University of Baghdad
College of Engineering
JE
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq

Volume 31 Number 10 October 2025

Influence of Nanomaterial Modifiers on Fatigue Resistance of Asphalt Concrete Mixtures: A Review Paper

Ali M. Al Hamdou *, **Amjad H. Al Bayati**

Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq

ABSTRACT

Enhancing fatigue resistance in asphalt binders and mixtures is crucial for prolonging pavement lifespan and improving road performance. Recent advancements in nanotechnology have introduced various nanomaterials such as alumina (NA), carbon nanotubes (CNTs), and silica (NS) as potential asphalt modifiers. These materials possess unique properties that address challenges related to asphalt fatigue. However, their effectiveness depends on proper dispersion and mixing techniques. This review examines the mixing methods used for each nanomaterial to ensure uniform distribution within the asphalt matrix and maximize performance benefits. Recent research findings are synthesized to elucidate how these nanomaterials and their mixing processes enhance mechanical properties, durability, and overall pavement performance. Evidence suggests that incorporating well-dispersed nanomaterials significantly improves fatigue resistance, leading to reduced cracking and extended pavement life. The review concludes that integrating nanotechnology with effective mixing strategies presents a potentially effective approach for advancing asphalt technology, optimizing performance across diverse environmental conditions, and paving the way for more resilient infrastructure.

Keywords: Fatigue resistance, Nanomaterials, Nano-silica, Nano-aluminum, Carbon nanotubes.

1. INTRODUCTION

Highway networks are crucial for economic and social development. In Iraq, rapid social changes have led to a surge in vehicles, increasing pavement loads due to limited transport alternatives. Considering the substantial financial investments in roadway infrastructure, further targeted investigations are required to improve construction and rehabilitation methodologies. Most highways use asphalt concrete pavement **(Ismael and Ahmed, 2019).** Pavement consists of multiple layers with different materials, designed to act as a single structure. Proper layer bonding ensures effective load transfer from traffic and climate impacts **(Ali et al., 2023)**. Flexible pavements in Iraq suffer premature failure, mainly from

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2025.10.12

Article received: 28/05/2025
Article revised: 26/07/2025
Article accepted: 02/08/2025
Article published: 01/10/2025

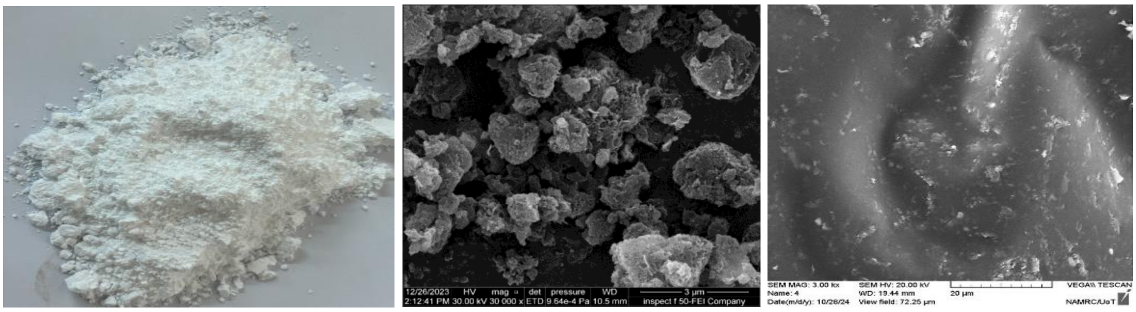
fatigue cracking, rutting, and thermal cracking due to poor construction, materials, maintenance, and design. Fatigue cracking is the most critical **(Sarsam and Allamy, 2016; Mohammed et al., 2024).** There are two basic causes of fatigue distress, two types of fractures can occur in asphalt cement (AC): (1) cohesive fracture in the (AC) or mastic phase, and (2) adhesive fracture at the AC and aggregate contact **(Cheng et al., 2002).** The behavior of asphalt binders is typically influenced by factors such as loading duration, temperature, and the magnitude of strain or stress. Under shorter loading durations or at higher loading frequencies, the binder exhibits more elastic characteristics, similar to its behavior at lower temperatures. This occurs because there is insufficient time for the molecular structure to reorganize. Conversely, at elevated temperatures or during prolonged loading periods (or at lower loading rates), the binder demonstrates a more viscous response. This is attributed to increased molecular mobility at higher temperatures, which leads to the viscous nature of the material **(Lakes, 2009; Hintz, 2012).** Fatigue life in asphalt mixtures is highly dependent on their material characteristics and structural configuration. Key influencing parameters include asphalt layer thickness, loading type and frequency, load configuration, recovery periods between applications, mixture composition, and environmental conditions all of which interact to affect the pavement's long-term fatigue resistance **(Wen, 2001).** The fatigue life of asphalt mixes is typically evaluated through the four-point bending beam fatigue test and the indirect tensile strength test, using either stress or strain control modes **(Mirhosseini et al., 2017; Xiao et al., 2009)**. The important correlation between asphalt binder and asphalt mixes' fatigue and rutting has been validated by several research **(Santagata et al., 2017; Saboo and Kumar, 2016; Safaei et al., 2016).**

Numerous investigations on modifying asphalt binders have demonstrated the effectiveness of nanomaterials and polymers in extending fatigue life and rutting resistance **(Fang et al., 2013; Keymanesh et al., 2017).** Polymers improve the ductility of asphalt at low temperatures, reducing fatigue, but they tend to separate from asphalt when stored at high temperatures due to their poor compatibility with asphalt. In addition, their properties decrease when exposed to ultraviolet rays, oxygen, and heat **(Safaei et al., 2014)**. Manufacturing materials on the nanoscale, with dimensions somewhere between 1 and 100 nm (nanometers), while maintaining properties similar to the same materials in real size, is known as nanotechnology **(Diab et al., 2014; Zhu et al., 2004)**. More atoms are present on the surface area of nanoscale materials due to their more specialized nature, which significantly alters the material's overall surface morphologies and energy as well as its physicochemical characteristics **(Poole and Owens, 2003; Whatmore and Corbett, 1995)**. A comprehensive understanding of nanoparticle properties and behavior in road construction materials necessitates in-depth characterization and experimental investigation. Key attributes such as particle size, geometry, surface morphology, crystalline structure, and chemical composition can be investigated through advanced techniques including Fourier Transform Infrared Spectroscopy, Scanning Electron Microscopy (SEM), Transmission Electron Microscopy, and X-ray Diffraction **(Huseien et al., 2022).**

This paper reviews the impact of nano-sized alumina oxide (NA), carbon nanotubes (CNTs), and silica (NS) on the fatigue properties of asphalt concrete.

2. NANO ALUMINUM OXIDE (AL_2O_3)

Nano-aluminum oxide (nano-alumina) is a relatively uncommon additive in asphalt binder and mixture modification. It can be synthesized in multiple crystalline phases, such as alpha, delta, gamma, and theta. Notable characteristics of nano-alumina include its high specific surface area and excellent durability **(Hart, 1990).** This nano-material is widely used in cosmetics, ceramics, cladding, and catalysts **(Piriyawong et al., 2012).** Research indicates that incorporating nano-alumina can enhance bitumen performance by improving high-temperature resistance to rutting and moderate-temperature resistance to fatigue **(Ali et al., 2016b; Mubaraki et al., 2016)**. **Fig. 1** shows SEM of Al_2O_3 nanoparticles and 2% Al_2O_3-modified bitumen.



NA powder **SEM of NA** **SEM of asphalt 2% NA**

Figure 1. NA Morphology and Dispersion in Asphalt Binder

2.1 Mixing of Nano Al_2O_3

(Bhat and Mir, 2020) added nano Al_2O_3 to asphalt binder at rates of 0.5%, 1%, and 2% by weight. The binder was heated to 150 °C and mixed at 3000 rpm for 90 min. A concentration of 2% was selected based on the softening point stability, and 90 min was identified as the optimal mixing duration **(Bhat and Mir, 2020).** The nano-alumina was dispersed into asphalt using a wet mixing method with kerosene. The asphalt was heated to 150 °C and cut at 4000 rpm. The nano-alumina (3%, 6%, 9%, and 12%) were dissolved in kerosene and then added to the hot asphalt. The mixture was heated until the kerosene completely evaporated **(Cao et al., 2022)**. A wet mixing method was employed to disperse nano-alumina into asphalt using kerosene. The binder was heated to 150 °C and mixed at 4000 rpm, while nano-alumina (0.3–1.2%) was dissolved in kerosene and added gradually. Heating was maintained to ensure complete evaporation of kerosene **(Song, 2023)**. The mixing process is summarized in **Table 1**.

Table 1. Summary of the mixing process for nano Al_2O_3.

References	Binder	Dosage%	Mixer*	T (°C)	Speed (rpm)	Time (min)	Mixing method
(Ali et al., 2016a)	60/70	3,5,7	HSM	170	5000	90	dry
(Bhat and Mir, 2020)	VG-10	0.5,1,2	HSM	150 ±5	3000	90	dry
(Karahancer, 2020)	PG 64-22	3,5,7	HSM	160	3000	60	dry
(Khudhur et al., 2021)	40-50	3,5,7	MM	145	1500	60	dry
(Cao et al., 2022)	70# matrix	3,6,9,12	HSM	150	4000	-	wet
(Alas et al., 2022)	60/70	3,5,7	HSM	170	5000	90	dry
(Song, 2023)	70 #	0.3,0.6,0.9,1.2	HSM	150	4000	-	wet
* HSM = High Shear Mixer, MM = Mechanical Mixer							

2.2 Modified Binder Properties (nano Al_2O_3)

2.2.1 Penetration and Softening Point

A penetration test is performed according to ASTM D5, and a softening point is performed according to ASTM D36. Higher nano-alumina content reduces bitumen penetration and softening point, increasing stiffness and resistance to deformation **(Morshed et al., 2019)**. The results of the penetration and softening points are summarized in **Table 2.** The increase in softening point with nano-alumina (NA) addition is attributed to the formation of a nanoparticle network within the binder, enhancing thermal stability and high-temperature performance **(Morshed et al., 2019).**

Table 2. penetration and softening point (nano Al_2O_3).

REFERENCES	Binder	dosage%	Penetration (0.1mm, at 25°C)				Softening Point (°C)			
(Nejad et al., 2014)	-	0,2,4,6	77	75	68	70	47	51	51	50
(Albrka, 2018)	60/70	0,3,5,7	70	27.6	25.5	38.2	47	51	53	51
(Morshed et al., 2019)	60/70	0,0.5, 1, 1.5	70	46	36	30	52	61.4	69.3	75
(Khudhur et al., 2021)	40/50	0,3, 5, 7	42	30	24	26	55	59	62	60
(Mamuye et al., 2022)	AC20	0,1,2,3	65.8	63.5	59.8	56	43.9	44.8	47.4	49.1
(Alas et al., 2022)	60/70	0,3,5,7	70	27.6	25.5	38.2	46	51	53	51
(Albayati et al., 2024)	40/50	0,2,4,6	49	47	44	41	49.7	50.1	51.1	52.9

2.2.2 Rotational Viscometer Test

(Ali et al., 2016a) concluded that modified asphalt exhibited increased viscosity relative to unmodified asphalt. These increased viscosity results may be due to the hardening effect of NA, which enhances dispersion and bonding strength, limits asphalt flow, and improves physical properties. **(Mubaraki et al., 2016)** concluded that the viscosity of base and modified asphalt (regardless of additive dosage) decreased with increasing temperature and higher viscosity was obtained with modified asphalt. Rotational viscosity values from the cited literature are shown in **Fig. 2.** The increase in viscosity may be attributed to the improved dispersion of nanomaterials, which enhances bonding and restricts asphalt flow, resulting in greater stiffness and improved binder properties **(Khudhur et al., 2021).**

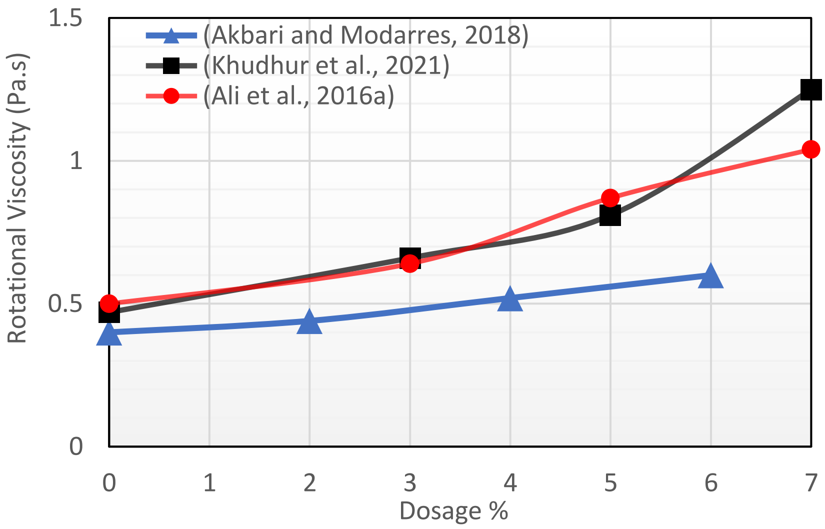


Figure 2. Rotational viscosity at 135°C (NA).

2.2.3 Effect of Nano Al_2O_3 on Fatigue (Binder Level) [DSR (G*. sin δ) – Time Sweep]

The Superpave method sets a maximum allowable fatigue cracking coefficient of 5000 kPa **(McGennis et al., 1994).** The base and modified asphalt had a value higher than the allowable limit at test temperatures of 10-35°C. However, a decrease in fatigue coefficient was observed at 5% dosage at 25°C **(Ali et al., 2016a).** The Superpave fatigue parameter only estimates damage within specific viscoelastic ranges, therefore, alternative methods such as the Time Sweep test have been developed to assess fatigue beyond these limits **(Bhat and Mir, 2020)**. A time sweep test was performed at strain levels of 2, 4, and 6% with a frequency of 10 Hz at 25°C,0.5-2% NA. Fatigue performance improved with increasing additive dosage. The enhancement in performance is attributed to the ability of nano-alumina to inhibit crack initiation and delay crack propagation mechanisms. DSR test was also conducted, and it was concluded that the complex modulus of the composite increased and the phase angle decreased, which led to an increase in fatigue parameters and consequently a reduction in fatigue life **(Bhat and Mir, 2020).** Around 3-7% of the optimal fatigue performance was observed at a 5% dosage, and an improvement in fatigue resistance was observed in all modified samples **(Karahancer, 2020).** Fatigue parameter was evaluated at 25 °C, and an increase was found in (G*. Sin δ) but all samples were less than 5000 kPa **(Mamuye et al., 2022; Alas et al., 2022)**. Fatigue parameter values from the cited literature are shown in **Fig. 3**.

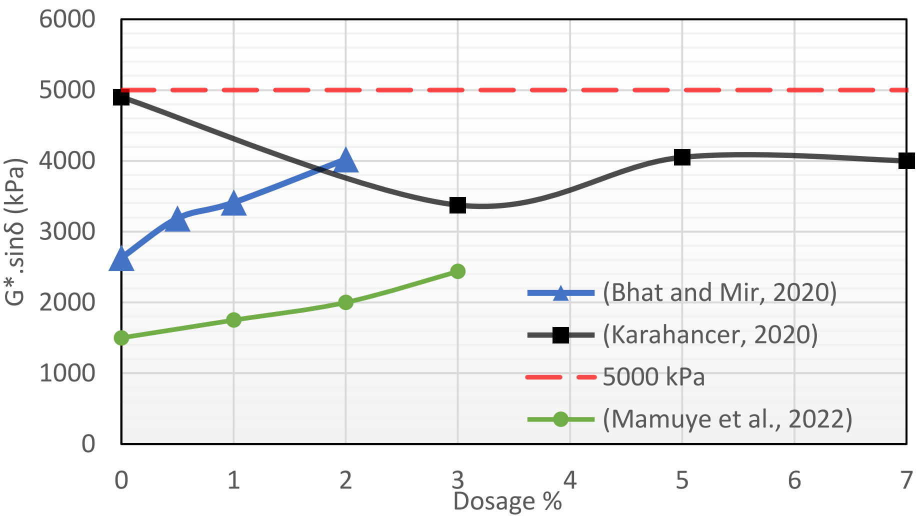


Figure 3. Fatigue parameter (G*. sin δ) at 25°C (nano Al_2O_3).

2.3 Modified Asphalt Mixture Properties (nano Al_2O_3)

2.3.1 Effect of NA on Fatigue (Mixture Level) [IDTF – Ideal CT]

(Lotfi-Eghlim and Karimi, 2016) subjected specimens produced according to **(ASTM D1559-89, 1989)** with diameters and thicknesses of 100 and 40 mm were subjected to the indirect tensile fatigue (ITF) test. The nominal maximum aggregate size (NMAS) of 12.5 mm was used, repeated loads at 1 Hz frequency were applied to the specimens, and constant stresses of 250 and 400 kPa were used at 5, 25, and 40 °C. NA 2-8%. The results showed significant improvement in the fatigue life of asphalt at all stress levels and temperatures compared to base asphalt. The better cohesion and adhesion between nano-Al_2O_3 modified bitumen and stone aggregates enhance fatigue life by reducing displacement and slowing down crack propagation. A decrease in fatigue life was observed for all specimens with increasing temperature due to the high-temperature sensitivity of asphalt in HMA. The best fatigue life was obtained at 8% dosage.

(Mamuye et al., 2022) evaluated the cracking resistance of asphalt concrete using the Indirect Tensile Cracking Test **(ASTM D8225-19, 2019)**, commonly known as IDEAL-CT. This method utilizes the Cracking Tolerance Index (CT Index) to assess fatigue cracking potential. Tests were conducted on cylindrical specimens (150 mm diameter, 62 mm thickness, 7 ± 0.5% air voids) at 25 °C with a loading rate of 50 mm/min. Nano-alumina was added at 1–3% dosages. Results indicated that nano-alumina incorporation enhanced the Cracking Tolerance Index, with 3% yielding the highest enhancement in fatigue resistance **(Mamuye et al., 2022).**

(Cao et al., 2022) performed an indirect tensile stress test with stress amplitudes of 0.2 and 0.3 MPa and frequencies of 10 Hz at 5, 15, and 25°C. (NMAS=13.2mm), NA 3-12%. The results showed increased loading time of asphalt at low temperatures and stresses due to the hardness of asphalt and high strength at low temperatures. Loading times decreased with increasing temperature and stress. The best life was obtained at 6% dosage **(Cao et al., 2022). (Song, 2023)** conducted an indirect tensile fatigue test on cylindrical specimens with a diameter of 100 mm and a height of 63.5 mm, NMAS= 13.2mm, at a frequency of 0.1 Hz and a stress of 0.2 and 0.3 MPa at 5, 15, and 25 °C. NA 0.3-1.2%. The results showed an increase in fatigue life at all loading conditions up to a dose of 0.6%, then it decreased. Fatigue life in asphalt is highly dependent on temperature and applied stress levels, with lower values typically resulting in extended durability. Lowering the asphalt mixture's sensitivity to temperature and stress, using nano alumina, improves its fatigue life since ambient conditions can't be changed **(Song, 2023). Table 4** provides a summary of the effects of nano-alumina on asphalt fatigue

2.3.2 Indirect Tensile Strength (ITS) & Tensile Strength Ratio (TSR)

(Karahancer, 2020) concluded that the indirect tensile strength (IDT) of the modified samples increased with increasing Al_2O_3 content, with the sample containing 7% Al_2O_3 showing the highest IDT dry and IDT wet values. The sample containing 3% Al_2O_3 also showed the highest TSR, indicating better moisture resistance. All modified samples exceeded the specification limits for moisture resistance **(Karahancer, 2020).** The addition of nano-Al_2O_3 improved moisture resistance by increasing TSRs, due to its anti-stripping effect. The best performance was achieved at 3% content **(Mamuye et al., 2022).** The results of the indirect tensile test are summarized in **Table 3**.

Table 3. ITS & TSR result summary

References	Dosage%	ITS-Dry (kPa)				ITS-Wet (kPa)				TSR			
(Hamedi and Esmaeili, 2018)	0,0.5	1000		1240		700		1160		0.7		0.94	
(Karahancer, 2020)	0,3,5,7	845	846	857	871	758	779	784	789	0.89	0.92	0.91	0.91
(Mamuye et al., 2022)	0,1,2,3	794	1000	1040	1075	670	837	885	920	0.84	0.84	0.85	0.85

2.3.3 Marshall Stability

The results of the Marshall stability test conducted by **(Morshed et al., 2019)** showed an improvement in Marshall stability with increasing nano alumina content. The higher Marshall stability of modified blends is due to increased viscosity, which forms a thicker binder film and improves pavement durability. A water stability test was performed on

Marshall samples, and results showed increased stability of samples with increasing nano content before and after immersion. The freeze-thaw split test was also conducted, and the results showed an increase in the split strength of the frozen-thawed and unfrozen-thawed mixture with increasing nano content. Due to its high lipophilicity, nano-alumina exhibits a strong affinity for the asphalt binder, enabling it to effectively convert a greater portion of the free asphalt into structural asphalt within the mixture. This transformation enhances the internal cohesion and mechanical integrity of the asphalt composite **(Cao et al., 2022).**

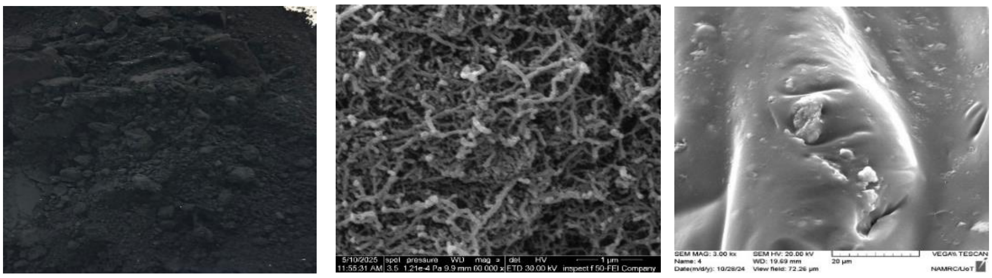
Table 4. Summary of the effect of nano-aluminum on fatigue in asphalt binder and mixture.

References	Binder	Fatigue test	Dosage% (by wt. of AC.)	Conclusion
(Ali et al., 2016a)	60/70	DSR (G*. sin δ)	3,5,7	Opt.=5%, At 25 °C, increase the nano content of AL_2O_3 to 5% to extend its fatigue life.
(Ali et al., 2016b)	60/70	DSR (G*. sin δ)	3,5,7	Opt.=5%, Improved fatigue, and rutting resistance.
(Lotfi-Eghlim and Karimi, 2016)	60/70	IDFT	2,5,8	As the amount of nano Al_2O_3 in the traditional mixtures increased, it increased the mixtures' fatigue lives.
(Bhat and Mir, 2020)	VG-10	DSR &Time sweep	0.5,1 ,2	a time sweep tests indicated an increase in fatigue life, DSR results indicated a decrease in fatigue life.
(Karahancer, 2020)	PG 64-22	DSR (G*.sin δ)	3,5,7	Opt.=7%, all modified binder provides increased resistance to fatigue cracking.
(Mamuye et al., 2022)	AC20	DSR (G*. sin δ) & Ideal CT	1,2,3	The CT index results showed that the crack resistance increases with increasing the added dose. All binders meet Superpave, G*Sinδ < 5000 kPa (DSR).
(Cao et al., 2022)	70# matrix	IDFT	3,6,9,12	The fatigue life of modified asphalt was improved and the best fatigue life was obtained at 6% dosage.
(Alas et al., 2022)	60/70	DSR (G*. sin δ)	3,5,7	The asphalt stiffness was increased, and the effect of nano was not positive on the elastic properties but all values were within the specifications of Superpave.
(Song, 2023)	70 # base asphalt	IDFT	0.3 ,0.6 ,0.9, 1.2	When the amount of NA increases, the fatigue cracking performance first improves and then decreases. The asphalt mixture's fatigue performance is optimal when the content is 0.6%.

3. CARBONE NANOTUBES (CNTs)

CNTs are a leading nano-reinforcement material due to their high aspect ratio, small size, and outstanding physical and chemical properties, making them ideal for asphalt modification **(Hasan et al., 2012)**. CNTs are carbon allotropes, formed by rolling a one-atom-thick graphene sheet into a hollow cylinder with a diameter of about 1 nm **(Husain and Husain, 2005)**. CNTs are classified into three types: single-walled (SWCNTs), double-walled (DWCNTs), and multi-walled (MWCNTs).

SWCNTs consist of a single graphene layer, while MWCNTs are made of multiple concentric nanotubes, similar to tree rings **(Rafique and Iqbal, 2011).** MWCNTs range from two to over 100 layers, with each tube kept at a specific distance by interatomic forces. DWCNTs, with exactly two layers, act as a bridge between SWCNTs and MWCNTs **(Saito et al., 2011). Fig. 4** shows SEM of CNTs nanoparticles and 2% CNTs-modified bitumen.



CNTs powder **SEM of CNTs** **SEM of asphalt 2% CNTs**

Figure 4. CNTs Morphology and Dispersion in Asphalt Binder

3.1 Mixing of Nanomaterials (CNTs)

(Arabani and Faramarzi, 2015) performed a two-step process of mixing 0.1-1% CNTS with asphalt binder: First, the carbon nanotubes were manually mixed with the binder, followed by high-shear mixing at 1550 rpm for 40 min at 160 °C using an oil bath **(Arabani and Faramarzi, 2015)**. **(Latifi and Hayati, 2018)** mixed 0.5-2% CNTs into asphalt binders using wet and simple methods. Both methods were tested separately. In the simple method, CNTs were blended into asphalt at 1550 RPM for 40 minutes at 160°C using a high-shear mixer. In wet mixing, CNTs were sonicated in three 8-minute steps with 25-minute breaks, then mixed at over 3000 RPM. About 70% of particles were under 3 mm. Sonication used 240 Watts and 90% pulse. Kerosene (290 g) dispersed CNTs, which were mixed with asphalt at 160°C until 2% of the kerosene remained after 165 minutes. SEM images show that the wet-mix technique disperses CNTs better than simple mixing, though it is more complex and costly **(Latifi and Hayati, 2018)**. The mixing process is summarized in **Table 5**.

Table 5. Summary of the mixing process for CNTS

References	Binder	Dosage%	Mixer*	T (°C)	Speed (rpm)	Time (min)	Mixing method
(Arabani and Faramarzi, 2015)	60/70	0.1,0.5,1	HSM	160	1550	40	dry
(Ameri et al., 2016)	60/70	0.2, 0.5, 0.8, 1.2,1.5	USM	-	60 (watt)-15 min		dry
(Amin et al., 2016)	60/70	0.5, 1, 2,3	HSM	120	2500	60	dry
(Ashish and Singh, 2018)	AC-10	0.4, 0.75, 1.5, 2.25	HSM	155 ± 5	5000	60	dry
(Latifi and Hayati, 2018)	PG 64-22	0.5,1,2	HSM	160	1550	40	Wet & dry
(Ashish and Singh, 2021)	AC-10	0.4, 0.75, 1.5, 2.25	HSM	155 ± 5	5000	60	dry
(Eisa et al., 2022)	PG64–22,	0.1, 0.5, 1%	HSM	150	-	60	dry
* HSM = High Shear Mixer, USM = Ultrasonic Mixer							

3.2 Modified Binder Properties (CNTs)

3.2.1 Penetration and Softening Point

Adding carbon nanotubes (CNTs) reduces bitumen penetration due to CNTs' high stability. Higher CNT content further decreases penetration, making the bitumen suitable for warmer climates and heavy traffic. While low CNT levels lower the softening point due to aging, higher CNT levels increase it. This is because CNTs enhance bitumen stability, making it suitable for high-temperature and heavy-traffic areas **(Faramarzi et al., 2013).** Penetration and softening point results are summarized in **Table 6.**

Table 6. penetration and softening point (CNTS)

References	Binder	Dosage%	Penetration (0.1mm, at 25°C)				Softening Point(°C)			
(Faramarzi et al., 2013)	60/70	0,0.1, 0.5, 1	53	53	50	46	49	48	50	53
(Faramarzi et al., 2015)	60/70	0,0.1, 0.5, 1	61	59	56	52.5	49	48.5	50	52.5
(Zahedi et al., 2017)	60/70	0 ,0.25, 0.50, 1	65	64	62	57	49	50.4	50.5	50.7
(Haq et al., 2018)	60/70	0, 0.5, 1, 1.5	64	56.7	55	47	49	51	56	57.2
(Gilani et al., 2021)	60–70	0, 0.5, 1	69	53.7	52.1	-	48	53.4	56.2	-
(Le and Le, 2021)	60/70	0, 0.1, 0.15, 0.25	61.2	50	51	50.1	48.6	51	50.5	50
(Ismael et al., 2021)	60/70	0, 0.5, 1, 1.5, 2	64	60	56	52	48	50	53	57
(Eisa et al., 2022)	60/70	0, 0.1, 0.5, 1	67	64	61	56.4	51	51.7	54	55

3.2.2 Bending Beam Rheometer (BBR) Test

(Amin et al., 2016) tested BBR and observed that the control asphalt met Superpave standards for creep stiffness and m-value at 0°C. However, adding CNTs increased stiffness but reduced the m-value, raising the risk of thermal cracking. While all CNT-modified asphalts met stiffness standards, they failed to meet the m-value requirements. Overall, CNTs raised the low-temperature grade of the asphalt **(Amin et al., 2016)**. **(Mansourkhaki and Aghasi, 2019)** concluded that adding 1.2% of carbon nanotubes reduces the stiffness and increases the m-value, which enhances the resistance of asphalt to cracking caused by low temperatures **(Mansourkhaki and Aghasi, 2019)**. Binder stiffness and m- values from the cited literature are shown in **Figs. 5 and 6.**

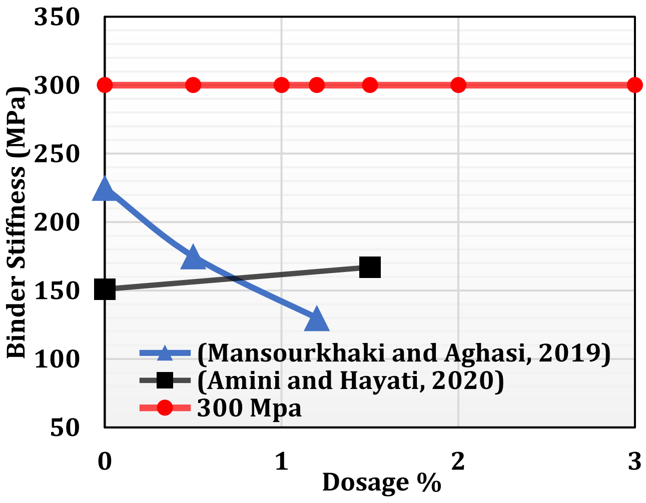


Figure 5. Binder stiffness at -12 °C (CNTs)

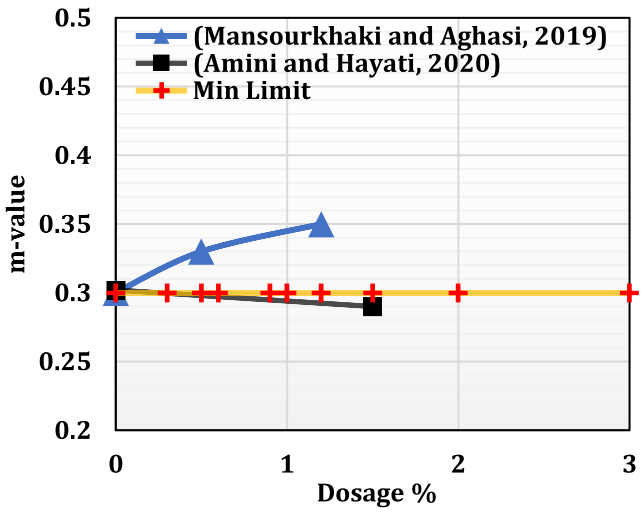


Figure 6. m-value at -12 °C (CNTs)

3.2.3 Rotational Viscosity Test

(Amin et al., 2016) concluded Viscosity rises with increased P-MWCNTs, peaking at 3.0%. The 0.5% P-MWCNTs viscosity is similar to the control asphalt, and all modified binders stay within the Superpave PG limit (below 3000 cP) at 135°C. Higher P-MWCNTs reduce temperature susceptibility, as shown by lower VTS values compared to the control, with 2% and 3% P-MWCNTs having the lowest VTS **(Amin et al., 2016)**. The presence of ultra-fine particles increases binder viscosity by enhancing shear resistance, due to the higher surface area of dispersed colloidal particles **(Ismael et al., 2021).** Higher viscosity enhances the binder's resistance to flow, improving high-temperature rutting resistance. The addition of MWCNTs increases density, thereby raising internal friction and binder viscosity **(Shah and Mir, 2021).** Rotational viscosity values from the cited literature are shown in **Fig. 7**.

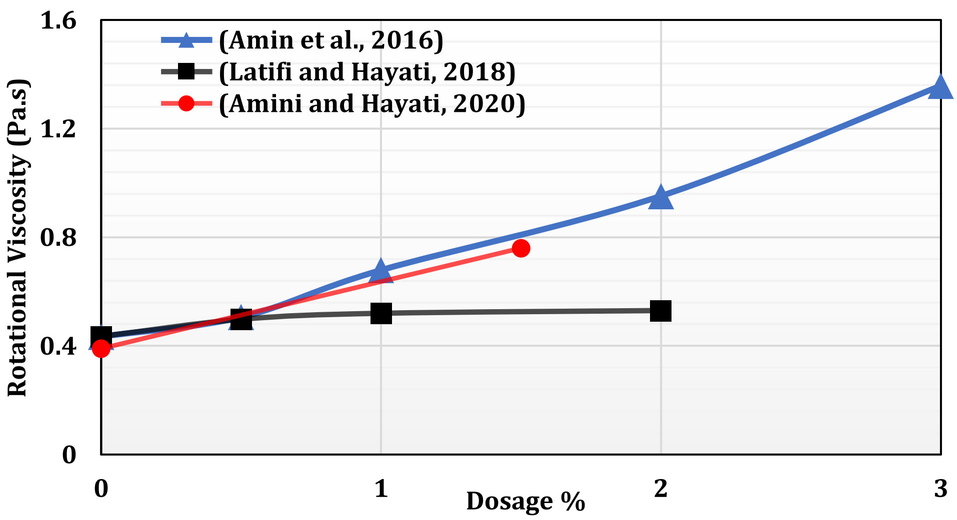


Figure 7. Rotational viscosity at 135 °C (CNTs)

3.2.4 Effect of CNTS on Fatigue (Binder Level) [DSR (G*. sin δ) - LAS]

From the DSR test, it was concluded that with 0.3-1.5% CNTS an improvement in the low-temperature fatigue performance of CNT-modified asphalt **(Ziari et al., 2014b)**. A 0.5-3% Pristine (P-MWCNTs) was added to asphalt and a DSR test was conducted. The results showed an increase in the fatigue parameter (G*. sin δ) which leads to a rise in the cracking tendency of modified asphalt with increasing nano content **(Amin et al., 2016)**. **(Ashish and Singh, 2018)** concluded that the results of the LAS test at a 1% strain level showed an improvement in the fatigue strength of modified asphalt (0.4-2.25% CNTS). This improvement may be due to efficient load transfer from the binder matrix phase to the carbon nanotube phase. Despite a slight reduction in stiffness due to CNT agglomeration above 1.5%, increasing CNT content to 2.25% significantly improves fatigue life **(Ashish and Singh, 2018)**. It was conducted a DSR test on asphalt modified with 1.5% CNTS and the results showed an increase in the fatigue parameter of the modified asphalt **(Amini and Hayati, 2020).** A DSR test was conducted and concluded that the addition of MWCNTs. makes the mixture stiffer, which increases G*. Sin δ and fatigue cracking susceptibility. Therefore, MWCNT does not significantly improve fatigue resistance **(Shah and Mir, 2021)**. Fatigue parameter values from the cited literature are shown in **Fig. 8**.

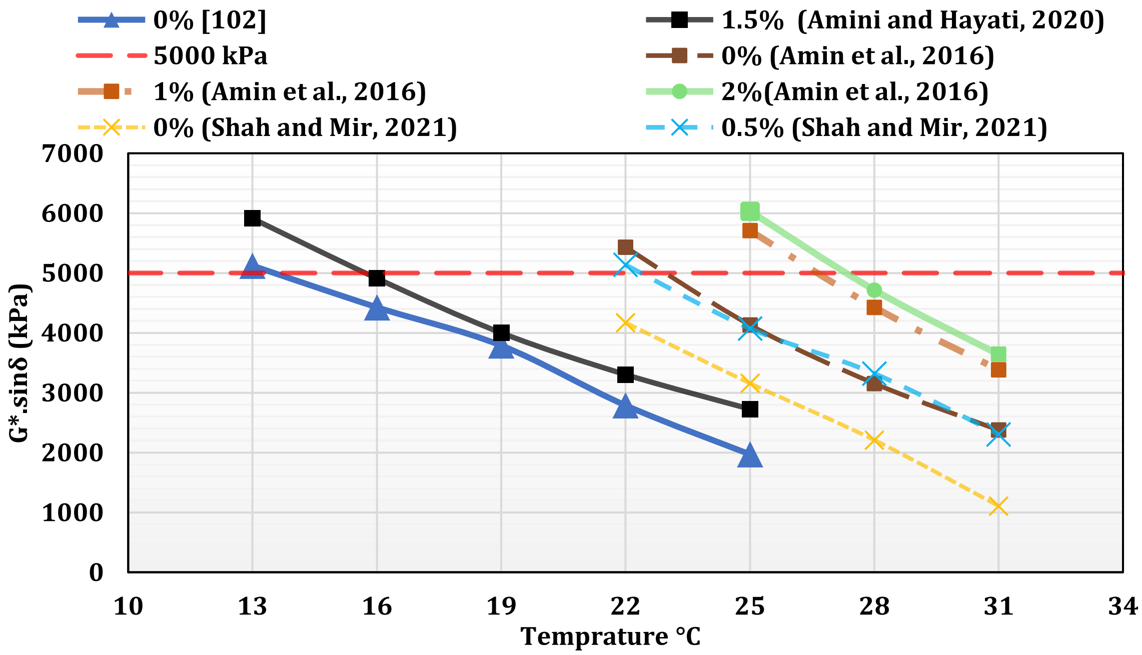


Figure 8. Fatigue parameter (G*. sin δ) (CNTs).

3.3 Modified Asphalt Mixture Properties (CNTs)

3.3.1 Effect of Nanomaterials on Fatigue (Mixture Level) [4-POINT BENDING Beam -ITFT-CT Index]

A flexural beam was subjected to a 4-point semi-sinusoidal loading for a constant strain (600 micro-strain) at 20°C during the fatigue test (NMAS=12.5mm),0.3-1.5% CNTS. Fatigue life is estimated to be reached at the end of these samples when the initial stiffness is reduced by 50%. The findings demonstrate that the fatigue life of asphalt mixes, and the cumulative dissipated energy, all significantly increase with an increase in the proportion of CNTS in the

fatigue samples, and the rate of damage propagation is reduced **(Ziari et al., 2014a)**. **(Arabani and Faramarzi, 2015)** performed ITF test on specimens having a diameter of 100 mm and a depth of 40 mm (NMAS=11.5mm). at 1 Hz, 5, 25, and 40 °C, 100 and 300kpa stress. The results showed that the modified blends had higher fatigue life than the conventional blends. The addition of CNT could increase the tensile strength of HMA and inhibit the propagation of microcracks **(Khattak et al., 2013)**. This is due to the higher energy absorption of CNT compared to the binder phase **(Arabani and Faramarzi, 2015).**
The four-point flexural beam fatigue test was performed by (AMERI et al.) . The specimen was subjected to a constant strain of 400 μ-strain. (NMAS=9.5mm). The failure of the mixture was determined at a 50% decrease in initial stiffness according to AASHTO T-321-07. The results showed an increase in the fatigue life of the modified mixtures, an increase in storage modulus, and a decrease in the phase angle of the binder **(Khattak et al., 2013)**. An ITF test was performed with constant stress using Nottingham apparatus according to ASTM D4123. Stresses of 150 and 300 kPa were used at 5, 25 and 40 °C. (NMAS=9.5mm), 0.5-2% CNTS. Results showed an improvement in fatigue life of approximately twice that of the modified mixes. The final strain was also improved. The optimum dosage of 1% was determined **(Latifi and Hayati, 2018)**. **(Ashish and Singh, 2021)** conducted ITF test on asphalt mixtures at 25 °C and stresses of 190, 250, and 300 kPa with loading and rest periods of 100 and 400ms. (NMAS=19mm), 0.4-2.25 CNTS. It was concluded that the addition of carbon nanotubes enhanced the fatigue performance of the mixture. It was also observed that the CT index value increased with increasing nano content added, which leads to a higher energy requirement for fracture failure **(Ashish and Singh, 2021). Table 7** provides a summary of the effects of CNTs on asphalt fatigue.

3.3.2 Indirect Tensile Strength (ITS) & Tensile Strength Ratio (TSR)

A modified Lottman test was conducted and 1.5% CNTS was added to the asphalt. The results showed that the modified asphalt has higher ITS (conditional and unconditional) values and TSR than the base asphalt, but the TSR value of the asphalt modified with 1.5% CNTS is less than 80%. This is the minimum acceptable TSR value in the experiment **(Amini and Hayati, 2020)**. The effect of carbon nanotubes on the resistance of asphalt mixture to moisture damage was studied according to ASTM D4867, where nano doses of 0.4, 0.75, 1.5, and 2.25% were added to the asphalt. The results showed an increase in TSR and ITS values (unconditional and conditional) with increasing nano content added. Doses of 0.75, 1.5, and 2.25% gave a TSR value above 80%. This suggests that adding CNTS can improve the mixture's resistance to moisture damage. **(Ashish and Singh, 2021)** This result may be explained by the hydrophobic properties of carbon nanotubes and their chemical affinity to asphalt binders **(De Melo et al., 2018).**

3.3.3 Marshall Stability and Flow

The use of carbon nanotubes leads to increased Marshall stability of asphalt concrete and reduced flow due to the high Young's modulus of nanotubes **(Faramarzi et al., 2013).** Carbon nanotubes significantly improve the Marshall strength of bitumen due to their high density and tensile strength **(Zahedi et al., 2017).** The incorporation of CNTs improved bonding between mixture components and enhanced interlocking, resulting in a denser structure with reduced air void content **(Ismael et al., 2021).** The effect of carbon nanotubes on stability and flow is summarized in **Table 8.**

Table 7. Summary of the effect of CNTS on fatigue in asphalt binder and mixture

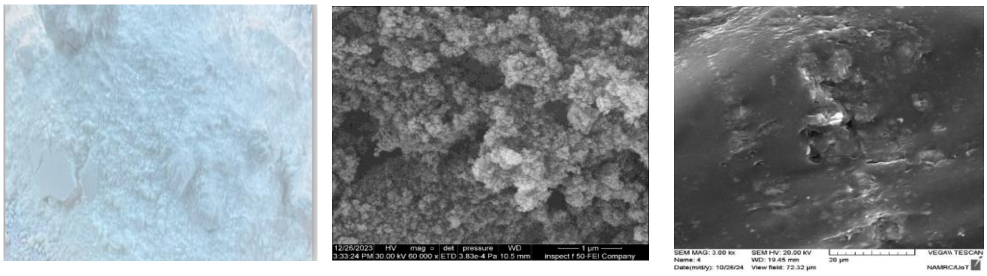
References	Binder	Fatigue test	Dosage% (wt. of AC.)	Conclusion
(Ziari et al., 2014a)	PG58-16	4-point flexural beam	0.3, 0.6, 0.9, 1.2, 1.5	Life fatigue increased with increasing added dose.
(Ziari et al., 2014b)	60/70	DSR (G*. sin δ)	0.3, 0.6, 0.9, 1.2, 1.5	Opt. = 1.2%, The physical properties, complex modulus, fatigue, and rutting parameters are improved.
(Arabani and Faramarzi, 2015)	60/70	ITFT	0.1, 0.5, 1	CNTS reduces the strain and permanent deformations and increases fatigue life.
(Ameri et al., 2016)	60/70	flexural beam fatigue test	0.2, 0.5,0.8, 1.2, 1.5	Life fatigue increased with increasing added dose.
(Amin et al., 2016)	60–70	DSR (G*. sin δ)	1,2,3	Increasing the content of Pristine (P-MWCNTs) increased the fatigue cracking susceptibility of asphalt.
(Ashish and Singh, 2018)	AC-10	LAS	0.4, 0.75, 1.5, 2.25	There was a significant improvement in fatigue life.
(Latifi and Hayati, 2018)	PG 64-22	ITFT	0.5, 1, 2	Opt. = 1%, Adding nano-material improved the fatigue life by almost double. The improvement rate decreased significantly when adding a more than 1% dose.
(Amini and Hayati, 2020)	PG 64-22	DSR (G*.sin δ)	1.5	Increase fatigue parameter
(Shah and Mir, 2021)	80/100	DSR (G*.sin δ)	0.5,1,1.5,2,2.5	The risk of fatigue cracking in the modified asphalt binder rises with higher MWCNT percentages.
(Ashish and Singh, 2021)	AC-10	ITFT & ideal CT	0.4, 0.75, 1.5, 2.25	The results indicate an improvement in fatigue life.

Table 8. Marshall stability and flow (CNTS).

References	Dosage%	Marshall stability (KN)					Marshall flow (mm)				
(Faramarzi et al., 2013)	0,0.1,0.5,1	13.17	13.66	15.08	17.46	-	3.33	3.2	3.16	3.05	-
(Zahedi et al., 2017)	0,0.25,0.5, 1, 1.5	9.86	12	13.24	14.65	16.73	3.1	2.4	3	2.6	2.8
(Le and Le, 2021)	0,0.05, 0.1, 0.15, 0.2	11.55	11.95	13.25	13.63	14.15	3.49	3.87	3.95	3.91	3.89
(Ismael et al., 2021)	0,0.5,1,1.5,2	10.1	11.2	12	12.7	12.9	3.1	2.9	2.8	2.7	2.6

4. NANO SILICA OXIDE (NS)

Silica, commonly added to bitumen as nanoparticles, is silicon dioxide (SiO_2) and serves as a key reference point. It forms a covalent solid, with silicon at the center of a tetrahedron bonded to four oxygen atoms. Silica exists in both crystalline forms like quartz and amorphous forms like silica glass **(Napierska et al., 2010).** Nano-silica (NS) is stable and cost-effective, with a 2018 price of 50 CNY (about 7 USD) per kilogram. Typically, NS for asphalt modification is white or off-white, spherical, and around 30 nm in size **(Shi et al., 2018; Bala et al., 2018)**. **Fig. 9** shows SEM of NS nanoparticles and 2% NS-modified bitumen.



NS powder **SEM of NS** **SEM of asphalt 2% NS**

Figure 9. Ns Morphology and Dispersion in Asphalt Binder

4.1 Mixing of Nanomaterials (Nano-Silica)

(Nazari et al., 2018) mixed 2% and 4% of NS with 60/70 asphalt using a Polytron PT 6100 homogenizer. The binder was heated to 160°C, and 600g was stirred at 4000 RPM for 10 minutes while 2% and 4% (by weight) of nanoparticles were slowly added. Mixing then continued at 6100 RPM for 50 more minutes. XRD and SEM analysis confirmed uniform nanoparticle distribution **(Nazari et al., 2018)**. **(Shafabakhsh et al., 2020)** first dispersed (0.3-1.2%) nano silica in kerosene using a high-shear mixer. The optimal dispersion was achieved by mixing for 30 minutes at 2500 RPM. The nanomaterial solution was mixed with heated (60-70) bitumen (150°C) at 4000 RPM to create a homogeneous mixture **(Shafabakhsh et al., 2020)**. The mixing process is summarized in **Table 9**.

Table 9. Summary of the mixing process for Nano silica

Reference	Binder	Dosage% (wt. of AC)	Mixer*	T (°C)	Speed (rpm)	Time (min)	Mixing method
(Taherkhani and Afroozi, 2017)	60/70	1,3,5	HSM	160	3000	60	dry
(Hasaninia and Haddadi, 2017)	60/70	2, 4, 6, 8	HSM	135	4000	120	dry
(Saltan et al., 2017)	PG 64-22	0.1, 0.3, 0.5	HSM	160	4000	120	dry
(Crucho et al., 2018)	35/50	4	HSS	160	2000	60	dry
(Taherkhani and Tajdini, 2019)	60/70	2, 4, 6	HSM	160	4000	40	dry
(Motamedi et al., 2021)	85-100	3, 5, 7	HSM	160	4000	-	dry
(Aljbouri and Albayati, 2023)	40-50	1,3,5	-	140 ± 5	1800	30	dry
(Albayati et al., 2024)	40-50	2,4,6,8	HSM	140	4000	20	dry
* HSS = High-Speed Stirrer, HSM = High-Shear Mixer, HSS= High-Speed Stirrer							

4.2 Modified Binder Properties (Nano-Silica)

4.2.1 Penetration and Softening Point

(Sadeghnejad and Shafabakhsh, 2017) found that 1.2% Nano SiO2 reduces bitumen penetration by 15% and increases the softening point by 16%, enhancing stiffness and thermal resistance **(Sadeghnejad and Shafabakhsh, 2017)**. This makes the bitumen more durable and suitable for high-temperature and heavy-traffic areas **(Ghaffarpour and Ahmadi, 2011)**. The increase in hardness and softening range with the addition of nano-silica (NS) is attributed to its ability to adsorb light volatile components from the maltene phase, leading to a higher asphaltene concentration and enhanced binder stiffness due to the inherently rigid nature of NS **(Zghair et al., 2020)**. NS increases binder stiffness by enhancing asphalt absorption and molecular interactions through its high surface area and reactive surface chemistry **(Fini et al., 2015)**. Penetration and softening are summarized in **Table 10**.

Table 10. Penetration and softening point (NS)

Reference	Binder	Dosage%	Penetration (0.1mm, at 25°C)				Softening Point (°C)			
(Zafari et al., 2014)	60-70	0, 2, 4, 6	58	56	50	43	47	50.5	54.1	58
(Enieb and Diab, 2017)	60/70	0, 2, 4, 6	65	49	39	36	51	50	55	53
(Taherkhani and Afroozi, 2017)	60/70	0, 1, 3, 5	67	65	60	53	48.9	49	50.4	54.8
(Sadeghnejad and Shafabakhsh, 2017)	60/70	0, 0.3, 0.6, 0.9	68	66	63	61	50	52	55	57
(Moeini et al., 2019)	PG 64-16	0, 2, 4, 6	67	65	62	60	50.4	51.9	54.6	56.8
(Zghair et al., 2020)	60/70	0, 2, 4, 6	66	43	35	29	49.5	53	56	57
(Oda et al., 2020)	-	0, 3, 5, 7	54	52	43	55	42.5	44.3	46	45.8
(Qassim et al., 2022)	60/70	0, 2, 4, 6	66	63	59	56	47	49	51	55
(Mohammed and Abed, 2023)	40/50	0, 1, 3, 5	47	40	36	32.7	49	57	60	64
(Taher and Ismael, 2022)	40/50	0,2,4,6	44	42	37	26	51	53	55	59

4.2.2 Bending Beam Rheometer (BBR) Test

(Saltan et al., 2017) concluded that compared with base asphalt, SiO_2NP 0.3% modified bitumen exhibits lower creep stiffness, which improves thermal cracking resistance. All modified bitumen, including the base, meets creep stiffness limits and m-value specifications, with SiO2NP 0.3% achieving the best performance **(Saltan et al., 2017)**. The nanomaterials did not significantly improve low-temperature cracking, as 5% nanomaterials increased the hardness and decreased the m-value without affecting the asphalt grade **(Mohammed and Abed, 2023)**. Binder stiffness and m-values from the cited literature are shown in **Figs. 10 and 11**

4.2.3 Rotational Viscosity Test

The SiO2NP 0.1% and 0.3% modified bitumens have lower viscosity and better workability than basic bitumen, while SiO2NP 0.5% has lower workability **(Saltan et al., 2017)**. The addition of nanomaterials increases the viscosity of the basic binder at 135 °C. This change is due to the hardening effect and better dispersion of nanomaterials, which enhances the bonding strength and improves the physical properties of asphalt **(Khudhur et al., 2021)**. The addition of NS increases binder viscosity, with higher NS content leading to greater viscosity due to its elevated surface area and reactivity **(Enieb and Diab, 2017)**. The increased stiffness of the modified asphalt is likely attributed to the absorption and diffusion of silica particles into the binder. Silica reduces the molten oily phase by converting it into resin-like material and contributes to stiffness due to its higher hardness compared to the asphalt binder **(Rasheed et al., 2023).** Rotational viscosity values from the cited literature are shown in **Fig. 12**.

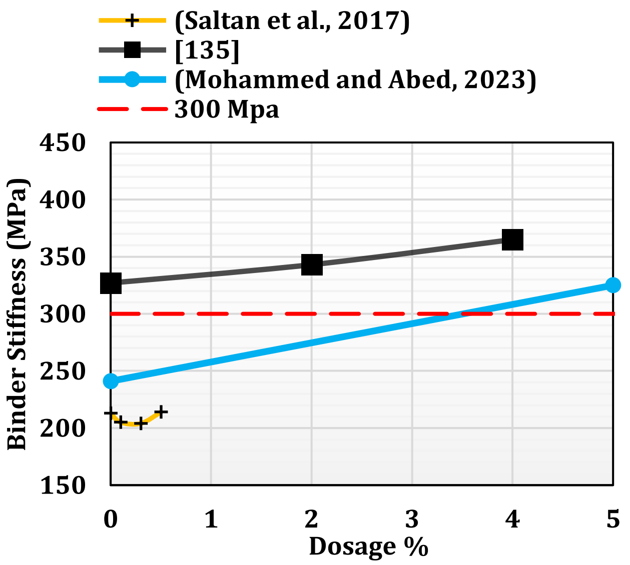


Figure 10. binder stiffness at -12 °C (NS).

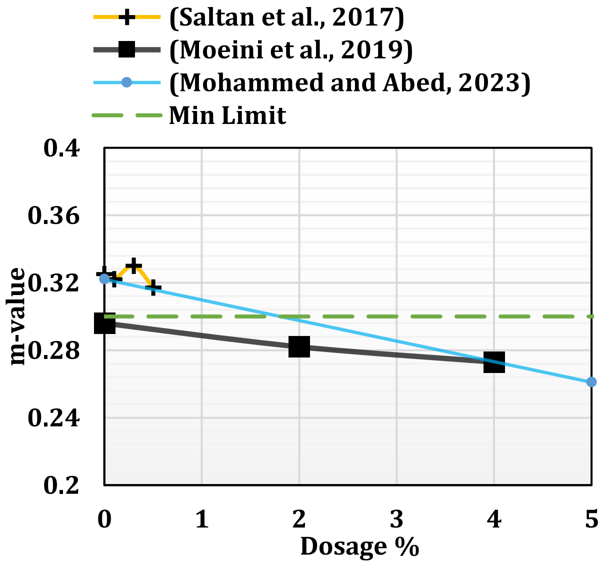


Figure 11. m-value at -12 °C (NS).

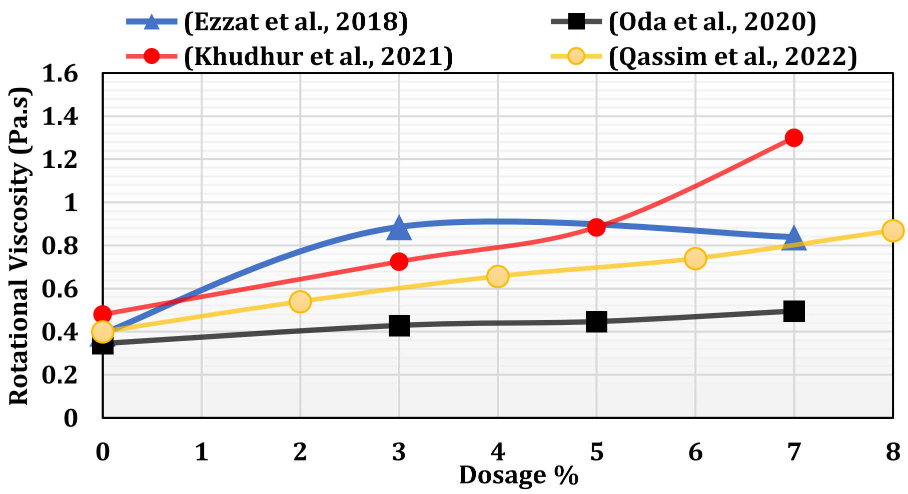


Figure 12. Rotational viscosity at 135 °C (NS).

4.2.4 Effect of NS on Fatigue (Binder Level) [LAS- DSR (G*. sin δ) -Time Sweep]

The NS was addedat doses of 0.1-0.5%. DSR test results showed that the dose of 0.3% had the best fatigue performance. Performance was reduced compared to base asphalt at doses of 0.1% and 0.5% **(Saltan et al., 2017). (Leiva-Villacorta and Vargas-Nordcbeck, 2017**) conducted a DSR test at 22°C on asphalt modified with 0.5-6% NS. It was concluded that adding 3 and 6% NS improved fatigue resistance but adding 0.5% reduced fatigue resistance **(Leiva-Villacorta and Vargas-Nordcbeck, 2017**). **(Nazari et al., 2018)** conducted a time sweep test at 10 Hz, 22 °C, and strain levels of 3, 4, and 6%. Doses of 2 and 4% NS were added to asphalt. The results showed that nano silica increased fatigue life at all shear strain levels. The LAS test showed similar results, where the fatigue life of the asphalt modified with NS was improved and the highest fatigue life was obtained at 2% dosage. SiO_2 nanoparticles likely enhance interactions with asphalt binder, forming a network that helps resist microcrack formation **(Nazari et al., 2018).** Time sweep test results (at 20°C and 10 Hz) on asphalt samples modified with 3-7% NS showed an increase in fatigue resistance compared to control asphalt. 7% dosage had the highest fatigue life **(Shafabakhsh et al., 2019a).** The LAS test was conducted on asphalt modified with 4-8% NS. The results showed that adding 4 and 6% nanomaterials led to an increase in fatigue life compared to base asphalt. However, a reduction in fatigue performance was recorded when adding 8% NS (long-term aging) and also at 5% strain level (short-term aging) **(Shafabakhsh et al., 2019b). (Motamedi et al., 2021)** added NS at doses of 3-7% and the results of the Time sweep test (20°C, 10 Hz, strain levels 2.5 and 5%) showed an improvement in the fatigue life of the modified asphalt, and the best improvement was obtained at 7% NS **(Motamedi et al., 2021)**. **(Shafabakhsh et al., 2020)** added 0.3-1.2% NS. The LAS test results showed an increase in fatigue life with increasing additive dosage, and the DSR test results showed an improvement in fatigue resistance of the asphalt.

4.3 Modified Asphalt Mixture Properties (Nano-Silica)

4.3.1 Effect of NS on Fatigue (Mixture Level) [4-Point Bending Beam -ITFT]

(Taherkhani and Afroozi, 2017) added 1-5% of NS. An improvement in the indirect tensile strength (ITS) value of the modified mixture was obtained, indicating an improvement in the resistance of the mixture to fatigue cracks with increasing the nano content. **(Hasaninia and Haddadi, 2017)** added 2-8% NS. A four-point fatigue beam test was performed at strain levels of 600, 800, and 1000 microstrain and sinusoidal modes of loading. (NMAS = 12.5mm). Adding nano-silica increases fatigue life and cumulative dissipated energy (CDE) at all strain levels, indicating improved energy absorption and greater resistance to cracking **(Yoo and Al-Qadi, 2010)**. **(Crucho et al., 2018)** added 4% NS. A 4-point bending beam test was conducted at three strain levels of 150, 250, and 350 lm/m applied by a sinusoidal load at 10 Hz and 20°C. It was concluded that NS-modified mixes had better fatigue resistance compared to the control mix. **(Taherkhani and Tajdini, 2019)** added 2-6% of NS. ITF (25°C, 10 Hz, 200 kPa stress) was performed and the results showed an increase in fatigue life with increasing NS content. **(Shafabakhsh et al., 2019b)** added 4-8% of NS. Four-point flexural bending fatigue test was conducted at strain levels of 400, 700, and 1000 at 10 Hz at 20 °C, (NMAS = 12.5 mm). Results showed that higher strain levels reduce fatigue life by increasing stress, accelerating cracks, and weakening binder-aggregate bonds. Among the nano-modified asphalt mixtures, asphalt containing 8% NS had the highest fatigue life, followed by 6% and 4%. **Table 11** provides a summary of the effects of nano-silica on asphalt fatigue.

Table 11. Summary of the effect of NS on fatigue in asphalt binder and mixture.

Reference	Binder	Fatigue test	Dosage% (wt. of AC.)	Conclusion
(Taherkhani and Afroozi, 2017)	60/70	ITST	1,3,5	Fatigue life increased with increasing nano content.
(Hasaninia and Haddadi, 2017)	60/70	4 Point beam fatigue	2, 4, 6, 8	Fatigue life increased with increasing nano content.
(Saltan et al., 2017)	PG 64-22	DSR (G*.sin δ)	0.1, 0.3, 0.5	Opt. = 0.3%, Fatigue life increased by 11.52% with the addition of 0.3% nano content.
(Leiva-Villacorta and Vargas-Nordcbeck, 2017)	PG 64-22	DSR (G*.sin δ)	0.5, 3, 6	The best fatigue performance was obtained at a dose of 3%, a dose of 6% showed a significant improvement in fatigue life, and a dose of 0.5% showed a decrease in performance.
(Nazari et al., 2018)	60/70	LAS & Time sweep	2, 4	The highest fatigue life was obtained at a dose of 4%.
(Crucho et al., 2018)	35/50	4 Point beam	4	Improved fatigue resistance
(Shafabakhsh et al., 2019a)	85/100	Time sweep	3,5,7	Increased fatigue life, best performance at 7% dose.
(Taherkhani and Tajdini, 2019)	60/70	ITFT	2, 4, 6	Fatigue resistance is improved, 6% dosage has the highest fatigue life.
(Shafabakhsh et al., 2019b)	60–70	LAS & 4 Point bending	4, 6,8	The best fatigue life was obtained at a dose of 8%, then 6%, and 4%.
(Motamedi et al., 2021)	85-100	Time sweep	3, 5, 7	Improved fatigue resistance, the optimal dosage is 7%.
(Shafabakhsh et al., 2020)	60–70	DSR (G*. sin δ) &LAS	0.3, 0.6, 0.9,1.2	Improved fatigue resistance

4.3.2 Indirect Tensile Strength (ITS) & Tensile Strength Ratio (TSR)

The Nano-silica improves the tensile strength of asphalt and its resistance to fatigue cracking. It also enhances resistance to moisture damage, with the tensile strength ratio (TSR) increasing with higher nano-silica content. At 5% nano-silica, nano-silica also enhances Marshall stability, with higher content showing better resistance due to reduced air voids **(Taherkhani and Afroozi, 2017)**. Increased binder stiffness from nano-silica enhances resistance to moisture damage, making it harder for the binder to lose adhesion to aggregates **(Hamedi et al., 2015)**. The results showed that ITS increased with higher NS content, attributed to the stiffening effect of nano-silica. This is due to the interaction between the abundant nano-sized particles and the binder, where the particles absorb binder solvents, leading to increased stiffness and improved tensile resistance before failure **(Taherkhani and Tajdini, 2019)**. The effect of nano-silica oxide on Moisture damage resistance is summarized in the following **Table 12.**

Table 12. ITS & TSR (NS).

Reference	Dosage%	ITS-Dry (kPa)				ITS-Wet (kPa)				TSR%			
(Taherkhani and Afroozi, 2017)	0,1,3,5	755.4	685.8	763.5	909.8	340.1	362.7	468.5	699.2	45	52.9	61.4	77
(Saltan et al., 2017)	0,0.1, 0.3,0.5	880	1053.6	1086	1271	704	821.8	1097	889.7	80	78	101	70
(Taherkhani and Tajdini, 2019)	0,2,4,6	560	612	707	765	359	465.1	593.68	680.85	64.1	76	84	89

4.3.3 Marshall Stability and Flow

Adding 2%, 4%, and 6% nano-silica (NS) increased the optimal asphalt content and Marshall stability, improving by 11.47%, 26.09%, and 39.9% respectively. The increased binder stiffness and surface area of NS reduced Marshall flow, air voids, and VMA% while increasing bulk density, resulting in a denser, more durable asphalt mixture **(Taher and Ismael, 2023)**. Nano-silica increases the Marshall quotient by enhancing binder absorption and stiffness, due to its high surface area and strong interaction with the binder, improving resistance to permanent deformation **(Taherkhani and Afroozi, 2017)**. The effect of nano-silica oxide on stability and flow is summarized in the following **Table 13**.

Table 13. Marshall stability and flow

Reference	Dosage%	Marshall stability (KN)				Marshall flow (mm)			
(Taherkhani and Afroozi, 2017)	0,1,3,5	14.38	14.77	15.2	16.13	2.97	2.5	2.23	2.15
(Hasaninia and Haddadi, 2017)	0,2,4,6	10.23	11.3	12.1	12.73	4.2	4.32	4.41	4.55
(Taher and Ismael, 2023)	0,2,4,6	9.85	10.23	12.42	13.79	3.51	3.38	3.12	2.87

5. CONCLUSIONS

In recent years, nanomaterials have gained significant attention in the field of asphalt technology due to their potential to improve pavement performance. This review focuses on applying nanomaterials (alumina, carbon nanotubes (CNTs), and silica) to enhance the fatigue resistance of asphalt binders and mixtures. Based on the findings, the following conclusions can be derived:

1- Nano-alumina increases binder hardness and improves fatigue resistance at 3-7% dosage. Mixing effectively at 150-170°C for 60-90 min at 3000-5000 rpm using a high shear mixer (HSM).
2- Though some studies report a negative impact of CNTs on fatigue life, most show that 1-2.25% of CNTs enhance asphalt fatigue performance. Mixing effectively at 120-160°C for 40-60 minutes at 1550-5000 rpm using an HSM).
3- Incorporating 3%-8% nano-silica enhances the fatigue resistance of asphalt. Efficient mixing is performed at 135-160°C for 40-120 minutes at 3000-4000 rpm using a (HSM).
4- The Indirect Tensile Cracking Test (ideal CT) is a simple and effective method for evaluating asphalt mixture cracking properties.
5- The addition of nanomaterials enhances dry and wet indirect tensile strength.

NOMENCLATURE

Symbol	Description	Symbol	Description
AASHTO	American Association of State Highway and Transportation Officials	MPa	Megapascal
AC	asphalt cement	MWCNTs	multi-walled Carbone nanotubes
Al2O3	Aluminum Oxide	NA	Nano Aluminum Oxide
ASTM	American Society for Testing and Materials	nm	nanometers
BBR	Bending Beam Rheometer	NMAS	nominal maximum aggregate size
CNTs	Carbone Nanotubes	NS	Nano Silica Oxide
cP	centipoise	NT	Nano Titanium Oxide
CT Index	Cracking Tolerance Index	NZ	Nano Zinc Oxide
DSR	Dynamic Shear Rheometer	Pa.s	Pascal-second
DWCNTs	double-walled Carbone nanotubes	PG	performance grade
G*. sin δ	fatigue parameter	P-MWCNTs	Pristine multi-walled Carbone nanotubes
HSM	high shear mixer	rpm	revolutions per minute
HSS	high-speed stirrer	SEM	Scanning Electron Microscopy
Hz	Hertz	SiO2	Silica Oxide
IDT	indirect tensile strength	SWCNTs	single-walled Carbone nanotubes
IDTF	Indirect Tensile Fatigue Test	T (C°)	Temperature (Celsius)
ITS	Indirect Tensile Strength	TSR	Tensile Strength Ratio
kPa	kilopascal	USM	ultrasonic mixer
LAS	Linear Amplitude Sweep	VTS	Viscosity Temperature Susceptibility
MM	mechanical mixer	XRD	X-ray Diffraction

Acknowledgements

The author would like to acknowledge the support provided by the University of Baghdad

Credit Authorship Contribution Statement

Amjad H. Al Bayati: Supervision, Validation, Methodology, Selection of discussion sections, Writing – review & editing. Ali M. Al Hamdou: Writing – original draft, Literature collection, Data organization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Akbari, A. and Modarres, A., 2018. Fatigue response of HMA containing modified bitumen with nano-clay and nano-alumina and its relationship with surface free energy parameters. *Road Materials and Pavement Design*, 21(6), pp. 1490–1513. https://doi.org/10.1080/14680629.2018.1553733

Alas, M., Abba, S.I., Ali, S.I.A., Rahim, A. and Yusoff, N.I.M., 2022. Evaluating the performance of aluminum oxide nanoparticle-modified asphalt binder and modelling the viscoelastic properties by using artificial neural networks and support vector machines. *Advances in Materials Science and Engineering*, 2022, pp. 1–11. https://doi.org/10.1155/2022/9685454

Albayati, A.H., Latief, R.H., Al-Mosawe, H. and Wang, Y., 2024. Nano-additives in asphalt binder: Bridging the gap between traditional materials and modern requirements. *Applied Sciences*, 14(10), P. 3998. https://doi.org/10.3390/app14103998

Albayati, A.H., Oukaili, N.K., Moudhafar, M.M., Allawi, A.A., Said, A.I. and Ibrahim, T.H., 2024. Experimental study to investigate the performance-related properties of modified asphalt concrete using nanomaterials Al_2O_3, SiO_2, and TiO_2. *Materials*, 17(17), P. 4279. https://doi.org/10.3390/ma17174279

Albrka, S.I., 2018. Evaluation of the performance of asphalt binder modified with nanoparticles. *Trends in Civil Engineering and Its Architecture*, 1(1). https://doi.org/10.32474/tceia.2018.01.000104

Ali, M., Albayati, A.H. and Wang, Y., 2023. A review of interface bonding testing techniques. *Journal of Engineering*, 29(09), pp. 14–30. https://doi.org/10.31026/j.eng.2023.09.02

Ali, S.I.A., Ismail, A., Karim, M.R., Yusoff, N.I.M., Al-Mansob, R.A. and Aburkaba, E., 2016b. Performance evaluation of Al_2O_3 nanoparticle-modified asphalt binder. *Road Materials and Pavement Design*, 18(6), pp. 1251–1268. https://doi.org/10.1080/14680629.2016.1208621

Ali, S.I.A., Ismail, A., Yusoff, N.I.M., Hassan, N.A. and Ibrahim, A.N.H., 2016a. Characterization of the performance of aluminum oxide nanoparticles modified asphalt binder. *Journal Teknologi*, 78(4). https://doi.org/10.11113/jt.v78.8003

Aljbouri, H.J. and Albayati, A.H., 2023. Effect of nanomaterials on the durability of hot mix asphalt. *Transportation Engineering*, 11, P. 100165. https://doi.org/10.1016/j.treng.2023.100165

Ameri, M., Nowbakht, S., Molayem, M. and Aliha, M.R.M., 2016. Investigation of fatigue and fracture properties of asphalt mixtures modified with carbon nanotubes. *Fatigue & Fracture of Engineering Materials & Structures*, 39, pp. 896–906. https://doi.org/10.1111/ffe.12408

Amin, I., El-Badawy, S.M., Breakah, T. and Ibrahim, M.H., 2016. Laboratory evaluation of asphalt binder modified with carbon nanotubes for Egyptian climate. *Construction and Building Materials*, 121, pp. 361–372. https://doi.org/10.1016/j.conbuildmat.2016.05.168

Amini, N. and Hayati, P., 2020. Effects of CuO nanoparticles as phase change material on chemical, thermal and mechanical properties of asphalt binder and mixture. *Construction and Building Materials,* 251, P. 118996. https://doi.org/10.1016/j.conbuildmat.2020.118996

Arabani, M. and Faramarzi, M., 2015. Characterization of CNTs-modified HMA's mechanical properties. *Construction and Building Materials*, 83, pp. 207–215. https://doi.org/10.1016/j.conbuildmat.2015.03.035

Ashish, P.K. and Singh, D., 2018. High and intermediate temperature performance of asphalt binder containing carbon nanotube using different rheological approaches. *Journal of Materials in Civil Engineering*, 30(1), P. 04017254. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002106

Ashish, P.K. and Singh, D., 2021. Performance-based laboratory evaluation of asphaltic mixture containing asphalt binder-carbon nanotube composite. *Road Materials and Pavement Design*, 23(6), pp. 1370–1389. https://doi.org/10.1080/14680629.2021.1888779

ASTM D1559-89, 1989. Test method for resistance of plastic flow of bituminous mixtures using Marshall apparatus (withdrawn 1998). ASTM International, West Conshohocken, PA, USA.

ASTM D8225-19, 2019. Standard test method for determination of cracking tolerance index of asphalt mixture using the indirect tensile cracking test at intermediate temperature. ASTM International, West Conshohocken, PA, USA.

Bala, N., Napiah, M. and Kamaruddin, I., 2018. Effect of nano silica particles on polypropylene polymer modified asphalt mixture performance*. Case Studies in Construction Materials*, 8, pp. 447–454.

Bhat, F.S. and Mir, M.S., 2020. Investigating the effects of nano Al_2O_3 on high and intermediate temperature performance properties of asphalt binder. *Road Materials and Pavement Design*, 22(11), pp. 2604–2625. https://doi.org/10.1080/14680629.2020.1778509

Cao, Y., Liu, Z. and Song, W., 2022. Performance and overall evaluation of nano-alumina-modified asphalt mixture. *Nanotechnology Reviews*, 11(1), pp. 2891–2902. https://doi.org/10.1515/ntrev-2022-0485

Cheng, D., Little, D., Lytton, R. and Holste, J., 2002. Surface energy measurement of asphalt and its application to predicting fatigue and healing in asphalt mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 1810, pp. 44–53.

Crucho, J.M.L., Neves, J.M.C., Capitão, S.D. and Picado-Santos, L.G., 2018. Mechanical performance of asphalt concrete modified with nanoparticles: nanosilica, zero-valent iron and nanoclay. *Construction and Building Materials*, 181, pp. 309–318. https://doi.org/10.1016/j.conbuildmat.2018.06.052

De Melo, J.V.S., Trichês, G. and Rosso, L.T., 2018. Experimental evaluation of the influence of reinforcement with multi-walled carbon nanotubes (MWCNTs) on the properties and fatigue life of hot mix asphalt. *Construction and Building Materials*, 162, pp. 369–382. https://doi.org/10.1016/j.conbuildmat.2017.12.033

Diab, A., You, Z., Hossain, Z. and Zaman, M., 2014. Moisture susceptibility evaluation of nanosized hydrated lime–modified asphalt–aggregate systems based on surface free energy concept. *Transportation Research Record*, 2446(1), pp. 52–59. https://doi.org/10.3141/2446-06

Eisa, M.S., Mohamady, A., Basiouny, M.E., Abdulhamid, A. and Kim, J.R., 2022. Mechanical properties of asphalt concrete modified with carbon nanotubes (CNTs). *Case Studies in Construction Materials*, 16, e00930. https://doi.org/10.1016/j.cscm.2022.e00930

Enieb, M. and Diab, A., 2017. Characteristics of asphalt binder and mixture containing nanosilica. International *Journal of Pavement Research and Technology*, 10(2), pp. 148–157. https://doi.org/10.1016/j.ijprt.2016.11.009

Ezzat, H., El-Badawy, S., Gabr, A., Zaki, S. and Breakah, T., 2018. Predicted performance of hot mix asphalt modified with nano-montmorillonite and nano-silicon dioxide based on Egyptian conditions. *International Journal of Pavement Engineering*, 21(5), pp. 642–652. https://doi.org/10.1080/10298436.2018.1502437

Fang, C., Yu, R., Liu, S. and Li, Y., 2013. Nanomaterials applied in asphalt modification*: A review. Journal of Materials Science & Technology*, 29(7), pp. 589–594. https://doi.org/10.1016/j.jmst.2013.04.008

Faramarzi, M., Arabani, M., Haghi, A. and Mottaghitalab, V., 2013. A study on the effects of CNTs on hot mix asphalt Marshal parameters. Unpublished manuscript.

Faramarzi, M., Arabani, M., Haghi, A. and Mottaghitalab, V., 2015. Carbon nanotubes-modified asphalt binder: Preparation and characterization. *International Journal of Pavement Research and Technology*, 8(1), pp. 29–37. https://doi.org/10.6135/ijprt.org.tw/2015.8(1).29

Fini, E.H., Hajikarimi, P., Rahi, M. and Nejad, F.M., 2015. Physiochemical, rheological, and oxidative aging characteristics of asphalt binder in the presence of mesoporous silica nanoparticles. *Journal of Materials in Civil Engineering*, 28(2). https://doi.org/10.1061/(ASCE)MT.1943-5533.0001423

Ghaffarpour, S. and Ahmadi, N., 2011. Engineering properties of nanoclay modified asphalt concrete mixtures. *International Journal of Earth Sciences and Engineering*, 4(6), pp. 941–944.

Gilani, N.M.M., Hosseinian, S.M., Safari, D. and others, 2021. Investigation of the impact of deicer materials on thermodynamic parameters and its relationship with moisture susceptibility in modified asphalt mixtures by carbon nanotube. *Arabian Journal for Science and Engineering*, 46, pp. 4489–4502. https://doi.org/10.1007/s13369-020-05000-9

Hamedi, G.H. and Esmaeili, N., 2018. Investigating of the effects of nano-materials on the moisture susceptibility of asphalt mixtures containing glass cullets. *AUT Journal of Civil Engineering*, 3(1), pp. 107–118. https://doi.org/10.22060/ajce.2018.14665.5492

Hamedi, G.H., Moghadas Nejad, F. and Oveisi, K., 2015. Investigating the effects of using nanomaterials on moisture damage of HMA. *Road Materials and Pavement Design*, 16(3), pp. 536–552.

Haq, M.F.U., Ahmad, N., Nasir, M.A., Jamal, H., Rafi, J., Zaidi, S.B.A. and Haroon, W., 2018. Carbon nanotubes (CNTs) in asphalt binder: *Homogeneous dispersion and performance enhancement. Applied Sciences,* 8(12), p.2651. https://doi.org/10.3390/app8122651

Hart, L.D., 1990. Alumina Chemicals: Science and Technology Handbook. Columbus, OH: American Ceramic Society.

Hasan, Z., Kamran, R., Mohammad, F., Ahmad, G. and Hosein, F., 2012. Evaluation of different conditions on the mixing bitumen and carbon nanotubes. *International Journal of Civil and Environmental Engineering*, 12(6), pp. 53–63.

Hasaninia, M. and Haddadi, F., 2017. The characteristics of hot mixed asphalt modified by nanosilica. *Petroleum Science and Technology*, 35(4), pp. 351–359. https://doi.org/10.1080/10916466.2016.1258412

Hintz, C., 2012. Understanding mechanisms leading to asphalt binder fatigue. PhD thesis. University of Wisconsin-Madison.

Husain, Z. and Husain, M., 2005. Carbon nanotube and its possible applications. Indian Journal of Engineering and Materials Sciences, 12, pp. 529–551.

Huseien, G.F., Nur, N. and Mirza, J., 2022. *Nanotechnology for Smart Concrete*. CRC Press.

Ismael, M.Q. and Ahmed, A.H., 2019. Effect of hydrated lime on moisture susceptibility of asphalt mixtures. *Journal of Engineering,* 25(3), pp. 89–101. https://doi.org/10.31026/j.eng.2019.03.08

Ismael, M.Q., Fattah, M.Y. and Jasim, A.F., 2021. Improving the rutting resistance of asphalt pavement modified with the carbon nanotubes additive. *Ain Shams Engineering Journal*, 12(4), pp. 3619–3627. https://doi.org/10.1016/j.asej.2021.02.038

Karahancer, S., 2020. Effect of aluminum oxide nanoparticle on modified bitumen and hot mix asphalt. *Petroleum Science and Technology*, 38(13), pp. 773–784. https://doi.org/10.1080/10916466.2020.1783292

Keymanesh, M.R., Ziari, H., Damyar, B. and Shahriari, N., 2017. Effect of waste EVA (Ethylene Vinyl Acetate) and waste CR (Crumb Rubber) on characteristics of bitumen. *Petroleum Science and Technology*, 35(22), pp. 2121–2126. https://doi.org/10.1080/10916466.2017.1384840

Khattak, M.J., Khattab, A. and Rizvi, H.R., 2013. Characterization of carbon nano-fiber modified hot mix asphalt mixtures. *Construction and Building Materials*, 40, pp. 738–745.

Khudhur, S., Hussein, T. and Khoshnaw, G., 2021. Impact of nano materials on the properties of asphalt cement. *Eurasian Journal of Science and Engineering*, 7(1). https://doi.org/10.23918/eajse.v7i1p155

Lakes, R.S., 2009. *Viscoelastic materials*. Cambridge: Cambridge University Press.

Latifi, H. and Hayati, P., 2018. Evaluating the effects of the wet and simple processes for including carbon nanotube modifier in hot mix asphalt. *Construction and Building Materials*, 164, pp. 326–336. https://doi.org/10.1016/j.conbuildmat.2017.12.237

Le, V.B. and Le, V.P., 2021. Performance evaluation of carbon nanotubes as a binder modifier for asphalt mixtures. *International Journal of Civil Engineering*, 19, pp. 1143–1153. https://doi.org/10.1007/s40999-020-00599-0

Leiva-Villacorta, F. and Vargas-Nordcbeck, A., 2017. Optimum content of nano-silica to ensure proper performance of an asphalt binder. *Road Materials and Pavement Design*, 20(2), pp. 414–425. https://doi.org/10.1080/14680629.2017.1385510

Lotfi-Eghlim, A. and Karimi, M.S., 2016. Fatigue behavior of hot mix asphalt modified with nano Al_2O_3 – an experimental study. *Advances in Science and Technology Research Journal*, 10(31), pp. 58–63. https://doi.org/10.12913/22998624/64011

Mamuye, Y., Do, N.D. and Liao, M.C., 2022. Nano-Al_2O_3 composite on intermediate and high temperature properties of neat and modified asphalt binders and their effect on hot mix asphalt mixtures. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4017442

Mansourkhaki, A. and Aghasi, A., 2019. Low-temperature fracture resistance of asphalt mixtures modified with carbon nanotubes. *Proceedings of the Institution of Civil Engineers - Transport*, 174, pp. 1–25. https://doi.org/10.1680/jtran.18.00165

McGennis, R.B., Shuler, S. and Bahia, H.U., 1994. Background of Superpave asphalt binder test methods. Washington, DC: Federal Highway Administration, Office of Technology Applications.

Mirhosseini, A.F., Kavussi, A., Kamali, M.H.J., Khabiri, M. and Hassani, A., 2017. Evaluating fatigue behavior of asphalt binders and mixes containing Date Seed Ash. *Journal of Civil Engineering and Management*, 23(8), pp. 1164–1175.

Moeini, A.R., Badiei, A. and Rashidi, A.M., 2019. Effect of nanosilica morphology on modification of asphalt binder. *Road Materials and Pavement Design*, 21(8), pp. 2230–2246. https://doi.org/10.1080/14680629.2019.1602072

Mohammed, A.M. and Abed, A.H., 2023. Enhancing asphalt binder performance through nano-SiO2 and nano-CaCO3 additives: Rheological and physical insights. *Case Studies in Construction Materials*, 19, e02492. https://doi.org/10.1016/j.cscm.2023.e02492

Mohammed, F.A., Latief, R.H. and Albayati, A.H., 2024. Assessment of traditional asphalt mixture performance using natural asphalt from sulfur springs. *Journal of Engineering*, 30(01), pp. 54–73. https://doi.org/10.31026/j.eng.2024.01.04

Morshed, M., Atiyah, A.A. and Al-Jadiri, R., 2019. Predicting the effect of adding the nanoalumina on the characterization of asphalt base composite. *International Journal of Civil Engineering and Technology*, 10, pp. 1418–1430.

Motamedi, M., Shafabakhsh, G. and Azadi, M., 2021. Rehabilitation of asphalt binder to improve rutting, fatigue and thermal cracking behavior using nano-silica and synthesized polyurethane. *Journal of Rehabilitation in Civil Engineering*, 9(1), pp. 19–28. https://doi.org/10.22075/jrce.2019.17579.1335

Mubaraki, M., Ali, S.I.A., Ismail, A. and Yusoff, N.I.M., 2016. Rheological evaluation of asphalt cements modified with ASA polymer and Al_2O_3 nanoparticles. *Procedia Engineering*, 143, pp. 1276–1284. https://doi.org/10.1016/j.proeng.2016.06.135

Napierska, D., Thomassen, L.C.J., Lison, D., Martens, J.A. and Hoet, P.H., 2010. The nanosilica hazard: another variable entity. *Particle and Fibre Toxicology*, 7, pp. 1–32.

Nazari, H., Naderi, K. and Nejad, F.M., 2018. Improving aging resistance and fatigue performance of asphalt binders using inorganic nanoparticles. *Construction and Building Materials*, 170, pp. 591–602. https://doi.org/10.1016/j.conbuildmat.2018.03.107

Nejad, F.M., Tanzadeh, R., Tanzadeh, J. and Hamedi, G.H., 2014. Investigating the effect of nanoparticles on the rutting behaviour of hot-mix asphalt. *International Journal of Pavement Engineering*, 17(4), pp. 353–362. https://doi.org/10.1080/10298436.2014.993194

Oda, A.W., El-Desouky, A., Mahdy, H. and Moussa, O.M., 2020. Effects of asphalt modification by nanosilica and nanoclay on asphalt binder and hot mix asphalt properties. IOP Conference Series: *Materials Science and Engineering*, 974(1), P. 012003. https://doi.org/10.1088/1757-899x/974/1/012003

Piriyawong, V., Thongpoo, V., Asanithi, P. and Limsuwan, P., 2012. Preparation and characterization of alumina nanoparticles in deionized water using laser ablation technique. *Journal of Nanomaterials*, 2012, Article ID 819403, 6 pages.

Poole, C.P. and Owens, F.J., 2003. *Introduction to nanotechnology*. Hoboken: Wiley, pp. 145–150.

Qassim, Z., Al-Sahaf, N. and Al-jameel, H., 2022. Effectiveness of micro-and nano-silica as modifiers in asphalt concrete mixture. Unpublished manuscript.

Rafique, M.M.A. and Iqbal, J., 2011. Production of carbon nanotubes by different routes – a review. Journal of Encapsulation and Adsorption Sciences, 1, pp. 29–34.

Rasheed, S.S., Joni, H.H. and Al-Rubaee, R.H., 2023. Enhancement of physical properties of asphalt binder by using silica powder. *E3S Web of Conferences*, 427, P. 03031. https://doi.org/10.1051/e3sconf/202342703031

Saboo, N. and Kumar, P., 2016. Performance characterization of polymer modified asphalt binders and mixes. *Advances in Civil Engineering*, 2016, Article ID 5938270. https://doi.org/10.1155/2016/5938270

Sadeghnejad, M. and Shafabakhsh, G., 2017. Experimental study on the physical and rheological properties of bitumen modified with different nano materials (Nano SiO_2 & Nano TiO_2). International *Journal of Nanoscience and Nanotechnology*, 13(3), pp. 253–263.

Safaei, F., Castorena, C. and Kim, Y.R., 2016. Linking asphalt binder fatigue to asphalt mixture fatigue performance using viscoelastic continuum damage modeling. Mechanics of Time-Dependent *Materials*, 20, pp. 299–323. https://doi.org/10.1007/s11043-016-9304-1

Safaei, F., Lee, J.S., Nascimento, L.A.H., Hintz, C. and Kim, Y.R., 2014. Implications of warm-mix asphalt on long-term oxidative aging and fatigue performance of asphalt binders and mixtures. Road *Materials and Pavement Design,* 15(Sup1), pp. 45–61. https://doi.org/10.1080/14680629.2014.927050

Saito, R., Hofmann, M., Dresselhaus, G., Jorio, A. and Dresselhaus, M.S., 2011. Raman spectroscopy of graphene and carbon nanotubes. Advances in Physics, 60(3), pp. 413–550.

Saltan, M., Terzi, S. and Karahancer, S., 2017. Examination of hot mix asphalt and binder performance modified with nano silica. *Construction and Building Materials*, 156, pp. 976–984. https://doi.org/10.1016/j.conbuildmat.2017.09.069

Santagata, E., Baglieri, O., Riviera, P.P. and Alam, M., 2017. Correlating creep properties of bituminous binders with anti-rutting performance of corresponding mixtures. *International Journal of Pavement Research and Technology*, 10(1), pp. 38–44. https://doi.org/10.1016/j.ijprt.2016.11.008

Sarsam, S.I. and Allamy, A.K.J., 2016. Fatigue behavior of modified asphalt concrete pavement. *Journal of Engineering*, 22(2), pp. 1–10. https://doi.org/10.31026/j.eng.2016.02.01

Shafabakhsh, G., Motamedi, M., Firouznia, M. and Isazadeh, M., 2019a. Experimental investigation of the effect of asphalt binder modified with nanosilica on the rutting, fatigue and performance grade. *Petroleum Science and Technology*, 37(13), pp. 1495–1500. https://doi.org/10.1080/10916466.2018.1476534

Shafabakhsh, G., Rajabi, M. and Sahaf, A., 2019b. The fatigue behavior of SBS/nanosilica composite modified asphalt binder and mixture. *Construction and Building Materials*, 229, P. 116796. https://doi.org/10.1016/j.conbuildmat.2019.116796

Shafabakhsh, G.A., Sadeghnejad, M., Ahoor, B. and Taheri, E., 2020. Laboratory experiment on the effect of nano SiO_2 and TiO_2 on short and long-term aging behavior of bitumen. *Construction and Building Materials*, 237, P. 117640. https://doi.org/10.1016/j.conbuildmat.2019.117640

Shah, P.M. and Mir, M.S., 2021. Investigating the influence of carbon nanotube on the performance of asphalt binder. *Progress in Rubber Plastics and Recycling Technology*, 37(4), pp. 422–440. https://doi.org/10.1177/14777606211019413

Shi, X., Cai, L., Xu, W., Fan, J. and Wang, X., 2018. Effects of nano-silica and rock asphalt on rheological properties of modified bitumen. *Construction and Building Materials*, 161, pp. 705–714.

Song, W., 2023. Study on the high and low temperature performance of nano alumina modified asphalt mixture. *International Journal of Microstructure and Materials Properties*, 16(4), pp. 229–238.

Taher, Z.K. and Ismael, M.Q., 2022. Rutting prediction of hot mix asphalt mixtures modified by nano silica and subjected to aging process. *Civil Engineering Journal*, 9, pp. 1–14. https://doi.org/10.28991/cej-sp2023-09-01

Taher, Z.K. and Ismael, M.Q., 2023. Moisture susceptibility of hot mix asphalt mixtures modified by nano silica and subjected to aging process. *Journal of Engineering*, 29(4), pp. 128–143. https://doi.org/10.31026/j.eng.2023.04.09

Taherkhani, H. and Afroozi, S., 2017. Investigating the performance characteristics of asphaltic concrete containing nano-silica. *Civil Engineering Infrastructures Journal*, 50(1), pp. 75–93. https://doi.org/10.7508/ceij.2017.01.005

Taherkhani, H. and Tajdini, M., 2019. Comparing the effects of nano-silica and hydrated lime on the properties of asphalt concrete. *Construction and Building Materials*, 218, pp. 308–315. https://doi.org/10.1016/j.conbuildmat.2019.05.116

Wen, H., 2001. Fatigue performance evaluation of WesTrack asphalt mixtures based on viscoelastic analysis of indirect tensile test. PhD thesis. NC State University, Raleigh.

Whatmore, R.W. and Corbett, J., 1995. Nanotechnology in the marketplace. *Computers and Control Engineering Journal*, 6(1), pp. 106.

Xiao, F., Amirkhanian, S. and Juang, C.H., 2009. Prediction of fatigue life of rubberized asphalt concrete mixtures containing reclaimed asphalt pavement using artificial neural networks. *Journal of Materials in Civil Engineering*, 21(6), pp. 253–261.

Yoo, J. and Al-Qadi, I., 2010. A strain-controlled hot-mix asphalt fatigue model considering low and high cycles. *International Journal of Pavement Engineering*, 11(6), pp. 565–574. https://doi.org/10.1080/10298436.2010.488738

Zafari, F., Mahmoudi, S., Naji, H. and Bayat, M., 2014. The improvement of bitumen properties by adding nanoSilica. *Study of Civil Engineering and Architecture*, 3, pp. 62–69.

Zahedi, M., Barati, M. and Zarei, M., 2017. Evaluation the effect of carbon nanotube on the rheological and mechanical properties of bitumen and hot mix asphalt (HMA). *Electronic Journal of Structural Engineering*, 17, pp. 76–84. https://doi.org/10.56748/ejse.17221

Zghair, H., Joni, H. and Hassan, M., 2020. Rheological Characteristics of Nano Silica Modified Asphalt Binder Material. In: 2020 IEEE Conference Proceedings. IEEE. https://doi.org/10.1109/IEC

Zhu, W., Bartos, P. and Porro, A., 2004. Application of nanotechnology in construction. *Materials and Structures*, 37, pp. 649–658. https://doi.org/10.1007/BF02483294

Ziari, H., Farahani, H., Goli, A. and Akbari, T., 2014a. The effect of carbon nano-tube on the fatigue life of asphalt mixtures. *International Journal of Transportation Engineering*, 2(1), pp. 81–96. https://doi.org/10.22119/ijte.2014.6710

Ziari, H., Farahani, H., Goli, A. and Sadeghpour Galooyak, S., 2014b. The investigation of the impact of carbon nanotube on bitumen and HMA performance. *Petroleum Science and Technology*, 32(17), pp. 2102–2108. https://doi.org/10.1080/10916466.2013.763827.

تأثير المواد النانوية المحسنة على مقاومة الكلل في الخرسانة الاسفلتية المسلحة: ورقة مراجعة

علي محمود الحمدو*، امجد حمد البياتي

قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

يُعدّ تعزيز مقاومة الكلل في المواد الإسفلتية ومخاليطها أمرًا بالغ الأهمية لإطالة الكلل للتبليط وتحسين أدائه. وقد أدخلت التطورات الحديثة في تكنولوجيا النانو مواد نانوية متنوعة، مثل نانو الألومينا (NA) وأنابيب الكربون النانوية (CNTs) ونانو السيليكا (NS)، كمُعدِّلات محتملة للإسفلت. تتميز هذه المواد بخصائص فريدة تُعالج التحديات المتعلقة بظاهرة الكلل في الإسفلت. ومع ذلك، تعتمد فعاليتها على تقنيات التشتت والخلط المناسبة. يدرس هذا البحث مراجعة طرق الخلط المستخدمة لكل مادة نانوية لضمان توزيع موحد داخل مصفوفة الإسفلت وتعظيم فوائد الأداء. وقد تم تجميع نتائج الأبحاث الحديثة لتوضيح كيفية تعزيز هذه المواد النانوية وعمليات خلطها للخواص الميكانيكية والمتانة والأداء العام للرصف. وتشير الأدلة إلى أن دمج المواد النانوية جيدة التشتت يُحسّن بشكل كبير من مقاومة الكلل، مما يؤدي إلى تقليل التشقق وإطالة عمر التبليط. وخلصت المراجعة إلى أن دمج تكنولوجيا النانو مع استراتيجيات الخلط الفعالة يمثل نهجًا واعدًا لتطوير تكنولوجيا الأسفلت، وتحسين الأداء في ظل الظروف البيئية المتنوعة، وتمهيد الطريق لبنية تحتية أكثر مرونة.

الكلمات المفتاحية: مقاومة الكلل، مواد النانوية، نانو سليكا، نانو الألمنيوم، أنابيب الكاربون النانوية.