21]. These materials can chemically interact with the asphalt cement AC, modifying its properties to enhance durability and resistance to environmental factors [6]. Additionally, the incorporation of these materials can improve the mechanical properties of HMA, such as stiffness, strength, and fatigue resistance [21]. The microstructural characteristics and dispersion of Nano-silica NS within the asphalt mix can be observed in Figure 1, which presents Scanning Electron Microscope (SEM) images of blend rubber/Nano silica composite modified asphalt at various magnifications [22].

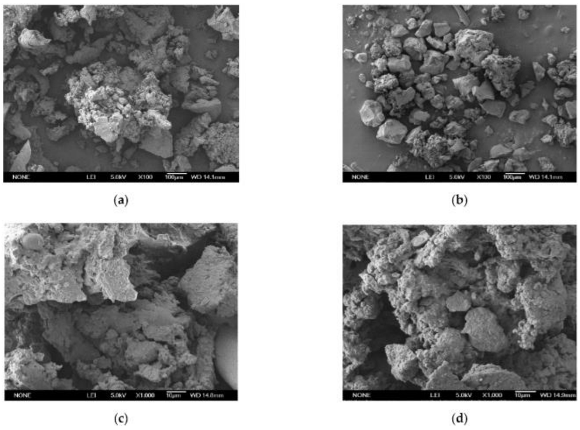

Figure 1: the microstructural characteristics of Nano Silica.

5. Materials Utilized in Nano-Enhanced Asphalt

Table 1 presents a summary of the main nanomaterials and base asphalts used in the production of nano-modified asphalts. It also includes their recommended dosage levels [23].

Table 1: Nanomaterials and their suggested dosages for asphalt modification [23]

Researcher	**Binder Grade**	**Nano. Mat.**	**Cont. (%)**
Yusoff et al. [24]	PG 76	NS	4.0%
Yao et al. [25]	PG 58-34	NS	6.0%
Goh et al. [26]	PG 58-28	NC	1.5%
Ghasemi et al. [27]	60/70	NS	2.0%
Khattak et al. [28]	PG 70-22	CNF	~4.0–12.0%
Ziari et al. [29]	60/70	CNT	1.2%
Faramarz et al. [30]	60/70	CNT	1.0%
Santagata et al. [31]	70/100	CNT	>0.5%
Abdelrahman et al. [32]	PG 58-28	NC	8.0%
Fang et al. [33]	AH 90 asphalt	NZnO	0.25%
Xiao et al. [34]	PG 64-22; PG 64-16; PG 52-28	Nano-Carbon	1.5%
Armirkhanian et al. [35]	PG 64-22	Carbon Nanotubes	1.0%

5.1 Nano-Carbon (nC)

Carbon nanoparticles are black and dusty materials. They possess an exceptionally high specific surface area. Xiao and his colleagues used this substance to modify the virgin binder. It was discovered that dark nano-sized clay particle significantly improves the flow and deformation characteristics of bitumen binder. Moreover, increasing the concentration of nanoparticles leads to higher viscosity and Young's modulus values. This improvement occurs regardless of the bitumen type used [36].

5.2 Nano-Clay (NC)

Nano-clay is a layered silicate whose thickness varies between 1 and 100 nm. It finds widespread application in improving materials' mechanical strength and thermal performance. It can be produced mainly by in-situ polymerization, solution blending, and melt processing. it is popular due to its low cost and natural abundance. Studies show that surface-modified montmorillonite NC significantly enhances the rheological properties of asphalt. Two primary types of NC are used in asphalt modification: non-modified nano-clay (NMN) and polymer-modified NC (PMN) [37].

5.3 Nano-TiO2 (NT)

Titanium dioxide nanotubes (NT) are derived from the naturally occurring oxide of titanium. In nature, titanium dioxide is typically found in three mineral varieties: rutile, anatase, and brookite . NT typically consists of approximately 80% anatase and 20% rutile. Compared to conventional TiO_2, NT features a significantly larger surface area and much smaller particle diameter. It also demonstrates lower opacity than regular titanium dioxide. These distinctive physical properties are presented in Table 2 [38]. Due to these characteristics, researchers have explored the use of NT to enhance the performance of modified asphalt. Several studies have shown promising improvements when NT is incorporated into asphalt mixtures [39]

Table 2: NT attributes [38].

Diam. (nm)	Density (g/cm3	Surface volume ratio (m2/g)	Loss of Ignition (%)
20	3.9	10-45	8.24

5.4. Nano-Fiber

Nano-scale carbon fibers (CNF) exhibit a large surface area and excellent bonding at interfaces. They are also characterized by a high tensile modulus and a significant aspect ratio. These outstanding characteristics make CNF a promising additive in various composite materials. The key physical and mechanical properties of this material are summarized in Table 3 [40]. Its high aspect ratio facilitates the development of a well-integrated nanocomposite network within the material matrix. This network enhances load transfer and strengthens the overall structural integrity. This network improves load transfer and contributes to the overall structural stability. In addition, CNFs exhibit a bridging effect that helps resist the growth of micro-cracks. This resistance is particularly beneficial subjected to the impacts of heavy traffic loads and environmental circumstances. As a result, CNF can significantly structural and deformation properties of bitumen binders. Several studies have demonstrated improved performance of asphalt mixtures when modified with CNF.

Table 3: Overview of CNF Characteristics [40]

Diam. (nm)	Length (um)	Surf. area. (m2/g)	Tensile mod. (GPa)	Tensile strength (GPa)
60–150	30–100	45	600	7

5.5. Nano-SiO2 (NS)

NS is a non-organic substance primarily produced from silica precursors. It has found extensive applications in fields such as medical sciences, pharmaceuticals, and farming. Due to its unique properties, NS has attracted attention in construction materials as well. In pavement engineering, it is commonly used as an additive to enhance the performance of asphalt binders. Its inclusion can improve the mechanical, thermal, and aging resistance properties of asphalt mixtures [41]. Due to its exceptionally large surface area, good dispersion ability, and excellent stability, NS significantly enhances the performance of base asphalt. Its incorporation leads to noticeable improvements in the mechanical and rheological properties of asphalt binders. These enhancements contribute to better durability and resistance to deformation under load. NS 's effectiveness as a modifier has been demonstrated in several studies [42]. Key properties of NS are summarized in Table 4. [47].

Table 4: Summary of nano-SiO2 properties [41]

Diam. (nm)	Density (g/cm3	Surface /vol. (m2/g)	Melting temperature (C)
20-30	2.1	130-600	1600

6. Methods of Mixing NMs with HMA

It was broadly assumed that nano-scale materials tend to form clustered structures upon blending with the asphalt binder. The strong internal resistance to movement in the asphalt cement combined with the excellent solubility of nanoparticles may explain this behavior. Accordingly, the accumulation caused by unequal dispersion can weaken the structural and rheological attributes of the modified binder [43]. Thus, selecting the right mixing process to guarantee even diffusion of nanomaterials is very important. There are several ways to add or mix various Nano-sized materials with the bituminous mixture to modify and enhance the resistance to moisture damage. Generally, there are five methods; dry, wet here, pre-mixed, solvent-assisted, in-situ synthesis and hybrid method [44].

In dry mixing method, the Nano sized material (such as Nano-silica, Nano-clay) are directly added to the combined aggregates before the bituminous binder. This technique comprises two phases. The first phase is to add the Nano-particles into asphalt.it is Simple and convenient. But the uniform dispersion of Nano particles is rather poor [45]. While in the second method, the NMs are blended into the asphaltic binder using high-shear mixer to ensure uniform dispersion before added to the combined aggregates. In this technique the Nano materials are firstly added to the heated bituminous binder. Following this, a high-shear mixer is often utilized to distribute the small particles evenly. This method ensures good interaction between the asphaltic binder and the nano-scale particles. It requires equipment, more time for the shear mixer and it very expensive [46]. Figure 2 shows the mixer used for the wet mixing method.

Figure 2: Preparation of modified HMA using high-speed shear mixer.

In the pre-mixing method, nanomaterials are first dispersed directly into the asphalt binder before it is combined with the aggregates. This step ensures a more uniform distribution of nanoparticles within the binder matrix, which can improve the chemical and physical bonding of bitumen binder with additives at the molecular level [47]. The other approach is solvent-assisted method. In this method, Nano particle sizes are first dissolved in a suitable solvent (e.g., ethanol, water). These materials are then added to the asphalt binder. During the mixing process, the solvent evaporates. This helps the Nano-materials spread more evenly in the asphaltic binder. However, using solvents can raise environmental concerns. So, the method is not often used in large-scale asphalt production [48]. In-situ Synthesis approach, Nanomaterials are chemically modified within the asphaltic cement during mixing. When the binder is modified through the addition of reactive agents. This method gives strong chemical bonding and performance but it is difficult method and not very common used [48].

Finally, hybrid approach is a combination of dry and wet mixing is sometimes used to optimize Nano-sized dispersion. For example, NMs may be pre-dispersed in bitumen and later mixed with the combined aggregates to improve adhesion and performance. This approach helps balance the advantages of both dry and wet methods [49].

7.Mixing Conditions

Establishing suitable mixing conditions for nano-modified asphalt is complex. Mixing conditions includes three main parameters mixing temperature, duration and the shear mixer speed. Raised temperatures improves the diffusion of nanoparticles and reduce virgin asphalt viscosity. However, asphalt is highly sensitive to heat and excessive heating can promote premature aging, negatively affecting its durability. Therefore, finding a balance is essential. It involves achieving uniform nanoparticle dispersion while limiting the thermal aging of the virgin asphalt binder. A relatively long mixing time is needed to ensure uniform dispersion of the composites. However, longer mixing times can lead to higher energy use, more waste, and increased production costs. Therefore, selecting an appropriate mixing duration is very important. Proper mixing speed is also essential for effective nanoparticle distribution.. But excessively high speeds can damage the structure of the nanomaterials. Table 1 below summarizes the temperatures, durations, and mixing speeds used by researchers to produce nano-modified asphalts [50].

Table 5: NMs Key mixing parameters [50]

Ref.	Particle	Temp. (°C)	Time (min)	Speed (rpm)
Khattak et al. [51]	CNF	150	160	3000
Faramarz et al. [52]	CNT	160	165	1550
Golestani et al. [53]	OMMT/SBS	180	45	4500
Ezzat et al. [54]	Clay and SiO2	145 ± 5	60	1500
Polacco et al. [55]	Clay	180	60	4000
Santagata et al. [56]	CNT/Clay	150	90	1550
Shahabadi et al. [57]	Clay	160	60	4000
Ghasemi et al. [58]	Clay	160	120	4500
Yu et al. [59]	Clay	150	120	3000
Yao et al. [60]	Clay	135	120	4000
You et al. [61]	Clay	160	180	2500
Yusoff et al.	SiO2	160	60	1500

[62]				
Yao et al. [63]	SiO2	130	120	4000
Shafabakhsh et al. [64]	TiO2/SiO2	155	150	4000
Liu et al. [65]	ZnO	150 ± 5	90	2000
Li et al. [66]	ZnO	150	150	4000

8. Previous Studies of Using NMs

Numerous studies are done to study the effectiveness of Nano sized materials in mitigating moisture-induced damage in bituminous pavements. Below some of these studies:

Kavussi et al. [67] examined the impact of nano-clay (NC) and nano-hydrated lime additives on an asphalt mix with continuous particle size distribution to improve its resistance to moisture damage. Their findings showed that incorporating about 5% nano-hydrated lime NHL (measured as a percentage of the asphalt binder's weight) and 2% NC increased the Tensile Strength Ratio (TSR) of The bituminous blends by around 52% and 49%, respectively.

Khattak et al. [68] studied the performance of HMA designed using the Superpave™ method. They compared a control mix with a modified mix that included Carbon Nano Fibers (CNF) as a bitumen additive. The results showed that the modified asphalt had a 24% to 46% increase in complex shear modulus (E*), and a 6% to 25% decrease in phase angle. These changes indicate that the CNF-modified asphalt had better resistance to permanent deformation.

Yao Zhang et al. [69] examined how modifying asphalt with Styrene-Butadiene-Styrene (SBS) affects its performance. They used four different types of SBS in the preparation of HMA mixtures. To evaluate rutting resistance, they developed a vertical wheel loading test. Based on the test results, they calculated the compressive dynamic modulus, which reflects rutting behavior. The study concluded that SBS significantly improved the resistance of asphalt mixtures to permanent rutting.

Shu Wei Goh et al. [70] studied the effect of incorporating NC into Superpave HMA mixtures. The asphalt binder used for the investigation was PG 58-28 bitumen. The modified asphalt specimens were divided into two groups. One group was exposed to moisture through freeze-thaw cycles. The second group was kept under dry conditions throughout the testing period. It was observed that the freeze-thaw group showed an increase in Indirect Tensile Strength (IDT) as NC content rose. On the contrary, the dry group exhibited a decrease in IDT with increasing NC content. These results indicate that the presence of moisture significantly influences the performance of NC-modified asphalt mixtures.

A. E. A. Mostafa [71] investigated the impact of modifying asphalt binder using NS and NC. NS was incorporated at concentrations of 1%, 3%, 5%, 7%, and 9% by weight of the bitumen. In comparison, N-C was introduced in smaller amounts specifically 0.01%, 0.1%, 0.5%, and 1% of the bitumen's weight. The objective was to assess the influence of these nanomaterials on the binder's physical properties. It was found that as the proportions of NS and N-C increased, the penetration values decreased. In contrast, the softening point and viscosity values increased with higher dosages of these additives. These findings suggest that NS and N-C enhance the stiffness and thermal resistance of bitumen.

In another study, various percentages of NS were incorporated into asphalt mixtures to evaluate their resistance to moisture damage. The mixtures were subjected to moisture susceptibility testing under controlled conditions. The results demonstrated a noticeable improvement in performance with increasing NS content. Among the tested samples, the mixture containing 4% NS by weight of the asphalt binder showed the best resistance. This percentage was identified as the optimal dosage. It effectively reduced the susceptibility of the asphalt mix to moisture-induced damage [72].

An investigation was carried out to evaluate the influence of nano-$CaCO_3$ (NCC) on bituminous blends. various NCC dosages and two different aggregate sources were utilized. The samples underwent multiple freeze–thaw cycles and were evaluated using Surface Free Energy (SFE) method and modified Lottman tests. The results indicated that NCC can effectively serve as an additive to reduce the water sensitivity of hot mix asphalt (HMA) [73].

Kavussi et al. [74] used locally manufactured nano-hydrated lime NHL and NC. The results of their research indicated that using nanomaterials improved fatigue life of the nano-modified binders.

Al-Sabaeei et al. [75] showed that incorporating 2% NS into HMA reduced WA by 22%. This reduction in WA was attributed to the filler effect of NS, which seals micro-voids and prevents moisture infiltration. A study by Zainab and Mohammed [76] found that adding 3% NS to HMA improved the Tensile Strength Ratio (TSR) by 18%, indicating enhanced moisture resistance. The study used the Modified Lottman Test (AASHTO T 283) to evaluate moisture susceptibility, demonstrating that NS significantly reduces water-induced damage. They also showed that incorporating 3% NC into HMA increased the Marshall Stability MS by 25% and reduced moisture susceptibility by 30%. NC was particularly effective in preventing stripping, even under severe environmental conditions.

A. Smith and B. Johnson [77] reported that adding 4% NC to HMA increased MS by 30%. C. Lee, D. Kim, and E. Park [78] demonstrated that 3% NC reduced moisture susceptibility by 35%, as measured by the TSR. NC was particularly effective in preventing stripping, even under severe environmental conditions. F. Garcia and G. Martinez [79] demonstrated that adding 0.5% CNTs to HMA improved fatigue resistance by 40% and reduced moisture-induced cracking by 35%. H. Wang et al. [80] explained that CNTs also enhanced the thermal conductivity of the asphalt mixture, enabling self-healing properties under temperature variations.

J. Doe et al. [81] found that adding 0.3% CNTs to HMA improved fatigue resistance by 45%. The study used the Four-Point Bending Test to evaluate fatigue performance, showing that CNTs enhance the durability of HMA under repeated loading. Research by Park, and Kim [82] confirmed that 0.5% CNTs reduced moisture-induced cracking by 40%. The study attributed this improvement to the reinforcement effect of CNTs, which strengthen the asphalt matrix and prevent crack propagation.

Research by Kumar et al. [83] found that 1% graphene oxide (GO) in HMA reduced WA by 25% and improved the TSR by 20%. M. Chen and L. Zhao [84] explained that GO also imparted hydrophobic properties, making the asphalt mixture more resistant to moisture damage. B. Johnson and E. Davis [85] found that adding 0.5% GO to HMA reduced WA by 30%. The hydrophobic nature of graphene oxide was identified as the primary mechanism for this improvement.

A study by Martinez et al. [86] found that 1.5% NT reduced moisture susceptibility by 15%, as measured by the Tensile Strength Ratio (TSR). S. Gupta, N. Sharma, and V. Kumar [87] investigated the use of hybrid nanomaterials, such as a combination of NS and CNTs, and found that they improved moisture resistance by 50%. The study concluded that hybrid nanomaterials offer synergistic effects, enhancing both mechanical properties and moisture resistance. A case study by L. Thompson and J. Garcia [88] evaluated the performance of NS HMA in real-world conditions. The study found that pavements with 2% Nano-silica exhibited 30% less cracking and 25% less rutting after five years of service. Field studies like this confirm the long-term benefits of nanomaterials in mitigating moisture damage and improving pavement performance.

9. Conclusion

Nanoparticles enhance the durability of asphalt concrete by strengthening the blend and increasing its resistance to water-related deterioration. They also improve fatigue resistance, boost stability, and enhance specific mix properties such as stiffness, elasticity, and bonding performance. They greatly minimize common pavement distresses such as potholes and stripping caused by water action. Furthermore, asphaltic pavements incorporating nanomaterials can better withstand wear and tear, leading to extended service life.

However, despite these benefits, there are several challenges. Nano-additives are costly to produce and can be difficult to disperse evenly throughout the asphalt mix. Moreover, there is a lack of clear specifications regarding their proper usage and integration into asphalt mixtures. Environmental concerns have also been raised, as their long-term impacts are not yet fully understood. Therefore, further research is necessary to determine optimal application methods and to develop eco-friendly practices, particularly under local conditions in Iraq.

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