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Original article

Rutting and fatigue behavior of neat and nanomodified asphalt mixture with SiO_2 and TiO_2

Ahmed Mahir Mohammed [a,*], Alaa H. Abed [b]

[a] Civil Engineering Department , University of Baghdad, Baghdad, Iraq
[b] Civil Engineering Department, Al-Nahrain University, Baghdad, Iraq

A R T I C L E I N F O

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A B S T R A C T

Modern asphalt technology has adopted nanomaterials as an alternative option to assert that asphalt pavement can survive harsh climates and repeated heavy axle loading during service life and prolong pavement life. This work aims to elucidate the behavior of the modified asphalt mixture fracture model and assess the fatigue and Rutting performance of Hot Mix Asphalt (HMA) mixes using the outcomes of indirect Tensile Strength (IDT), Semicircular bend (SCB) and rutting resistance; for this, a single PG (64−16) nanomodified asphalt binder with 5 % SiO_2 and TiO_2 have been investigated through a series of laboratory tests, including: Resilient modulus, Creep compliance, and tensile strength, SCB, and Flow Number (FN) to study their potential role of these nanomaterials to improve the rutting characteristics and fatigue life of wearing asphalt mixture at different temperatures. The outcome of this study revealed the positive role of these materials in enhancing mixture IDT characteristics, fracture energy, and viscoelastic deformation component of crack propagation; on the other hand, at higher temperatures, the modified mixture exhibited a superior performance in reducing the permanent deformation of asphalt mixture with SiO_2 followed by TiO_2 as compared to neat asphalt mixture.

1. Introduction

The issue of long pavement life has been given priority by researchers who have spent a lot of time, effort, and money. In recent years, researchers have widely suggested that the process of asphalt modification techniques overcome the failure that occurred during the production and construction of pavement roads. On the other hand, waste materials employed in pavement porous concretes, such as recycled crushed glass (RCG), steel slag, steel fiber, tires, plastics, and recycled asphalt, have all been studied in this work, and their corresponding mechanical, durability, and permeability functions. The use of waste materials in the partial replacement of cement will lower the cost of producing concrete. Additionally, the mechanical properties of concrete have a little impact on the removal of faults caused by the disposal of waste materials and the use of cement in the creation of Portland cement (PC). Different industrial wastes have substituted cement in PC manufacture, however the types of waste materials used have affected the PC permeability mixtures, split tensile strength, compressive strength, and flexural strength, Toghroli et al. [1]. Of these modification techniques, polymer modification [2,3], nanomaterial modification [4], crumb rubber [5], glass and polypropylene fibers [6] and [7], are still used and innovative to improve the performance of asphalt pavement materials. Related to this study's scope, Different nanomaterial types and sizes such as Nano: lime, silica, clay, calcium carbonate, titanium dioxide, and others have gained their benefit as essential additives for Hot Asphalt Mixture (HMA). SiO_2 and TiO_2 are mainly considered inorganic nanoparticles and have recently proven their ability to improve asphalt binder performance. Yao et al. [8] revealed that using 4 and 6 % Nano-SiO_2 as a binder modifier in SBS-modified will gain Asphalt fatigue cracking, delayed anti-oxidation and improved rutting, heightened viscosity, and temperature sensitivity at higher temperatures [9]. Shafabakhsh and Ani [10] studied the mechanical and rheological properties of asphalt modified with nanoTiO_2/SiO_2 composite. The modification reduced the sensitivity of asphalt to stress and prevented the formation and spread of tensile and vertical cracks. Shafabakhsh and Rajabi [11] conducted a study on the impact of SiO_2/SBS composite on the fatigue life of asphalt. They discovered that the fatigue life of this composite is 2–5 times longer than that of SBS polymer-modified asphalt. Albayati et al. [12] suggested an optimal performance of Nano CaCO3 and Nano Hydrated Lime at rate within 4 and 6 % that will

* Corresponding author.
E-mail addresses: ahmed.m.886@coeng.uobaghdad.edu.iq (A.M. Mohammed), Alaa.abed@eng.nahrainuniv.edu.iq (A.H. Abed).

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gain a significant improvement on physical and rheological properties of 40–50 penetration grade and these improvement will contribute to gain in Marshall stability, suppress resilient modulus, TSR values and increase resistance towards fatigue cracking. After that, Albayati et al. [13] compare the behavior of two nano types and conclude that 6 % Calcined Nano Montmorillonite and 4 % natural Nano Montmorillonite has impacted the stiffness of asphalt binder, increase the stability up to 15 %,enhance rutting resistance and reduce the fatigue cracking in terms of CTindex, as compared to neat asphalt. Besides these benefits, TiO_2 helps to improve the rheology of binder performance alongside SBS by increasing the asphalt stiffness, better aging resistance, enhanced elasticity, and recovery [14]. Increases the energy to produce cohesion cracking and wettability, facilitates the bonding between the asphalt binder and the aggregate, and reduces the amount of de-bonding Azarhoosh et al. [15,16] gap the lack of knowledge between the SHRP grading system to discover the effect of combined fatigue and aging on nanomodified asphalt with SiO_2, $TiO_{2,}$ and $CaCO_3$ using frequency sweep test and LAS presenting a superior development in fatigue performance, Antioxidant that finally related to branching and crack arrests which absorb energy and cause damage area to diminish, this funding also confirmed by Filho et al. [17] using standard testing, linear amplitude sweep, and repeated stress creep recovery, they discovered that nano-TiO_2 might increase fatigue resistance and later in Filho et al. [17] and his coworkers and [18] concluded that the addition of nano--TiO_2 showed a delay in the aging of asphalt. Considering nanomodified asphalt binder unique characteristics in HMA mixtures, [19], overview that HMA mixture modified with TiO_2/$CaCO_3$ can promote stiffness modulus and rutting resistance under static creep test. In another study by [20,21], the low-temperature cracking and related fatigue phenomena could be resisted with nano-SiO2 using SCB under mixed mode I/II. Also, [22], how found that using polyvinyl chloride (PVC) and nano silica (NS) as a modifier has gained SMA mixture higher marshall stability and rutting resistance at a rate of 5 % PVC and 1 % NS. Furthermore, a comprehensive examination of the nano modifications was conducted by [23], which considered all mechanical performance indicators (stiffness, fatigue, permanent deformation, and water sensitivity). The results indicated that the silica modification exhibited the highest overall performance, precisely elastic behavior in terms of fatigue life and stiffness by means of permanent deformation. It has been shown from the literature above that extensive research deals with the evaluation of nanomaterials based on rheological testing or extending the benefit of binder into mixture performance with traditional tests. So, there is a lack of knowledge to determine the influence, role, behavior, and healing effect on the combined effect on cracking behavior, propagation, and anti-rutting criteria based on Flow Number. Much research has contributed to IDT fracture mechanism. A visco-elastic fracture mechanics-based cracking model, recently developed at the University of Florida [24,25], was used to assess the cracking performances of the mixes. Based on this framework, it was discovered that the five tensile mixture properties—the m-value, the resilient modulus, the creep compliance, the dissipated creep strain energy to failure, and the total energy to fracture—that are readily obtained from the Superpave Indirect Tensile Test (IDT) are sufficient to regulate the cracking performances of asphalt mixtures; based on the outcome testing result, Several studies used SBS polymer [26] binder grade and aggregate gradation [27] recycled asphalt concrete [28,29] and hydrated lime [30] as possible enhancement factors to improve dissipated creep strain energy based on the theory that microcrack damage is completely reparable up until the development of micro cracks. Dissipated Creep Strain Energy (DCSE) was discovered to be independent of both monotonic and cyclic loading modes, and it was thought to constitute a threshold for microdamage that may recover. When this limit is surpassed during loading, macrocracks will form and expand. Therefore, high DCSE values are required for mixes resistant to fracture initiation, as DCSE theoretically assesses a material's resistance to crack initiation. [24], emphasize that the DCSE to failure is independent of the loading mode and may be utilized as a threshold to explain discrepancies between field and lab results, for this they proposed two potential causes of fracture illustrated in Fig. 1:(1) Continuous, repeated loads can accumulate damage because of creep strain energy, and fracture can occur if the DCSE threshold is achieved when the loading stress is below the tensile strength. It should be emphasized that fracture may occur if any large single load surpasses the FE threshold. (2) The mixture may not break if the healing keeps the induced-dissipated energy below the threshold, irrespective of the load repetitions. However, even if the DCSE is surpassed, cracking would not happen during a single load application unless the higher FE threshold is exceeded.

Other studies focused on SCB have a big advantage of correlating well with field loading in pavement and recently have received increasing attention and effort. As previously indicated, several studies examine nanomaterials' impact on the performance parameters of HMA mixes; nevertheless, the influence of nanomaterials on the fracture behavior of HMA mixtures has received very little attention. Thus, this work aimed to elucidate the behavior of the modified asphalt mixture fracture model and assess the fatigue performance of HMA mixes using the outcomes of IDT testing and SCB and rutting examine how modified HMA mixes with Nano SiO_2 and TiO_2

2. Aim of study

The main objective of this study is to determine the potential role of nanomodified asphalt binder with SiO_2 and TiO_2 in enhancing the tensile properties of asphalt mixtures and further benefits in improving IDT fracture parameters of HMA mixtures, cracking propagation with SCB and permanent deformation with flow Number.

3. Experimental investigations

The first part deals with modifying neat asphalt binder PG 64–16 with TiO_2 and SiO_2 at 5 % by weight of neat asphalt with a High Shear Mixer (HSM). The second part analyzes the effect of nanomodified asphalt binder within the HMA mixture. The Superpave-wearing asphalt course was conducted in a controlled laboratory setting. The laboratory testing included an IDT test via Resilient Modulus (Mr), creep Compliance (Dt), and finally, tensile strength (TS) beside semicircular bending (SCB) test and a Flow Number (FN).

3.1. *Material characterization and modification process*

Local paving materials were chosen to fabricate laboratory samples to simulate HMA combinations accurately in Iraq and compared to Standard Specification for Roads and Bridges **SCRB/R9 2003** [31] Revision limits. In this study, A single asphalt binder that meets Superpave specification PG (64−16) is listed in Table 1. A 12.5 mm nominal maximum size crushed quartz aggregate is widely used in Baghdad city for asphaltic mixes: coarse aggregate (5–12 and 5–12 mm) and fine aggregate (natural and crusher) presented in Tables 2 and 3 with limestone as a mineral filler. The selected gradation for the wearing course was presented in Fig. 2. Nano SiO_2 and TiO_2 were supplied by skyspring company -USA, which provides a variety of micro and nano materials used for versatile industries. Table 5 displays the unique properties of nano used in this study.

3.2. *Asphalt modification process and mixture design*

Neat asphalt binder PG (64−16) was modified with 5 % Nano material by weight of neat asphalt. The dry blending method uses HSM to disperse the nanomaterials in the asphalt binder matrix. Table 6 shows the selection of mixing/blending parameters of nanomodified asphalt binder. Then, the nanomaterial is added, and a shear mixing effect is applied for a specific period with the aid of HSM, distinguished from other mixers by the unique tip design, as presented in Fig. 3.

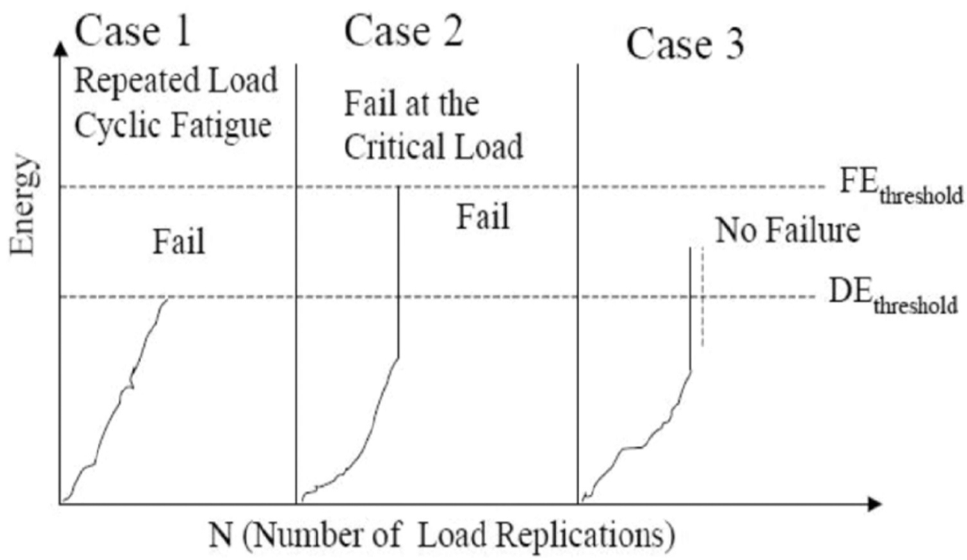

Fig. 1. potential loading condition [24].

Table 1
Asphalt Binder Specification of PG (64−16).

Property	Designation	Result	Temperature	AASHTO M320
		Original Test on Binder		
Rotational Viscosity, Pa.s.	AASHTO T 316	0.63	135 °C	Max. 3
		0.16	165 °C	————
		2.34	64 °C	Min.1
		0.84	70 °C	
Dynamic Shear Rheometer G*/Sinδ, kPa	AASHTO T 315		Tests on RTFO Residue	
		1.68	70 °C	Min 2.2
			Tests on PAV Residue	
		4266	25 °C	Max.5000
		3452	28 °C	
Creep Stiffness, Mpa	AASHTO T 313	241	−12°C	Max.300
Creep Slope		0.322	−12°C	Min. 0.3
Mass Loss, %	AASHTO T 240	0.61		Min.1

Table 2
Physical properties of coarse ag.

Property Bulk Specific gravity, (gm/cm^3)	Designation	Result		Specification
		5–12 mm	5–9 mm	
Apparent Specific gravity (gm/cm^3)	ASTM C127	2.627	2.618	————
		2.674	2.674	
Percent water absorption		0.66	0.797	
Percent Fractured Face	ASTM D5821	93	95	Min.90,%
		Consensus Properties		
Coarse Aggregate Angularity, %	ASTM D5821	97	98	Min. (95/90)
Flat and elongated particles	ASTM D4791	1.2	0.8	Max. 10, %
		Source Properties		
Los-Angeles Abrasion %	ASTM C131	21	15	Max.30, %
Soundness	ASTM C 88	3.71	2.81	Max.12, %
Clay Lumps and Friable Particles	ASTM C 124	0.57	0.82	Max.3, %

Fig. 4 presented the testing result of nanomodified asphalt with 5 % NS and NT based on the outcome of The rheological characteristics of the Dynamic Shear Rheometer (DSR) of the original and Rolling Thin

Table 3
Physical properties of fine aggregate.

Property	Designation	Result		Specification
		Crusher Sand	River Sand	
Bulk Specific gravity, (gm/cm^3)	ASTM C128	2.576	2.545	————
Apparent Specific gravity (gm/cm^3)		2.635	2.656	
Percent water absorption		0.854	1.647	
		Consensus Properties		
Fine Aggregate Angularity	ASTM D1252	60	49	Min. 45, %
Sand Equivalent	ASTM D2419	78	53	Max. 45, %

Film Oven (RTFO-aged) and Pressure Aging Vessel (PAV-aged) samples at an intermediate temperature. DSR test result indicated that the rutting factor after RTFO nano-modified asphalt with 5 % asphalt would satisfy the requirement specification and resist rutting at 82 and 76°C for NS and NT, respectively. This concludes that asphalt binder properties will be enhanced at this content and can be considered for further investigation as an optimal nano content for studying its primary effect on the HMA mixture.

Three different HMA mixtures in this laboratory were investigated: neat and two nanotypes.

The combined heated aggregate, neat, and nanomodified asphalt mixture were compacted using Superpave Gyratory Compactor (SGC) with varying amounts of asphalt binder. The mixture was made with a mechanical filling with the heated aggregates, the necessary amount of asphalt was added, and the mixture was stirred until the aggregates were evenly coated. In order to simulate short-term aging, the HMA mix was left for 2 hours in the oven at 145 °C and stirred for 30 minutes (**AASHTO R-30**) before compacting. The mixture volumetric properties following Superpave can be seen in Table 7.

3.3. IDT specimen preparation and test protocols

For the chosen HMA mixes, raw specimens with dimensions of 150 mm in diameter and 165 mm in height were initially formed on the necessary air void content (4 %) using a Troxler SGC. The results of

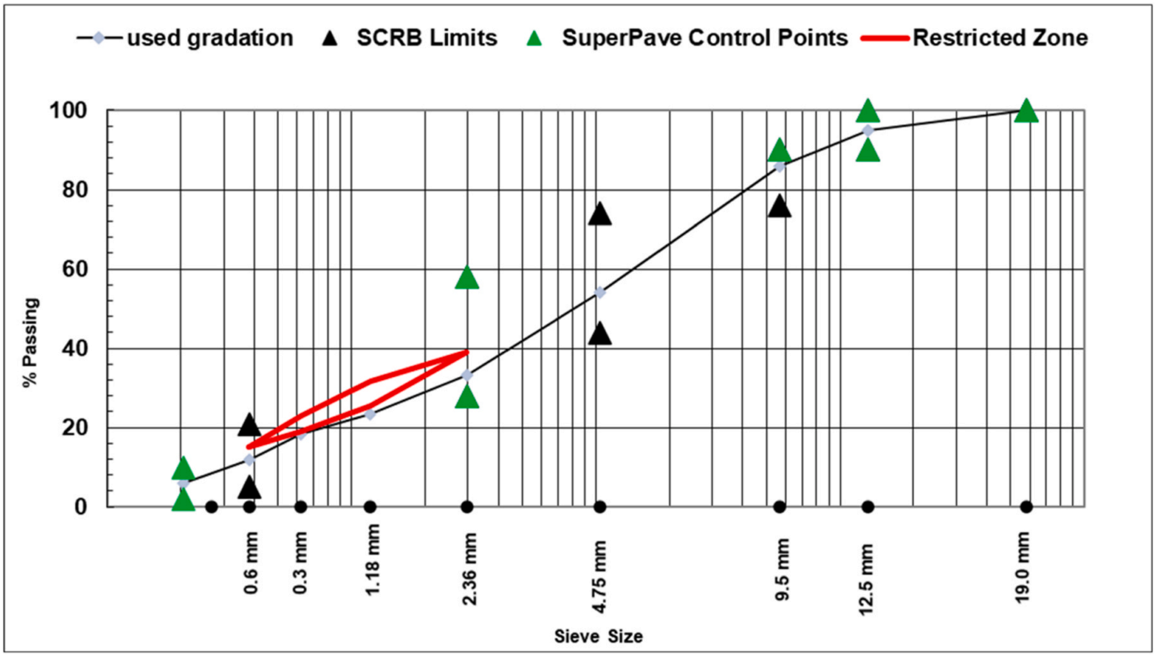

Fig. 2. Aggregate gradation.

Table 4
HMA mix used for this study.

Sieve Size	Gradation used	Job Mix Formula Tolerance			
		SCRB/ R9		Superpave	
Metric		Min	Max	Min	max
19.0 mm	100	100	100	100	100
12.5 mm	96	90	100	90	100
9.5 mm	89	76	90	-	90
4.75 mm	59	44	74	-	-
2.36 mm	38	28	58	28	58
1.18 mm	27	-	-	-	-
0.6 mm	22	-	-	-	-
0.3 mm	15	5	21	-	-
0.075 mm	7	4	10	2	10
Blending	Aggregate 5–12	Aggregate 5–9	Crusher Sand	River Sand	Limestone
%	8	29	45	12	6

Table 5
Physical properties of nanomaterial.

Properties	Nano-TiO_2	Nano-SiO_2
Appearance	white powder	white powder
Average Particle Size (nm)	10–30	15–20
True Density, g/cm^3	—	2.648
Specific Surface area: m^2/g	50–100	200–240
Purity	99.5 %	99.5 %
Solubility	Insoluble	Insoluble

Table 6
Dry blending configurations with HSM.

Nano Type	Coding	% Content	Temperature (oC)	Speed (rpm)	Duration (min.)
Nano Tio_2	NT	5	150–160	6000	45
Nano SiO_2	NS				

NCHRP 1–28 A" guided the sample preparation for the IDT test. Each test specimen had at least 6 mm sawed off of both sides in order to create smooth, parallel surfaces for installing the Linear Variable Displacement Transducer LVDT. After that, the testing specimen was sawed to the necessary thickness (three specimens out of each compacted pill, as shown in Fig. 5. For each HMA mixture, a, 150 mm in diameter by 50 mm thick test specimens underwent Mr, Dt, and TS tests.

Neat and nanomodified HMA mixtures were tested at a frequency of 1.0 Hz at varying temperatures of 5,15, 25, and 40 °C; all mixtures were tested with the aid of dynamic servo-hydraulic universal testing machine DTM-50, as exhibited in Fig. 6. Controlled target load limits to obtain horizontal strain within 0.038 and 0.089 mm to precisely assess the resilient modulus and Poisson's Ratio (ν) [32]. Metallic gauge points were glued at each sawed at a distance of 1/4 of the diameter. Each stress cycle consisted of a 0.1-second haversine pulse followed by a 0.9-second hold cycle. Based on a three-dimensional finite element analysis, Eqs. 1 and 2, created by Roque et al. [33] were used to derive the resilient modulus and the Poisson's Ratio.

$$\mathrm{Mr} = \frac{P \times GL}{\Delta H \times t \times D \times C_{CMPL}} \qquad (1)$$

$$\nu = -0.1 + 1.480 \times \left(\frac{\Delta H}{\Delta V}\right)^2 - 0.778 \times \left(\frac{t}{D}\right)^2 \times \left(\frac{\Delta H}{\Delta V}\right)^2 \qquad (2)$$

Since P: max. applied load,GL = gauge length, $\Delta H, V$ = horizontal and vertical deformation, t = specimen thickness, D = specimen diameter, C_{CMPL} = non-dimensional factor.

Like resilient modulus testing, the load was kept to produce horizontal deformation within limits at 100 seconds to keep the specimen without extreme permanent deformation. Creep compliance D (t) can be computed as:

$$D(t) = \frac{\Delta H \times t \times D \times C_{CMPL}}{P \times GL} \qquad (3)$$

Applying a power-law fitting curve to the logarithm creep compliance curve will yield the parameter D1 and m-value [34]. The creep

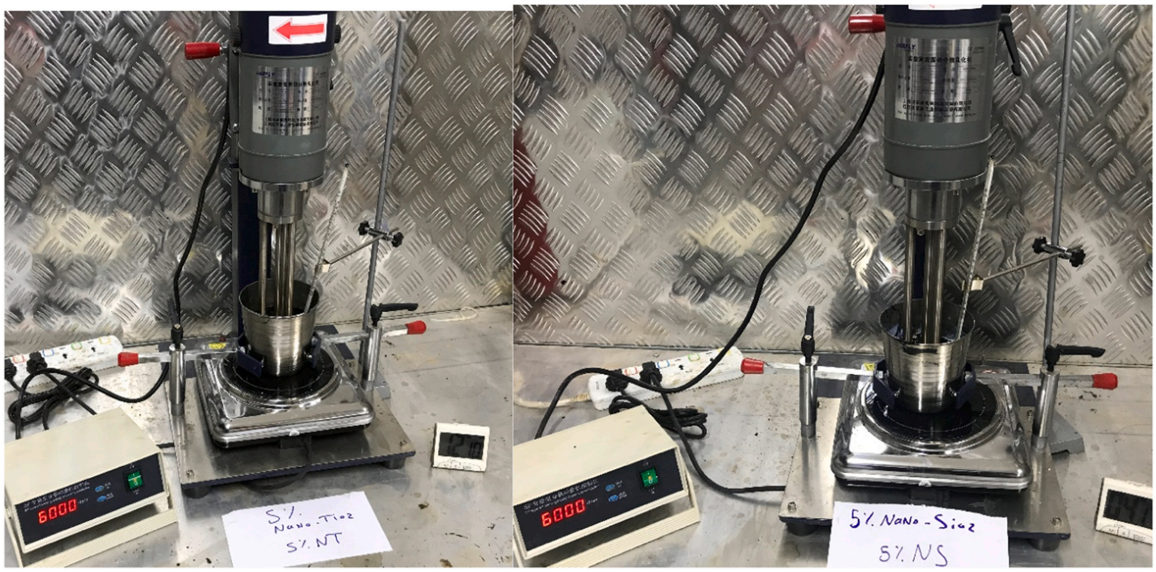

Fig. 3. Modification of asphalt binder with nanomaterial using HSM.

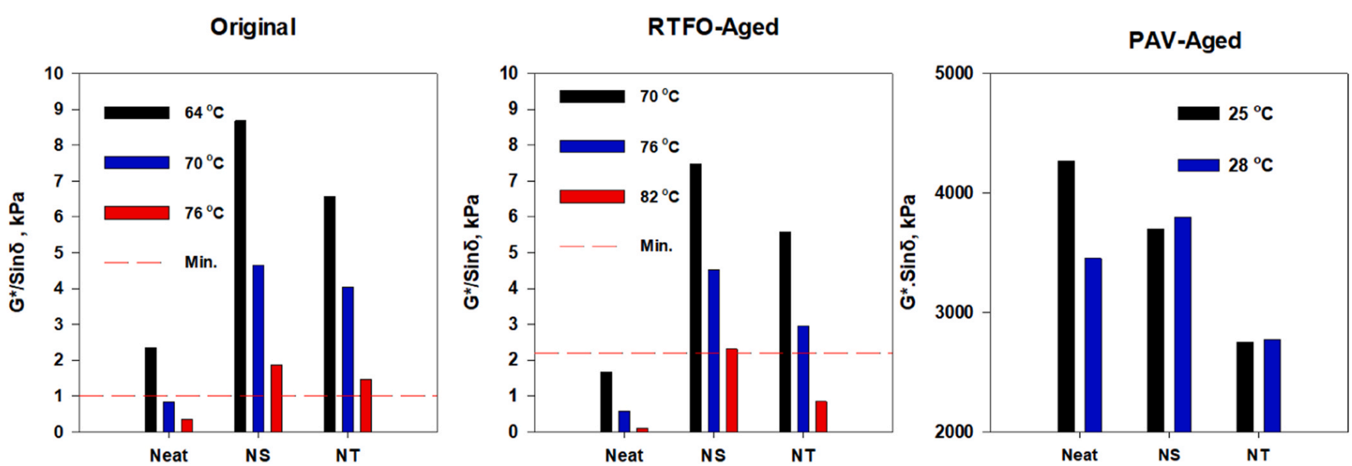

Fig. 4. DSR results of neat and nanomodified asphalt.

Table 7
volumetric properties of neat and nanomodified mixes.

Property	Neat	NT	NS	Requirement
OAC,%	4.6	5.2	5.2	4.0–6.0
Air Voids, %		4.0		4.0
VFA, %	73.3	72.92	72.88	65–75
VMA, %	14.38	14.73	14.55	Min 14.0
DP, %	1.18	1.04	1.09	0.8–1.6
% G_{mm} at N_{ini}	86.90	86.61	86.85	Less than 89 %
% G_{mm} at N_{des}	69.03	96.23	96.27	96 %
% G_{mm} at N_{max}	97.28	97.26	97.38	Less than 98 %

OAC = Optumim Asphalt content, VFA = voids filled with asphalt, VMA= void in mineral aggregate, DP= Dust Proportion

compliance test findings were examined using Roque et al. [33] as presented in Eq. 4:

$$D\quad(t) = D_o + D_1 t^m \tag{4}$$

In which,

D(t): creep compliance (in 1/GPa), t: time in seconds

D0, D1, m-value: power-law model parameter obtained using curve fitting using the least sum of squares approach with the solver function.

The tensile strength (ST), fracture energy (FE), dissipate creep strain energy (DCSE), and failure strain of an asphalt mixture were all determined using the strength test in conjunction with the MR test. The following equations [33] outline the methods used to determine these limits:

$$S_t = \frac{2P(C_{SX})}{\pi.t.D} = \frac{2P\left(0.948 - 0.01114.\left(\frac{t}{D}\right) - 0.2693.\nu + 1.436\left(\frac{t}{D}\right).\nu\right)}{\pi.t.D} \quad \dots \tag{5}$$

$$FE = \int_0^{S_t} \sigma.d\varepsilon \dots\dots \tag{6}$$

$$EE = \frac{(S_t)^2}{2.M_R} \quad \dots\dots \tag{7}$$

$$DCSE = FE - EE \dots\dots \tag{8}$$

CSX: factor corresponding to the stress correction and all other parameters defined previously. Like the resilient modulus and creep test, the specimen setup and transducer attachment are the same. On the

Fig. 5. SGC compacted samples and cutting.

Fig. 6. Preparing IDT test specimen for testing.

other hand, the tensile strength test was carried out in a displacement control mode while applying constant displacement rates of 50 mm/min.

3.4. Semi circular bending (SCB)

The SCB specimens were obtained by cutting them from an SGC specimen with a diameter and height of 150 mm for each, as shown in Fig. 7. The compressed specimens were divided into four pieces. A 57 mm thickness was divided into four SCB specimens prepeard with distinct depth of notches, measuring 15 mm, was created using a specialized saw blade that was 3.0 mm thick.The strength test involved subjecting the semicircular specimen to monotonic loading at 25 °C. This was achieved by applying a three-point bending arrangement at a constant rate of 50 mm per minute until failure occurred. Huang et al. [35] employed the subsequent equation to compute the tensile strength that arises at the midpoint of the bottom of the specimen in the context of SCB testing:

$$\sigma_x = 3.564\frac{P_{ult}}{Dt} \quad \ldots\ldots \quad (9)$$

Hence, σx represents the highest tensile stress at the center of the bottom surface of the specimen, P_{ult} denotes the load applied to the specimen at the point of failure. D represents

The diameter of the specimen, while t represents the thickness of the

Fig. 7. Testing configuration for the SCB.

specimen. It is important to observe that Eq. 9 holds exclusively when the distance separating the two lower supports is 67 times the diameter of the specimen.

3.5. Flow number test (FN)

SGC was utilized to fabricate a FN sample to attain target air voids of 7 ± 0.5 %. An HMA cylindrical sample with 180 mm in height and 150 mm in diameter was obtained for each neat and nanomodified asphalt sample type. In order to achieve a uniform distribution of air voids, the final specimen must be extracted with a core diameter of 100 mm and a height of 150 mm and trimming 20 mm from the top and 10 mm from the bottom, as illustrated in Fig. 8 below.

The test followed Annex B of the NCHRP Report 513, "Simple Performance Tester for Superpave Mix Design: First Article Development and Evaluation" by Bonaquist et al. [36]. The permanent deformation properties of paving materials were determined using a dynamic load applied for 10000 cycles at a temperature of 54.4°C and a stress level of 207 kPa. Each cycle consisted of a 0.1-second haversine load followed by a 0.9-second rest period. A triplicate specimen for the neat and nanomodified mixture was conducted using a DTM 50. At the same time, three LVDTs were mounted at 120° degrees on the sample surface to monitor deformation at a gauge length of 100 mm.

4. Testing result

4.1. Resilient modulus (Mr)

This section contrasts the outcomes of the resilient modulus test compared to neat asphalt mixtures from the nanomodified asphalt mixture. Three replicates for neat and each nano type, i.e., NS and NT, were carried on at varying temperatures. Table 8 presents peak load, Poisson ratio, maximum horizontal deformation, and moduli value for neat and nanomodified asphalt at 5 % nano content. Nanomodified asphalt improves moduli value with an increasing trend. In the case of NS, a significant increase was noted by about 11, 25.1, 30, and 18.1 % for temperature increases from 5 to 40 °C, as compared to neat asphalt. This leads to the conclusion that the addition of NS improves the asphalt mixes' elastic characteristics. These findings suggest that the inclusion of 5 % NS in asphalt cement results in combinations of asphalt that are stiffer at high temperatures and, consequently, have a higher load-bearing capacity.

Compared to nano-silica, the moduli value agrees with previous studies ([37] and [38]), which exhibits superior asphalt mixture performance regardless of the binder and test temperature. Meanwhile, the same trend occurred but with less effect with NT, which showed an increase of 5.3, 18.2, 22.4, and 10.8 % for the exact temperature range of 5–40 °C, irrespective of neat asphalt. This trend may be attributed to the complex interaction of NT with asphalt that improves the adhesion between the modified asphalt and aggregate in the asphalt mixture [39] beside, that nanosilica and asphalt binder interact, the surface property of the nanosilica changes, which is advantageous for the melting and dispersion of the nanosilica in the asphalt matrix, which yields higher levels of stress compared with neat asphalt mixture as presented in Table 7. NT-modified asphalt mixtures also have lower total recoverable strain values at a given temperature. At a particular temperature, for example, 25 and 40 °C, the final strain of mixtures is reduced, for instance (36.58–32.95 μm) at 25 °C and (75.0–71.47 μm) at 40 °C as compared to neat asphalt, this might be attributed to the titanium precursor by high-temperature oxidation within the reaction system. Generally speaking, there are two primary production processes for nano-TiO_2 [40,41]. The two processes are the chloride process and the sulfate process. Further consideration was also appears from data listed in Table 8. that increasing in testing temperature, exhibits an increased Poisson ratio value horizontal deformation and suffers a reduction in the applied loading. In fact, HMA mixes exhibit elastic properties and demonstrate negligible viscous behavior at lower temperatures; for this, a slight increase in Poisson value and total deformation value were seen at 5 and 15 °C. An increase in temperature results in a greater viscous behavior of HMA. Consequently, the degree of viscous flow demonstrated within the material will also impact the bulging, determined by Poisson's ratio for elastic materials. However, the Poisson ratio and applied loading flow a narrow corridor for neat and nanomodified asphalt with minimal change at lower temperatures and a noticeable reduction for NS at 25 and 40 °C. Fig. 9 compares the difference in Mr between neat and nanomodified asphalt at varying temperatures. In the light of finding it is appear that nano modified mixture has dominated IDT parameter than neat asphalt binder with more dominated value for NS followed by NT

The overall evaluation of adding 5 %: NS and NT, have impacted the moduli value, mainly at 25, and 40 °C due to the unique properties of nanomaterials that increase viscosity as well as produce stiffer HMA, which may explain the rationale behind the improvement in Mr characteristics. The viscoelastic deformation component in asphalt mixtures consists of linear and non-linear components. The non-linear viscoelastic deformation, which is the continuing recoverable portion of the total deformation, decreases substantially following load removal. The linear segment holds significance due to its complete recovery and commendable bitumen mixture quality. The improvement in stiffness of asphalt mixtures exhibits an increase in non-linear viscoelastic portion and an expanded linear viscoelastic region, enabling the utilization of the minimal elastic property to withstand dynamic vehicle loading on flexible pavements. The assessment of linear and non-linear viscoelastic deformations caused by dynamic loading in the haversine pattern for unmodified and nanomodified asphalt is illustrated in Fig. 10. Additionally, it is observed that a portion of the non-linear viscoelastic deformation persists following the removal of the load; thus, this deformation could potentially contribute significantly to the stress-deformation curve's non-recoverable portion by initiating further deformation.

Fig. 8. Testing configuration for the FN.

Table 8
Resilient modulus value, load, Poisson, and total deformation of neat and nanomodified asphalt at varying temperature.

Temperature, oC	Property	Peak load, N	Total deformation (μm)	V Poisson Ratio	Mr Mpa	Increment %
	Neat	2257	19.08	0.260	15223	——
5	NS	2313	18.11	0.252	17112	11.0
	NT	2233	18.82	0.259	16076	5.30
	Neat	1875	27.89	0.297	9670	——
15	NS	2357	25.39	0.280	12896	25.1
	NT	2221	26.63	0.288	11826	18.2
	Neat	1461	36.58	0.361	5362	——
25	NS	1723	31.63	0.326	7600	30.0
	NT	1573	32.95	0.340	6910	22.4
	Neat	555	75.00	0.405	1199	——
40	NS	637	67.74	0.374	1465	18.1
	NT	616	71.47	0.382	1345	10.8

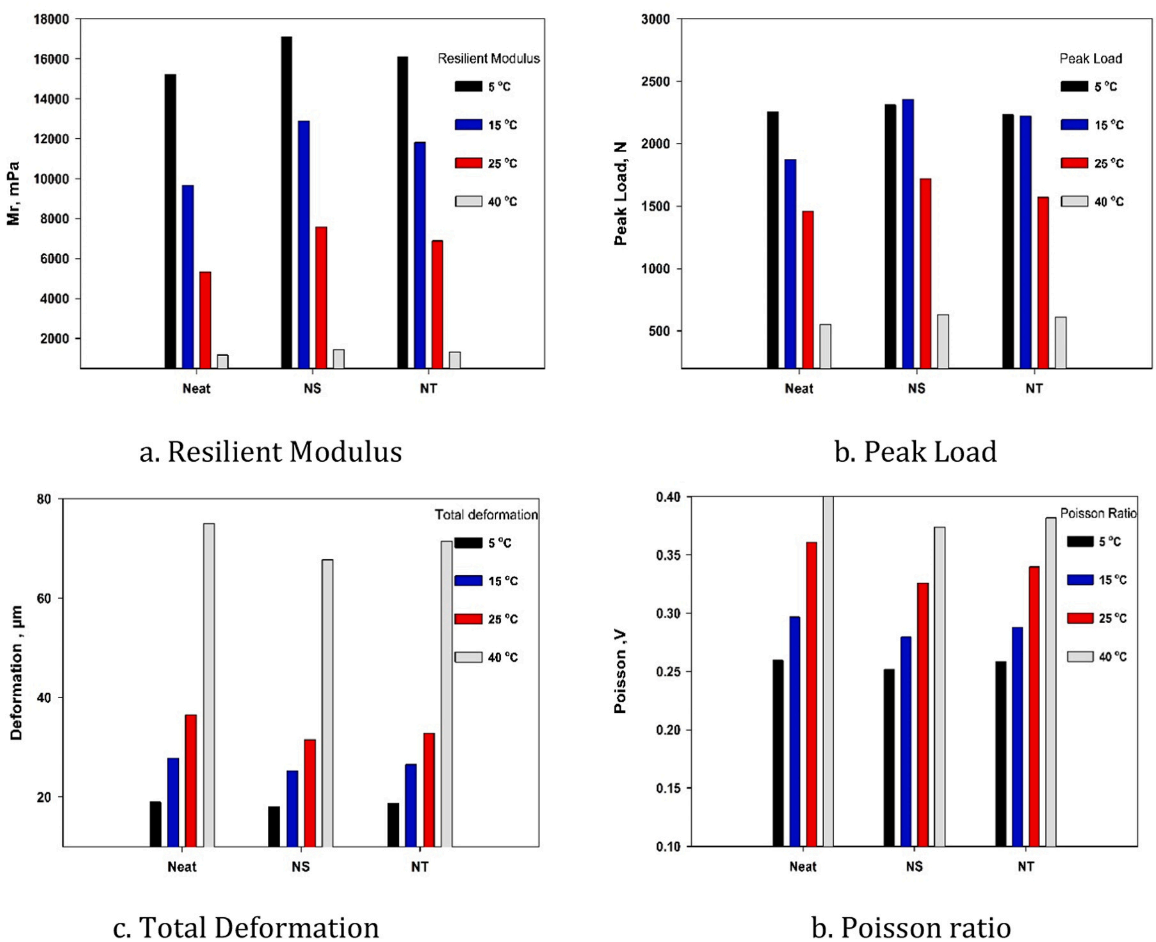

Fig. 9. Effect of different types of nanomodified asphalt IDT parameter at varying temperatures.

At 25 °C, the viscoelastic behavior of neat and nanomodified asphalt was investigated. The impact of nanomaterials causes varying degrees of linear segmentation reduction compared to a clean asphalt mixture. In contrast to neat asphalt, adding 5 % NS increased from 52.76 % to 61.98 % in non-linear viscoelastic deformation and decreased from 47.24 % to 38.02 % in linear viscoelastic deformation this behaviour may be attributed to chemical intraction since the asphalt binder interacts with the nanosilica group's surface, the hydrophilic surfaces of the nanosilica transform into hydrophobic surfaces. The white particles in the asphalt matrix, known as the nanosilica group, are evenly bonded to the asphalt binder to produce the new structure of the nanosilica modified asphalt binder. The modulus of the asphalt mixture treated with nanosilica may be improved by the dispersion of nanosilica in the asphalt binder. High melting and boiling point reactions can create new elements that can enhance the modulus value and temperature resistance of modified asphalt binders [42,43]. Similarly, the linear viscoelastic deformation of NT is observed to diminish by 42.13 % compared to the neat mixture's 47.24 %. However, the non-linear viscoelastic deformation of NT increased from 52.76 % to 58.57 %. In summary, the modifications above resulted in elevated Mr values, which are presented in Table 7. This indicates that including 5 % nanomodified asphalt in the mixtures reduce their resilience and reduced the non-linearity in the stress-strain behavior of the asphalt mixtures. The reduction in non-linearity additionally supports the durability of flexible pavements against permanent deformation.

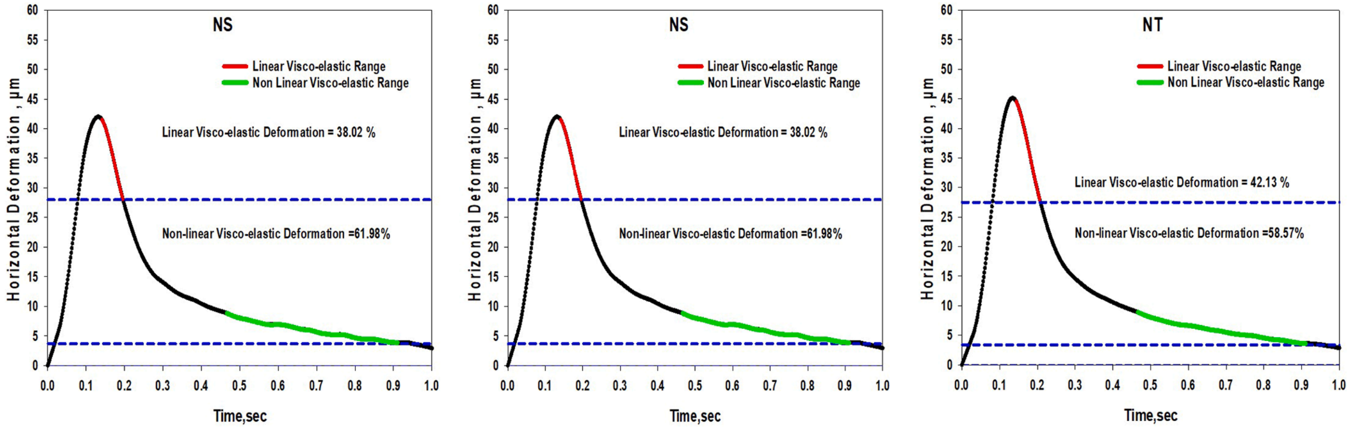

Fig. 10. Viscoelastic deformation for neat and nanomodified asphalt at 25 °C.

4.2. *Creep compliance (Dt)*

The same three specimens used for Mr testing within SuperPave IDT creep test were performed. The creep compliance expresses the relationship between the corresponding stress and the time-dependent strain. It is crucial in determining how much damage has accumulated in asphalt mixtures. According to the experimental research conducted by [44], it has been proposed that the creep strain rate is mainly influenced by two critical parameters, namely the m-value and the D1 value. A distinction between these two notions is that the m-value governs the creep strain rate in the long-term aspect of the creep compliance curve, while the D1 value predominantly impacts the early part. The m-value is of more significance to the rate at which unrecoverable strain accumulates. In contrast, a decrease in the m-value corresponds to a reduction in the extent of accumulated damage progress. Creep compliance fitting using power law for neat and nanomodified asphalt was illustrated in Fig. 11, while all parameters were tabulated in Table 9. As expected, the creep compliance increases with temperature increase and vice versa; hence, neat asphalt yields an average value of Dt of 0.581 1/GPa at 5 °C and increases to 1.872, 8.12, and 19.41 1/GPa for temperature increases

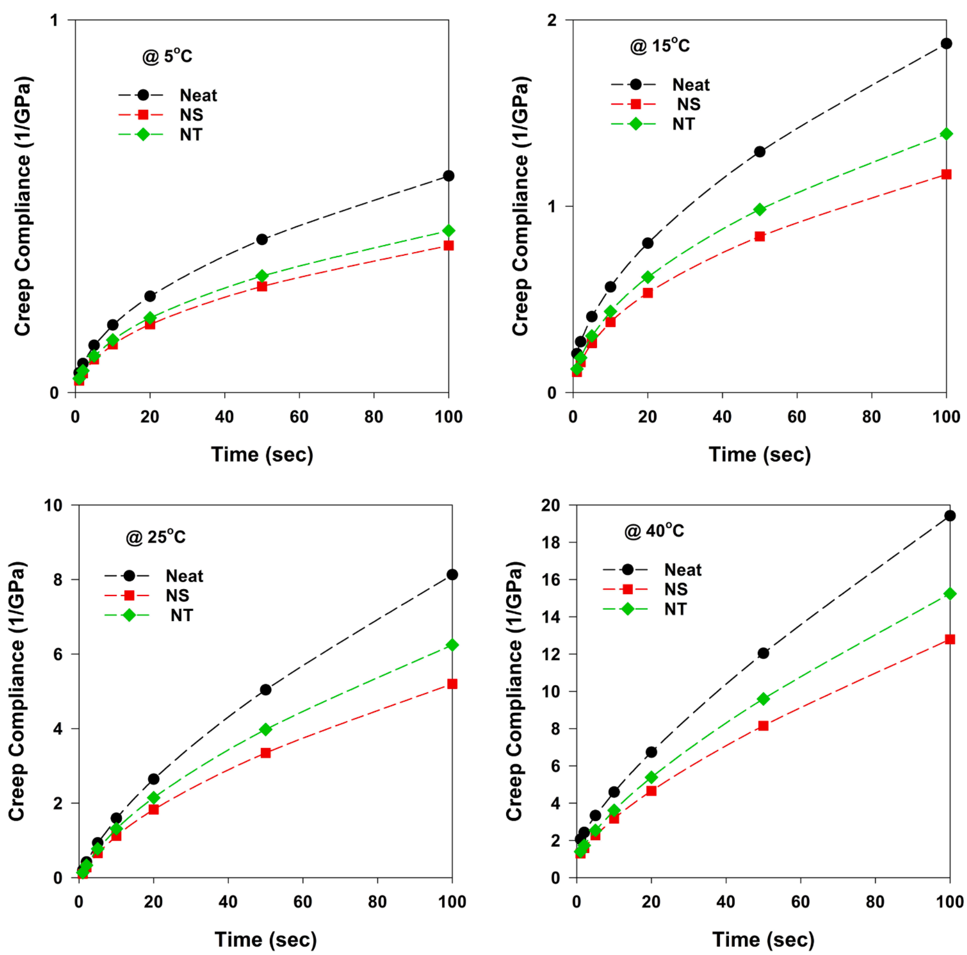

Fig. 11. Fitted Creep compliance curve for neat and nanomodified asphalt at varying temperatures.

Table 9
Calculated parameters from the IDT Creep test.

Type	Temp (°C)	D0 (1/GPa)	D1 (1/GPa)	m-value	D(t) at 100 sec. (1/GPa)	Poisson ratio ν50
Neat	5	0.0656	0.0823	0.493	0.581	0.226
	15	0.103	0.301	0.562	1.872	0.251
	25	0.186	0.381	0.670	8.12	0.318
	40	0.834	2.89	0.767	19.41	0.348
NS	5	0.0584	0.073	0.438	0.394	0.190
	15	0.077	0.1923	0.470	1.220	0.220
	25	0.131	0.231	0.600	5.16	0.271
	40	0.682	1.43	0.709	12.78	0.317
NT	5	0.0622	0.077	0.450	0.450	0.203
	15	0.084	0.211	0.490	1.389	0.232
	25	0.144	0.277	0.621	6.24	0.287
	40	0.743	1.53	0.720	15.23	0.324

15, 25, and 40 °C respectively. Modifying the asphalt binder with nanomaterial helps upgrade the creep performance of the asphalt mixture. Nanomodified asphalt was seen to be more compliant at lower testing temperatures of 5 and 15 °C and also had impacted the creep values at intermediate and higher temperatures of 25 and 40; These impacts are expected to enhance the ability of HMA mixtures to resist rutting and thermal cracking. Additionally, they serve as a reliable confirmation of the findings from prior research investigations conducted by Cao et al. in [45] and Zangena in [37].

Compared to the neat asphalt mixture, the NS modified mixture was able to exhibit an average compliance value of 0.394,1.22,5.16 and 12.78 1/GPa at a temperature range of 5–40 °C, showing a constant reduction in compliance value by nearly 30 % at all temperatures except at 40 °C with 36 % since the incorporation of nanomaterials into asphalt can decrease its sensitivity to heat, enhancing the cohesive strength of the asphalt mortar and mixture. This improves the resistance to creep and permanent deformation of the asphalt mixture. The same trend was also followed by incorporating 5 % NT into the asphalt mixture; hence, Dt shows a reduced value by about 19 and 22 % for the temperature range 5–25 °C and 40 °C, respectively, regarding the neat asphalt mixture. Fig. 12 compares the listed data in Table 8; creep properties m-value, and D1, nanomodified asphalt present mixtures are less than those with the neat binder. NS-modified mixtures are strongly affected by reducing these parameters, especially at 25 and 40 °C. This behavior will also seen for NT that had extant D1 and m-value to slight decrease as compared to neat attributed to the less deformation of nano modified mixes supported by the stiffening effect contributed from 5 % of each nano type. On the other hand, all nanomodified asphalt exhibits reduced compliance at lower temperatures of 5 and 15 °C since the material undergoes a decrease in ductility and exhibits a reduced capacity for stress relaxation. This implies that these asphalt mixes would have greater stress intensity under low-temperature conditions than neat asphalt. Consequently, it is anticipated that these nanomodified asphalt mixes would demonstrate an increased crack propagation rate once a crack is initiated, an essential aspect of considering thermal stresses.

Consequently, it is anticipated that these nanomodified asphalt mixes will demonstrate an increased crack propagation rate once a crack is initiated, which is essential when considering thermal stresses. This finding also demonstrates a correlation with the parameter G*/sinδ. A mixture characterized by a greater G*/sinδ exhibits a reduced creep compliance at 100 seconds.

4.3. Tensile strength (TS)

Table 10 summarizes the Tensile Strength (TS) and strain at failure (FS), while Fig. 13 compares the strength values of the neat and nanomodified mixes. Tensile stress demonstrates the predicted tendencies, which indicate that the strength value decreases with temperature increase. Ratings for all mixes tend to increase TS value for NS and NT modified mixtures at lower temperatures of 5 and 15̊C, with seemingly little difference for NCC corresponding to neat asphalt. On the other hand, the TS value of nanomodified mixtures is higher than that of neat asphalt mixtures at mid-to-high temperatures of 25 and 40̊C indicating that the strength property of the HMA at higher temperatures is positively impacted by adding 5 % of all nanomodified asphalt. As expected, NS exhibits a higher TS value among all nano types than neat and other nano types. Compared to a neat asphalt mixture, the NS modified asphalt mixture shows an average increase in TS by nearly 24 % as temperatures range from 5–25 °C than neat mixture. However, including NS may expand this improvement to about twice (nearly 41 %) when the HMA mixture bears a higher temperature by increasing the TS value from 0.21 to 0.36 MPa at 40 °C. Following these facts, 5 %

Table 10
TS and FS value for neat and nanomodified asphalt at varying temperature.

Neat				
Temperature,°C	5	15	25	40
TS, (MPa)	2.35	1.79	0.92	0.21
FS (10^3 micro)	1.66	4.51	7.06	10.78
NS				
Temperature,°C	5	15	25	40
TS, (MPa)	3.33	2.25	1.19	0.35
FS (10^3 micro)	2.11	5.67	9.04	13.68
NT				
Temperature,°C	5	15	25	40
TS, (MPa)	2.97	2.10	1.13	0.31
FS (10^3 micro)	2.02	5.18	8.39	12.68

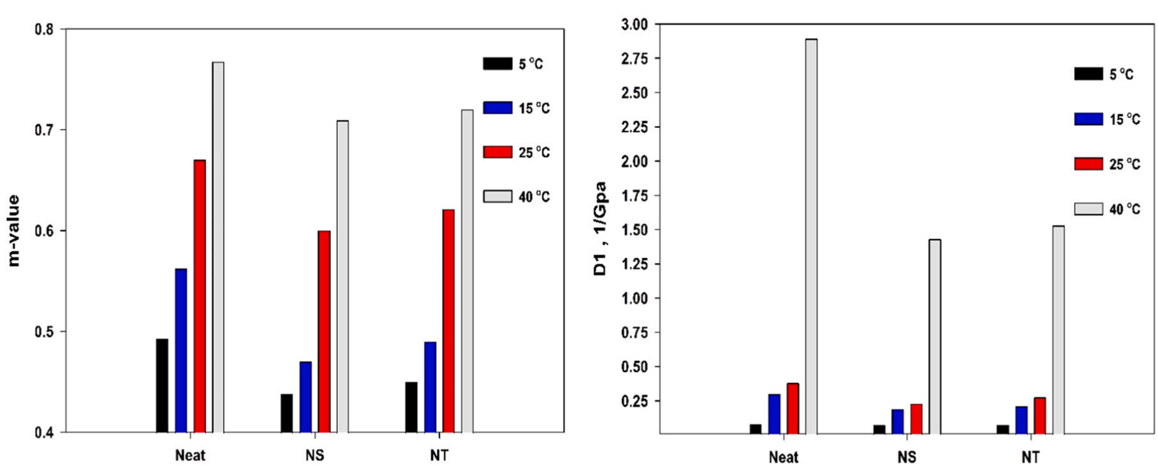

Fig. 12. Creep regression coefficients for neat and nanomodified asphalt.

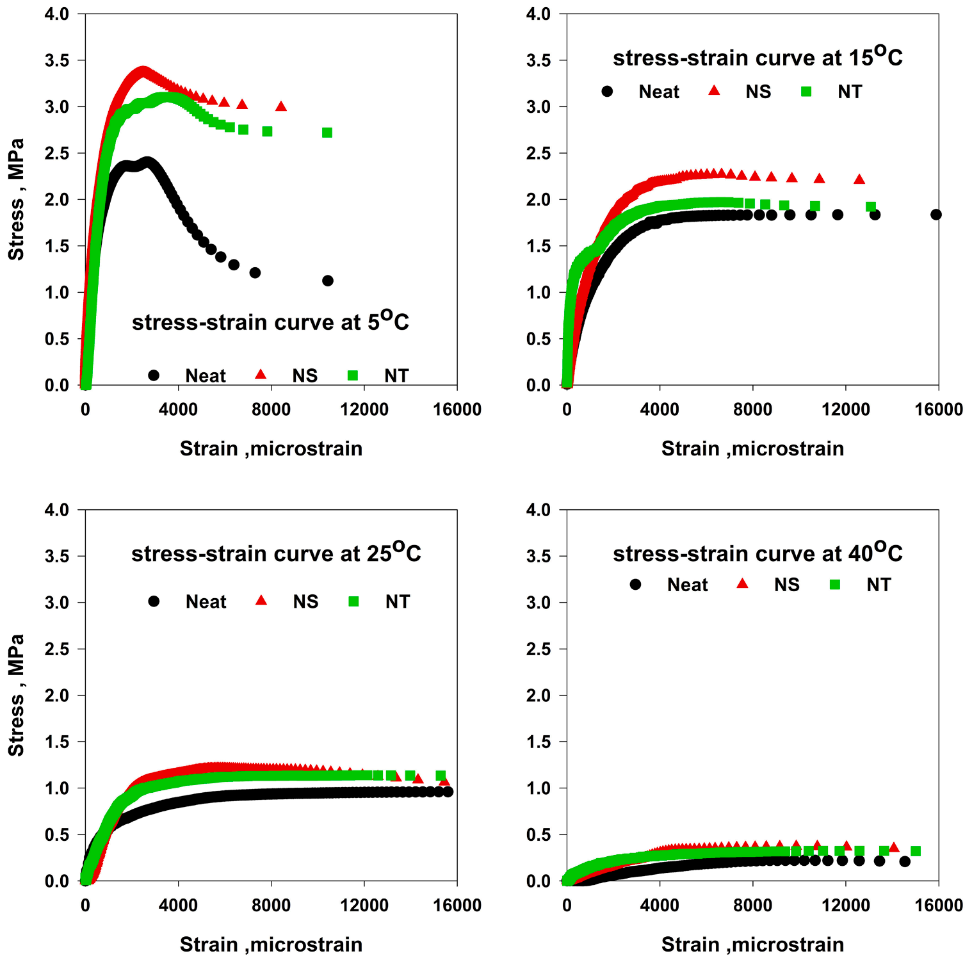

Fig. 13. stress -strain curve for neat and nanomodified asphalt at varying temperatures.

NS has impacted the TS value, especially at higher temperatures, due to the improved adhesion between the asphalt and aggregates with higher TS value. Other researchers confirmed similar behaviors; [20] and Yao et al., 2012 indicated that NS nanoparticles enhance asphalt mixture stiffness and brittleness, enhancing the load-bearing capability of asphalt pavements. Additionally, elastic behavior was also improved, as indicated by the increase in the value of FS at fracture by nearly 23 %. This implies that asphalt mixtures can absorb significantly more energy, thus prolonging fatigue resistance. [16]. The confirmation of this will be provided through the utilization of the fracture energy concept. The extent of other nano types, i.e., NT has also impacted the TS and FS value of IDT specimens with similar behavior to NS but less effectiveness due to different stiffening effects. Compared to neat asphalt, NT promotes TS value by about 20, 15,19, and 32 % when the temperature increases from 5 to 40 °C; simultaneously, it sustains greater endurance capacity and FS value at the exact temperature range by an average of 16 % as a

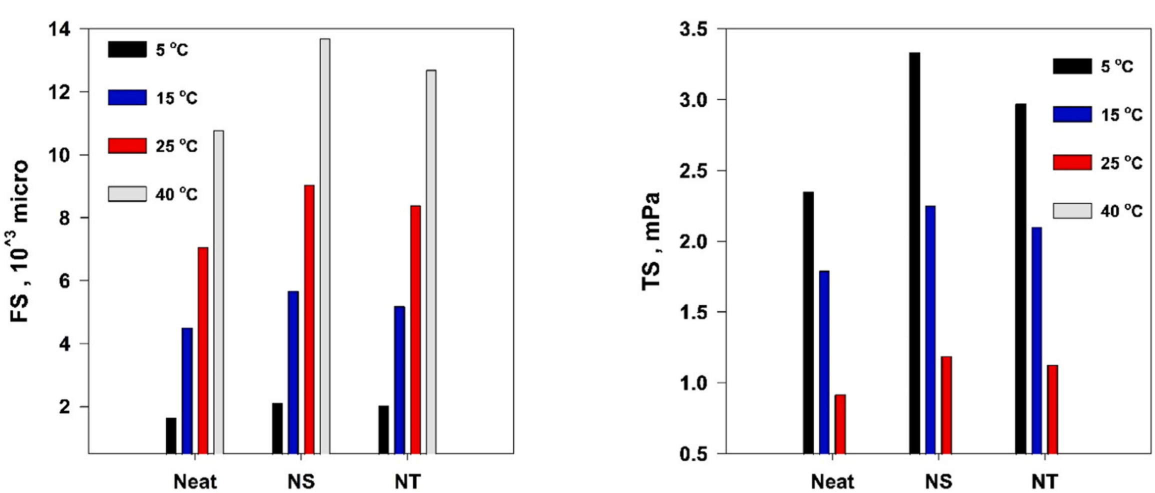

Fig. 14. compares TS and FS values for neat and nanomodified asphalt.

result; inhibiting the formation and propagation of tensile and vertical cracks caused by horizontal tensile stresses [39]. The testing result shows a good agreement with previous research by [46], who found that the incorporation of 8 % Nano TiO_2 into the initial mixture resulted in a significant increase of approximately 67 % in the TS value. Similarly, including 2 % Nano TiO_2 into the original mixture led to an improvement of approximately 30 % in the TS value. According to the previous analysis, utilizing nanomodified asphalt binder can potentially enhance the tensile strength and failure strain of asphalt mixtures compared to neat asphalt, mainly at mid to high temperatures of 25 and 40 °C, with notable enhancement at lower temperatures. Comparison between the three nano types indicates that both NS and NT can significantly improve IDT parameters due to the stiffing effect gained by nanoparticles, inhibiting the formation and propagation of cracks under tensile stress. Consequently, this would increase fracture energy value, allowing asphalt mixtures to absorb more energy. Asphalt mixtures' enhanced energy dissipation capability will enhance their resistance to fatigue and fracture failure, thus resulting in an extended lifespan of asphalt pavements. On the other hand, the modified mixture closely improved at lower temperatures with a lower effect at mid to higher temperatures concerning neat mixture. Fig. 14 compares both TS and FS values for neat and nanomodified asphalt.

4.4. Fracture parameter – DCSE and ER test results

According to previous Eqs. (5 to 8), HMA fracture parameters were obtained and noted in this section in Table 11; HMA fracture parameters dissipated creep strain energy (DCSE) and fracture energy (FE) for neat nanomodified mixtures were obtained at the testing temperature range from 5 to 25 °C. The DCSE refers to the maximum energy a mixture can tolerate before it fractures. Based on Rouque et al. [44]: the critical DCSE value of 0.75 KJ/m^3 can used to distinguish between cracked and uncracked pavements. Pavement with a DCSE value beyond 0.75 KJ/m^3 remained intact, but those below this threshold experienced cracking. Consequently, mixtures with lower DCSE values are deemed more susceptible to cracking than combinations with higher DCSE values under similar loading and climatic circumstances. Table 11 lists the result of the IDT fracture parameter acquired from the stress-strain curves presented in Fig. 15 for neat and nanomodified asphalt mixtures. Generally, higher energy values were seen for both DCSE and FE at mid-range temperatures 15 and 25̊C than at low 5̊C temperatures. This pattern results from the fact that the fracture energy is determined by calculating the area under the tensile strength test's stress-strain curve since HMA has a high tensile strength but a relatively modest failure strain at low testing temperatures. On the other hand, because of the flexible nature of the asphalt binder, HMA has the lowest tensile strength and the maximum failure strain at high temperatures; meanwhile, the integration of the stress and strain curve reaches a maximum value at a few mid-range temperatures.

Modifying asphalt binder with nanomaterial has significantly impacted the IDT-HMA fracture parameter mixture at all temperatures. In this scenario, a higher DCSE value was seen with NS modified mixture, which extended the neat HMA mixture threshold of fracture damage from 1.60 to 2.54, 3.71–5.79, and 3.09–5.10 KJ/m^3 at a temperature range of 5–25 °C by an average increasing rate of 36 %. It suggests incorporating 5 % NS may exhibit greater fatigue or fracture failure resistance than neat asphalt. Similarly, NT modified mixture, which holds a lower tensile strength than NS, will endure the failure criterion of the HMA neat mixture; for this, DCSE will reach a value of 2.18, 4.89, and 4.47 KJ/m^3 at a temperature range of 5–25 °C than neat asphalt mixture within average rate of 26 %. Fig. 16 compares the DCSE values for neat and nanomodified asphalt mixtures.

In conclusion, the nanomodified mix has significantly improved the mixture's performance against fatigue cracking potential and increased the threshold mixture's ability to fracture. The fatigue life of HMA mixtures is often longer for higher DCSE or FE values. However, these two characteristics alone will only provide preliminary data, not the whole picture of how the mixture will behave. As a result, [44], Incorporated into the HMA fracture mechanics model a dimensionless factor known as the Energy Ratio (ER), which can serve as a quantifiable indicator of the ability of mixes to withstand fractures with optimal cracking performance and stated that the minimum ratio for ER valuepresented in Eq. 10 should be greater than 1 since the computed dissipated creep strain energy was nominated as $DCSE_f$, whereas $DCSE_{min}$ is computed using Eq. 11, and their value is listed in Table 12.

$$ER = \frac{DSCE_f}{DCSE_{min}} \quad (10)$$

$$DSCE_{min} = m^{2.98} \times D_1/A \quad (11)$$

Since $A = 0.0299 \times \sigma^{-3.1} \times (6.36\text{-TS}) + 2.46 \times 10^{-8}$, The default value for tensile stresses, σ, is set at 150 psi specified [47] and will be used in this study.

According to the study's findings, ER is compared only at 5 °C since neat and nanomodified mixes at this temperature will meet the minimum criterion of 1. all nanomodified mixtures have gained higher ER than neat asphalt. Among these results, NS shows a significant increase in ER value by about 55 % with 2.54, which reflects a strong resistance to fracture and thermal cracking at lower temperatures when compared to a neat asphalt mixture that resulted in ER value equal to 1.12. Even though NT behave in similar trends with increasing ER value to about 43 %, based on these findings, nanomodified asphalt mixture with NS and NT has remarkably performed better than neat asphalt mixture regarding the ability to withstand load-related cracking.

4.5. SCB results

SCB testing was examined within DTM 50 to evaluate the potential of a neat and nanomodified mixture's tensile strength and fracture energy. Fig. 17 display the stress-strain curve for each mixture, while Table 13 lists the average tensile stress and bending strain of four specimens needed to spread cracks from the notches' tip across SCB specimens. In general, all nanomodified mixes appear to extend tensile strength as compared to neat asphalt mix; this behavior is expected because of nanomaterial that provides more durable asphalt mixtures, hence increasing the lifespan of asphalt pavements by means of increasing max

Table 11
HMA fracture parameter for neat and nanomodified asphalt at varying temperature.

Temp.	Type	Resilient Modulus Mrt, MPa	Final strain (εf) μm	TS MPa	Initial strain (εo) μm	EE (KJ/m^3)	DCSEmin (KJ/m^3)	FE (KJ/m^3)
5 °C	Neat	15223	1669	2.35	1515	0.181	1.60	1.78
	NS	17112	2111	3.33	1916	0.263	2.54	2.86
	NT	16076	2021	2.97	1836	0.251	2.18	2.45
15 °C	Neat	9670	4509	1.79	4324	0.155	3.70	3.87
	NS	12896	5672	2.25	5498	0.198	5.79	5.98
	NT	11826	5188	2.1	5010	0.162	4.89	5.07
25 °C	Neat	5362	7067	0.92	6895	0.086	3.09	3.17
	NS	7600	9047	1.19	8890	0.096	5.10	5.19
	NT	6910	8397	1.13	8233	0.089	4.47	4.56

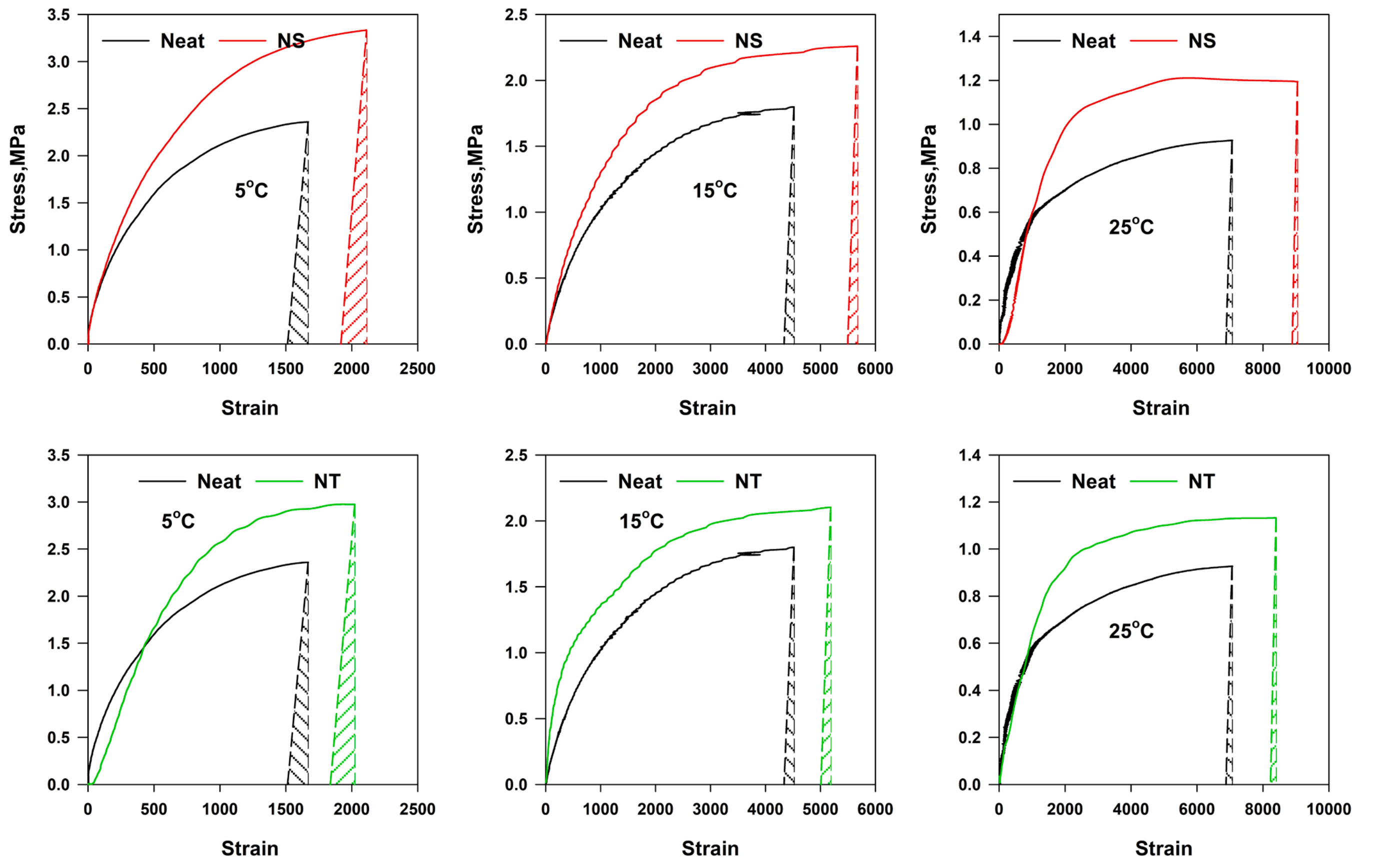

Fig. 15. Stress-strain curves generated from IDT tests for neat and nanomodified asphalt.

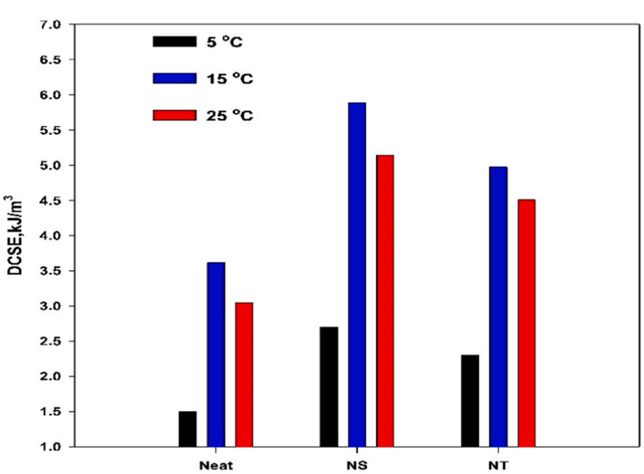

Fig. 16. Comparison of DCSE of neat and nanomodified asphalt.

load-capacity prior to crack propagation hence, The strength values obtained from the SCB were in agreement with the strength statistics obtained from the IDT. At the same time, these modified mixtures experienced noticeable changes in the bending Strain for the modified asphalt with NS and NT. This indicates that adding a modified asphalt binder did

not compromise the ductility of the SCB asphalt mixture. Nevertheless, all nanomodified asphalt binder can absorb more energy than neat mixtures with similar bending strain failure and enhanced strength.

Among the three mixes, NS modified mixture exhibited higher tensile strength, showing an average value of 4.205 MPa. A significant increase was noted when compared to neat asphalt mixture since NS modified mixes increase the tensile value by about 36.5 %; this could be attributed to the enhanced adherence between the NS modified asphalt and aggregates as a consequence of a dense framework structure formation resulting from NS modified asphalt as indicated by the previous researcher ([8,20]). Furthermore, including NS enhances the mixture's stiffness and viscosity with a slightly higher bending strain of 0.0283 mm/mm compared to the neat asphalt bending value of 0.0209. Similar behavior was also seen for NT mixes since the presence of NT has a higher viscosity than neat asphalt. As a result, it shows enhanced adhesive bonding properties for aggregating the particles. Furthermore, enhanced cohesion between nanomodified binders and aggregates enhances the combination and fracture resistance [10]. SCB samples exhibit an increase in tensile stress value by about 22 % beyond neat asphalt. Indeed, the gain in stiffness of asphalt will contribute to close bending strain at fracture, presenting a value of 0.0262 mm/mm as compared to a value of 0.0209 obtained from a neat mix. The concept of

Table 12
Summary of fracture parameters of neat and nanomodified asphalt mixes at a temperature of 5 °C.

Type	DCSEf KJ/m3	m-value	D1 1/GPa	Tensile stress, σ	TS MPa	A MPa-2	DCSEmin KJ/m^3	ER DCSEf/ DCSEmin
Neat	1.60	0.493	0.0823		2.35	0.007035	1.42	1.12
NS	2.54	0.438	0.073	150Psi (1Mpa)	3.33	0.006188	1.00	2.54
NT	2.18	0.450	0.077		2.97	0.006499	1.10	1.98

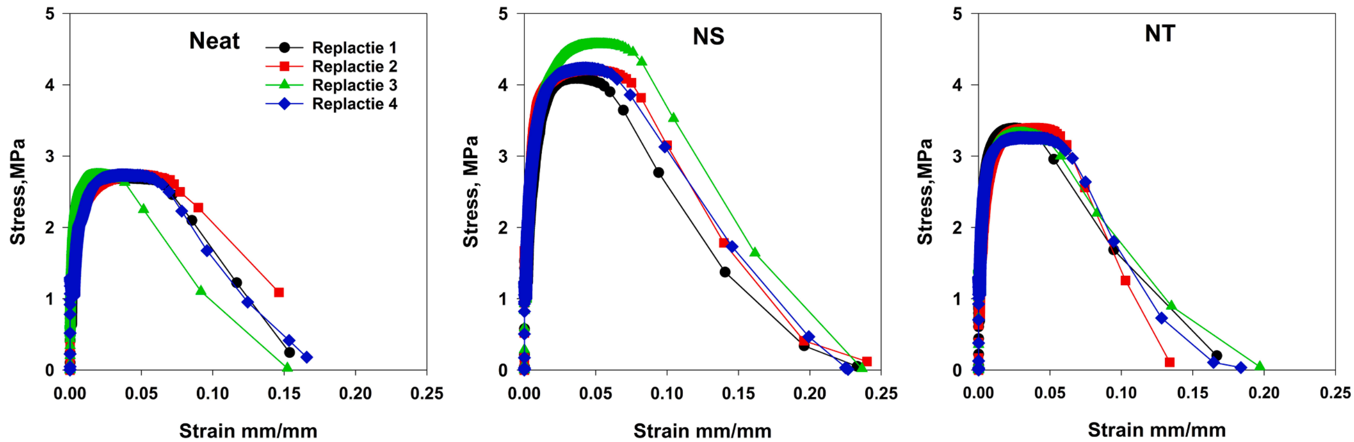

Fig. 17. Stress-strain derived from SCB test of neat and nanomodified asphalt.

Table 13
Average value of SCB parameter for neat and nanomodified asphalt.

Type	Sample size	Bending strain (mm/mm)	Tensile strength (MPa)	Fracture Energy, KJ/m2
Neat	4	0.0209	2.670	1.678
NS	4	0.0283	4.205	2.667
NT	4	0.0262	3.442	2.031

fracture energy (FE) is essential to explain and helpful in providing a more reliable picture of crack initiation potential in real traffic conditions. Asphalt mixtures that include nanomodified asphalt binders could absorb more energy than mixtures with neat asphalt binders in terms of bending failure strain and enhanced strength. Nanomodified binder has the potential to enhance the durability of asphalt mixtures against fatigue failure; higher FE value indices were obtained with NS modified mixture that tolerated higher stress and strain values before fracture reaching a value of 2.66 KJ/m^2, showing a 37 % improvement to neat asphalt mixture, the same behavior with NT that contributed to 18 % achievement in energy than neat asphalt with 2.03 KJ/m^2. This action may be explained by the variation in the amount of work needed for failure. For example, neat asphalt mixture materials require less force to fail compared to NS or NT, which are stiffer. However, a neat asphalt mixture requires higher deformation to achieve fracture, which is slightly lower compared to NS or NT mixes; this behavior was indicated by previous researchers when comparing the fracture energy value of stiff and flexible asphalt mixtures ([48] and [49]). Hence, fatigue life resistance will improve with increased energy absorption, indicating more elasticity when subjected to monotonic loading. Drawing a conclusion, it can be considered that mixes with higher tensile stress and FE values are preferable since they indicate a strong and durable mixture. Conversely, if the FE value decreases, the mixture absorbs less energy when subjected to tensile strain, increasing the likelihood of fatigue fracture formation. The addition of nanomaterial generally enhanced the tensile strength of all mixes. At the same time, it improved FE that resulted from the addition of NS and NT and would become more effective in resisting the possible development of fatigue cracks.

Table 14
FN Testing result of triplicate specimen for Neat and nanomodified asphalt.

Mix	Specimen	Flow Number (cycles)	Mean Flow Number	Strain at Flow	Average Strain
	1	1553		6625	
Neat	2	1756	1577	6100	6400
	3	1423		6475	
	1	10000		3200	
NS	2	10000	10000	3010	3005
	3	10000		2807	
	1	8443		4818	
NT	2	8210	8266	4231	4500
	3	8147		4452	

4.6. Flow number (FN) test result

The results of FN for neat and nanomodified asphalt were evaluated and tested within DTM-50. Triplicate specimens were tested for each type of mixture, listed in Table 14 and Fig. 18, representing a higher FN value obtained from triplicate specimens per mixture. If a specimen did not exhibit any tertiary flow for the whole loading cycle (i.e., 10000 cycles), the FN value for that specimen was recorded as 10000 cycles. A greater FN value indicates a superior resistance to rutting in the mixture. Generally, the FN of the neat asphalt mixture is less than that of the asphalt mixture enhanced with nanomaterial. Incorporating NS into the neat asphalt mixture significantly increases the flow number of the modified asphalt mixture.

The presence of 5 % NS in the asphalt mixture increases its potential for resistance against permanent deformation at higher temperatures; hence, after 10,000 cycles, the mixture reaches the tertiary zone, A significant improvement by about 6.2 times in average FN value that presents an increment to 10000 cycles and lower strain value of 3005 μm when compared to neat asphalt that exhibits 1577 cycles and 6400 μm. This phenomenon may be attributed to the significant surface area of NS and higher stiffness, as indicated by their performance grades. Besides, including nanoparticles in the asphalt adds aggregate to asphalt, enhancing its viscosity and stickiness. Consequently, this reduces the asphalt's susceptibility to high temperatures. This behavior was also seen in previous research done by [8] who found that the flow number of nano-silica-modified asphalt mixture increases by an average of 300 %. In addition, nanomaterials enhance the stiffness of the asphalt binder, enhancing the asphalt mixture's ability to withstand deformation within higher temperatures [50].

The second observation on FN was noted as the inclusion of 5 % NT extended a greater FN value and lower strain corresponding to a neat asphalt mixture. The modified mixture extended HMA mixture resistance to permanent deformation by increasing the FN cycle before reaching the tertiary zone by nearly 5.3 times than neat asphalt. At the same time, the final strain decreases to 4500 μm due to enhanced adhesion between aggregate and modified bitumen in asphalt mixture, as compared to neat asphalt mixtures. Based on the results, including NT enhances the resistance to rutting in the specimens. The possible explanation for this phenomenon is that introducing NT improves flexibility and decreases the temperature susceptibility of NT mixtures due to an increased penetration index, leading to greater resilience to rutting at higher temperatures. The test results indicate that using NT enhances

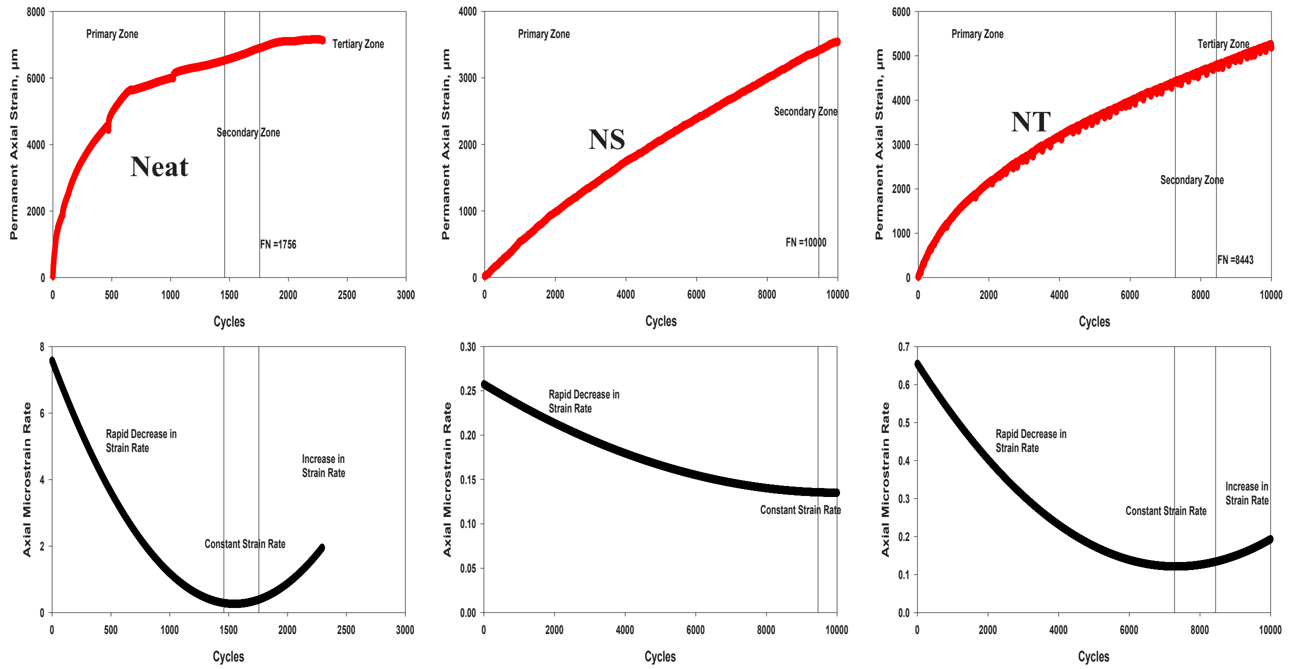

Fig. 18. FN test result of neat and NS modified asphalt.

the specimens' stiffness and viscosity, improving permanent deformation properties. These data align well with the previous research conducted by Ameli et al. in [46]. In their study, they used 2 % and 8 % NT addition in asphalt mixtures, resulting in a 24 % and 79 % increase in the FN of the samples, respectively. Finally, it can be inferred that the inclusion of 5 % nano has promoted mixture stiffness at higher temperatures since the magnitude of strain is reduced under the application of repetitive loading, and this behavior will reflect higher resistance to permanent deformation. A mixture containing NS and NT has a superior effect by increasing the FN value to about 6.2 and 5.3 times that of neat asphalt. Therefore, it can be concluded that a nanomodified mixture with 5 % NS and NT has a superior effect in improving the rutting resistance at higher temperature areas.

5. Conclusion

This study examined the influence of adding 5 % nano content was conducted using tests such as Superpave IDT, SCB and, FN, to assess the mixtures' fatigue life and permanent deformation. The section presents the key conclusions drawn from the analysis and discussion of results:

1. Compared to the neat mixture, the nanomodified mixture has significantly increased moduli value by about 11, 25.1, 30, and 18.1 % for NS and 5.3, 18.2, 22.4, and 10.8 % for NT at a temperature range from 5 to 40 °C.
2. Nanomodified asphalt was seen to be more compliant at lower testing temperatures and influence the creep values at intermediate and higher temperatures. NS and NT can interact more within the structure of the asphalt, suggesting that the creep compliance characteristics for the HMA were significantly altered compared to the neat mixture.
3. The utilization of nanomodified asphalt enhances the tensile strength and failure strain of asphalt mixtures compared to neat asphalt, mainly at mid to high temperatures. Comparison between nano types indicates that both NS and NT can significantly improve IDT parameters.
4. The nanomodified mixture has significantly improved performance against fatigue cracking and exhibited an increased IDT threshold to fracture, increasing DCSE value beyond neat mixture by an average rate of 36 and 26 % for NS, and NT, respectively, with remarkable cracking resistance to neat mixture as ER value increases by 55 % for NS and 43 % for NT at 5 °C.
5. SCB agreed with the strength obtained from the IDT. The addition of nanomaterial generally enhanced the tensile strength of all mixes and improved the FE that resulted from the addition of NS and NT, which would become more effective in resisting the possible development of fatigue cracks.
6. Nanomaterials have promoted mixture stiffness at higher temperatures since the magnitude of strain is reduced under the application of repetitive loading, and this behavior will reflect higher resistance to permanent deformation.
7. The presence of 5 % NS and NT can significantly improve FN value by about 6.2 and 5.3 times and lower strain value of 3005 and 4500 μm when compared to neat asphalt that exhibits 1577 cycles and 6400 μm which reflects a possible potential for resistance against permanent deformation at higher temperatures.
8. Modification of neat asphalt binder with nano material has improve the overall performance of HMA mixes with NS followed by NT.

CRediT authorship contribution statement

Alaa H. Abed: Supervision. **Ahmed Mohammed:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Conflict of Interest

The authors have declared no conflict of interest.

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