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Rheological Behaviour and Rutting Resistance of Asphalt Modified with SBS and Nano-silica

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ABSTRACT

This study is conducted to enhance the performance of bitumen at high temperatures. To do so, styrene-butadiene-styrene (SBS) and Nano-silica polymer additives were used. Initially, pure bitumen versus bitumen 60/70 samples with 2.5%, 3.5%, 4.5%, and 5.5% SBS polymer, and modified bitumen samples with 4.5% SBS polymer and 1%, 2%, 3%, and 4% Nano-silica were prepared using a high shear mixer. Polymer separation tests, rolling thin film oven tests, dynamic shear rheometer tests, and rotational viscosity tests were performed on the modified bitumen samples. Preliminary results of the dynamic shear rheometer test showed that SBS polymer improved the high-temperature performance of bitumen and increased its resistance to permanent deformation. However, Nano-silica had a more significant effect than SBS in improving the high-temperature performance of bitumen. The combination of 4.5% SBS and 4% Nano-silica enhanced the high-temperature performance of bitumen. Additionally, the results of the bitumen separation test showed that combining bitumen with SBS polymer caused the polymer to separate from the bitumen. Nevertheless, adding 1% Nano-silica resolved this issue. Asphalt mixture samples for the above compounds were then prepared based on the Superpave mix design method, and a dynamic creep test was performed. The results of this test showed that the combination of SBS and Nano-silica polymers significantly increases the resistance of the mixture at high temperatures. The combination of 4.5% SBS polymer and 4% Nano-silica, compared to the control sample with pure bitumen at 50 °C and 60 °C, reduces the cumulative strain by 51% and 41%, respectively, demonstrating the best

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performance. Therefore, the combination of Nano-silica with SBS polymer can be widely used in places with hot weather.

1 INTRODUCTION

Bitumen is one of the key and constructive components in asphalt mixtures that significantly affects the behaviour and performance of the mixture. It is also one of the most critical and effective factors in asphalt mixture failures, especially fatigue, due to defects related to bitumen. Therefore, to increase the durability of asphalt mixtures and reduce the shortcomings related to straight-run bitumen, modifying the properties of bitumen with additives is a viable option. In recent years, various methods and additives, such as sulphur, polymers, rubber powders, and nanomaterials, have been studied to improve the properties of bitumen. Pavements containing modified bitumen exhibit higher resistance to failures and can absorb more strain energy[1].

Styrene-butadiene-styrene (SBS) is a common modifier with a high molecular polymer, which can be miscible with the asphalt binder. SBS-modified asphalt improves high-temperature rutting resistance, low-temperature crack resistance, and anti-fatigue performance of asphalt pavements[2]. Currently, SBS-modified asphalt is widely applied to many high-grade pavements in China to meet increasing traffic demands, given its wide scope of application[3].

The primary purpose of using polymers is to increase the resistance of asphalt to permanent deformation (rutting), fatigue and thermal cracking. Due to the significant increase in traffic volume and the weight of trucks, conventional pavements made of asphalt mixtures often do not perform well. They may cause structural and functional failures before their expected design longevity. To address this issue, polymer-modified asphalt mixtures can be used[4]. While previous studies have investigated the effects of SBS polymer on bitumen properties, few have explored the combined impact of Nano-silica with SBS polymer in depth. Existing research primarily focuses on the individual contributions of these additives rather than their synergistic effects. Additionally, most studies have not thoroughly addressed polymer segregation issues or the mitigation strategies involving Nano-silica.

This study aims to fill this gap by evaluating both individual and combined effects of SBS polymer and Nano-silica on bitumen properties. Specifically, it focuses on polymer segregation, rheological behaviour, and high-temperature performance. To achieve this, SBS polymer and Nano-silica were utilized to enhance bitumen performance at medium temperatures. The modified bitumen was evaluated using polymer separation, dynamic shear rheometer (DSR), rotational viscosity and Linear Amplitude Sweep (LAS) tests.

2 RESEARCH BACKGROUND

Each year, researchers use different modifiers to alter the properties and behaviour of bitumen. Among these modifiers, polymers, especially styrene-butadiene-styrene (SBS) polymers, have increased in recent decades. In this three-block copolymer, the styrene blocks are separated by a butadiene block. They can form a three-dimensional elastic network of the polystyrene phase in bitumen, connected by a polybutadiene phase[5]. SBS polymer-modified bitumen has shown greater resistance to rutting, fatigue cracking, low-temperature cracking, stripping, and temperature sensitivity[6]. SBS copolymer is known as a thermoplastic-elastomer additive. The styrene provides strength, while the butadiene provides flexibility. The viscosity of SBS polymer bitumen is higher than pure bitumen, and it has better adhesiveness with aggregates, which increases the durability of the mixture. However, SBS tends to segregate from the bitumen during storage. The polymer phase in the bitumen storage tank segregates from the bitumen phase, causing problems in bitumen storage. In this situation, SBS particles accumulate suspended on the bitumen surface, resulting in the softening point of the upper third of the polymer bitumen containing more SBS

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than the lower part, and this difference is generally much greater than the 2.2 °C within the allowable range[7]. In another study by Glooyak[8], nano-clay was able to completely solve the storage instability problem of SBS polymer bitumen.

Recent studies have also shown promising results using other nanomaterials. For example, the use of graphene nanoplatelets has been found to significantly enhance the fatigue resistance and thermal stability of asphalt mixtures. Additionally, the incorporation of titanium dioxide nanoparticles has demonstrated improved anti-aging properties and reduced oxidative stress in bitumen[9].

Huang[10] used the multiple stress creep recovery (MSCR) test to investigate the effect of a cross-linking agent and SBS content on SBS-modified asphalt. The results showed that the effect of increasing SBS content was more prominent for binders at lower SBS content. The MSCR test failed to distinguish between 5.0% and 5.5% SBS-modified asphalt in the study[10].

Nanomaterials have high reactivity and specific surface area due to their very small particle size (less than 100 nm). Experiments performed on bitumen and asphalt mixtures containing modified bitumen with nano-clay have shown that nano-clay improves the rheological properties of bitumen and the mechanical properties of asphalt, such as tensile strength, creep resistance, and fatigue strength. Different physical properties of bitumen (toughness and tensile strength, tensile modulus, flexural strength, and thermal stability) are improved by adding clay nanocomposite. Bitumen modified with clay nanocomposite has more elasticity and less energy loss than unmodified bitumen[11]. Adding Nano-silica to pure bitumen has been improving the resiliency of bitumen. The low-temperature performance characteristics, properties, and stress drop capacity of Nano-silica modified bitumen are similar to those of pure bitumen. In other words, unlike other nanomaterials, this nanomaterial does not worsen the performance at low temperatures. Also, by adding Nano-silica to pure bitumen, the anti-aging properties, cracking and corrosion resistance, and anti-stripping properties of bitumen have been significantly improved[12]. The rheological investigations showed that the complex modulus of base bitumen increases by increasing the percentage of Nano-silica from 2 to 6 wt%. Phase angle and rut factor for the Nano-silica modified bitumen have also decreased significantly. From rheological analysis, 6 wt% Nano-silica has been selected as the optimum content[13].

Arabani[13] investigated the fatigue performance of Nano-silica-modified asphalt mixtures after short-term aging. In this study, Nano-silica at 2%, 4%, and 6% by weight of bitumen and the indirect tensile fatigue test were used. According to this study, Nano-silica at 4% increased the fatigue life of asphalt mixtures by 37%, and 4% was mentioned as the optimal amount of Nano-silica for fatigue resistance[13].

Another recent study highlighted using carbon nanotubes to improve the mechanical properties and durability of asphalt mixtures. The addition of carbon nanotubes enhanced the tensile strength, elasticity, and thermal stability of the bitumen, making it a promising material for future applications[14].

3 MATERIAL AND METHODS

3.1 Bitumen

The choice of bitumen used is affected by ambient temperature. Pure bitumen with a penetration of 85/100 is used for cold regions, while bitumen with a penetration of 60/70 is used for temperate regions. In this project, bitumen 60/70 from the Tehran refinery was used. The results of the bitumen test are described in Table 1.

3.2 Additives used in asphalt mixture samples

The SBS polymer used is a linear molecular structure, branded as SBS 501LG, and the Nano-silica used is the Nano-silica (Nano-SiO_2) type with particle diameters ranging from 11 nm to 13 nm. The specifications of the SBS and Nano-silica polymers are listed in Table 2 and 3.

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Table 1. Results of pure bitumen test

Test	Results (°C)	Size range (°C)	Adequacy
Penetration (25 °C), 0.1 mm	65	70-60	Ok
Softening point (°C)	50.3	56-49	Ok
Flash point (°C)	312	Min 232	Ok
Ductility (25 °C), cm	More than 100	Min 100	Ok
Rotational viscosity at 135 °C [PA·S]	0.323	Max 3	Ok
Rolling thin-film oven test (R)%	0.07	Max 1	Ok
G*/sinδ in dynamic shear rheometer test (pa) in 64 °C in 10 radian s^{-1} (1)	1057	Min 1000	Ok
Creep stiffness in bending beam rheometer (–6 °C), mpa1	255	Max 300	Ok
M in bending beam rheometer (–6 °C), MPA (2)	0.297	Min 0.3	Ok
Based on (1) and (2), the performance score of PG 64-16			

Table 2. Specifications of SBS used

Description	SBS 501LG
Molecular structure	Linear
Ratio of styrene to butadiene	31 styrene to 69 butadiene
Specific weight (g cm^{-3})	0.94
The amount of oil	0
Melting index (g)-200 ℃	Less than one
Hardness (shore A)	79
Soluble viscosity with toluene (cP)	13.40

Table 3. Specifications of Nano-silica used

Molecular structure	Spherical
Soundness	More than 99%
True specific gravity (g cm^{-3})	0.10
Appearance specific gravity (g cm^{-3})	2.4
Special area (m^2 g^{-1})	200
Particle size (nm)	11 to 13
Colour	White

3.3 Aggregates used in asphalt mix samples

The aggregates used in this research are dolomitic calcareous aggregates. The gradation and mixing ratio of the aggregates are shown in Table 4.

3.4 Preparation of asphalt mixture sample

To prepare dual-bitumen and SBS compounds, as well as triple-bitumen and SBS and Nano-silica compounds, a high shear mixer was utilised. For composite samples of 60/70 bitumen and SBS polymer, the bitumen was initially heated to 176 °C and maintained at this temperature for better mixing. The SBS polymer was slowly added to the bitumen while the mechanical mixer rotated. The bitumen-polymer mixture was thoroughly blended at 176 °C in a high shear mixer at 4,000 rpm for two hours.

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Table 4. Gradation and mixing ratio of aggregates used in the study

Sieve size	Percent finer by weight (%)	Range based on super pave (SHRP A-407)
3/4”	100	100
1/2”	95	100-90
3/8”	83	< 90
4#	60	-
8#	34	58-28
50#	10	-
200#	5	10-2

For triple-bitumen and SBS and Nano-silica compounds, the SBS polymer was gradually added to the mixture, and further mixing was conducted in a high shear mixer for an additional 30 minutes at 4,000 rpm. Table 5 describes the types of designs studied in this research.

Table 5. Different combinations of bitumen and additives

The first group (combination of pure bitumen with SBS polymer)	The second group (combination of pure bitumen with 4.5% polymer SBS polymer and Nano-silica)
Pure bitumen with 2.5% SBS	Pure bitumen with 4.5% SBS and 1% Nano-silica
Pure bitumen with 3.5% SBS	Pure bitumen with 4.5% SBS and 2% Nano-silica
Pure bitumen with 4.5% SBS	Pure bitumen with 4.5% SBS and 3% Nano-silica
Pure bitumen with 5.5% SBS	Pure bitumen with 4.5% SBS and 4% Nano-silica

In this research, the Superpave mix design method was employed. Initially, asphalt mixture samples containing 5% pure bitumen were prepared using a gyratory compactor. Subsequently, the following parameters were determined: maximum theoretical specific gravity (GMM), bulk density of asphalt mixture (GMB), percentage of air voids in the asphalt mixture (VA), percentage of air voids in the mineral aggregate (VMA), and percentage of air voids filled with bitumen (VFA).

By employing a trial-and-error approach and aiming for a 4% air voids target in the mixture, the amount of bitumen was adjusted. Ultimately, the final design included 3.5% bitumen by weight of the asphalt mixture.

4 RESULTS AND DISCUSSION

After fabricating bitumen samples with additives as detailed in Table 5, various tests were conducted on both pure and modified bitumen samples. These tests included polymer separation tests, dynamic shear rheometer (DSR) tests, moving thin film (MTF) tests, and rotational viscosity tests. Additionally, dynamic creep tests were performed on asphalt mixture samples.

4.1 Polymer segregation

The polymer segregation test is a critical laboratory criterion used to evaluate the propensity of a polymer to separate from modified polymer bitumen under storage conditions. This test assesses the stability of the polymer-bitumen blend against temperature variations, typically using the softening point test method. The results of polymer segregation tests, conducted according to ASTM D7173 standard on various compounds of SBS and Nano-silica polymer-modified bitumen are illustrated in Fig. 1.

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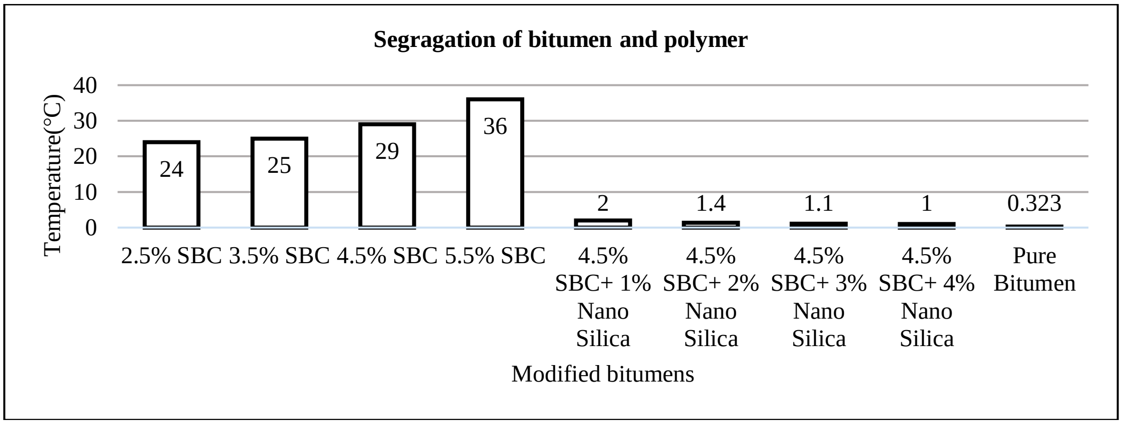

Fig. 1. Segregation test results of bitumen, polymer, and Nano-silica compounds.

Based on the test results, the addition of SBS to polymer-modified bitumen leads to varying degrees of segregation between the bitumen and polymer phases. The maximum observed segregation test value reaches as high as 24 °C, which significantly exceeds the permissible limit of 2.2 °C specified by the ASTM D7173 standard. This extensive segregation occurs due to the predominant presence of the polymer phase, which complicates achieving the desired homogeneity during the mixing of asphalt mixtures. However, when Nano-silica is incorporated into the bitumen-polymer mixtures, starting from a minimum of 1% by weight of bitumen, the segregation of the bitumen phase from the polymer phase is effectively controlled. The addition of Nano-silica ensures that the maximum segregation value remains within the acceptable limit of 2.2 °C, as mandated by the ASTM D7173 standard. This finding underscores Nano-silica's role in improving the stability and uniformity of the bitumen-polymer blend, thereby addressing segregation issues encountered with SBS-modified bitumen.

Nano-silica enhances the interfacial interaction between the bitumen and polymer phases, thereby minimising phase separation during storage and ensuring consistent performance characteristics in asphalt mixtures. This capability of Nano-silica to mitigate segregation not only improves the overall quality of polymer-modified bitumen but also enhances the durability and performance of asphalt pavements in service.

4.2 Dynamic shear rheometer

To assess the viscoelastic properties and rheology of bitumen, a Dynamic Shear Rheometer (DSR) is employed. Bitumen exhibits viscoelastic behaviour, particularly at medium temperatures, making it essential to analyse parameters that consider the influence of temperature and loading duration. These parameters include the complex modulus (G*) and the phase angle (δ), which are pivotal in characterising the material's response to deformation.

The complex modulus (G*) represents the overall stiffness and resistance of bitumen against deformation, reflecting its ability to maintain structural integrity under varying conditions. Meanwhile, the phase angle (δ) indicates the proportion of reversible to irreversible deformations, providing insights into energy dissipation characteristics[15].

The results of the DSR test, specifically the parameter (G*/sinδ), are reported at elevated temperatures ranging from 40 to 80 °C. Both non-aged bitumen specimens and samples subjected to short-term aging through the Rolling Thin Film Oven (RTFO) method are evaluated. Table 6 and 7 present these findings, detailing how the viscoelastic properties of bitumen change under different aging conditions. Additionally, Fig. 2, 3, 4, and 5 provide graphical representations of these results, offering a visual understanding of the bitumen's rheological behaviour across the temperature range.

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The DSR test outcomes play a critical role in assessing the performance of bitumen, especially in modified formulations such as those incorporating additives like SBS and Nano-silica. These evaluations help optimise asphalt mixture designs to enhance durability and performance under challenging environmental and traffic conditions.

The results of the DSR test (G*/sinδ) at high temperatures (40, 50, 60, 70 and 80 °C) for non-aged bitumen specimens and specimens subjected to short-term aging by RTFO are presented in Table 6 and 7 and plotted in Fig. 2, 3, 4 and 5.

Table 6. Different combinations of bitumen and additives

	Temperature (°C)	Bitumen 60/70	Bitumen 60/70 + SBS				Bitumen 60/70 + 4.5% SBS + Nano-SiO_2			
			2.5%	3.5%	4.5%	5.5%	1%	2%	3%	4%
Rheological behaviour G*/sinδ (kPa)	40	32.676	80.612	118.342	162.875	237.958	220.327	317.964	504.680	657.205
	50	9.015	23.136	37.707	51.962	70.226	71.76	97.893	145.154	184.321
	60	1.788	6.398	9.754	13.062	20.725	17.874	25.022	37.131	49.621
	70	0.477	1.688	2.917	3.830	6.116	5.466	7.188	9.337	13.449
	80	0.148	0.634	0.945	1.474	1.805	1.979	2.542	3.337	4.492

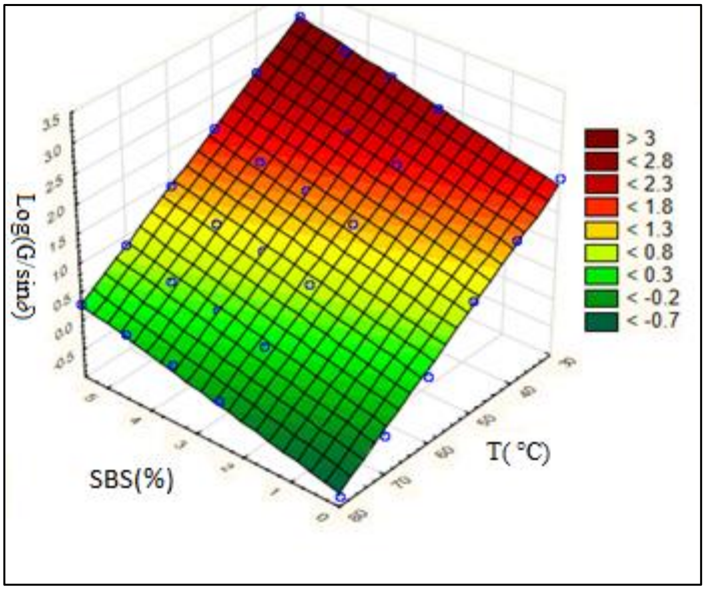

Fig. 2. Change in log(G∗/sinδ) with temperature and SBS polymer content for non-aged bitumen

Equations 1 and 2 estimate the results of G*/sinδ under non-aging conditions.

$$\log(G^*/\sin\delta) = 3.602 + 0.16 \times SBS - 0.053 \times T \qquad r\text{^}2 = 0.99 \qquad (1)$$

$$\log(G^*/\sin\delta) = 4.4 + 0.142 \times \text{Nano-}SiO_2 - 0.054 \times T \qquad r\text{^}2 = 0.99 \qquad (2)$$

In the above equations, the values of SBS and Nano-silica are in percentage and T is the temperature in Celsius.

Equations 3 and 4 estimate the results of G*/sinδ under aging conditions.

$$\log(G^*/\sin\delta) = 3.894 + 0.179 \times SBS - 0.053 \times T \qquad r2 = 0.99 \qquad (3)$$

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$$\log(G^*/\sin\delta) = 4.38 + 0.14 \times \text{Nano-SiO}_2 - 0.054 \times T \quad r2 = 0.99 \tag{4}$$

In the equations above, the values of SBS and Nano-silica are expressed as percentages, and T represents the temperature in Celsius.

As shown in Table 6 and 7, across temperatures ranging from 40 to 80 °C, increasing the proportion of SBS polymer in pure bitumen results in continuously rising parameter values($G^*/\sin\delta$), which signifies enhanced rutting resistance and high-temperature performance of modified bitumen samples. This trend is attributed to the increased mixed modulus (G^*) and reduced phase angle (δ) achieved by adding SBS polymer to pure bitumen under high-temperature conditions.

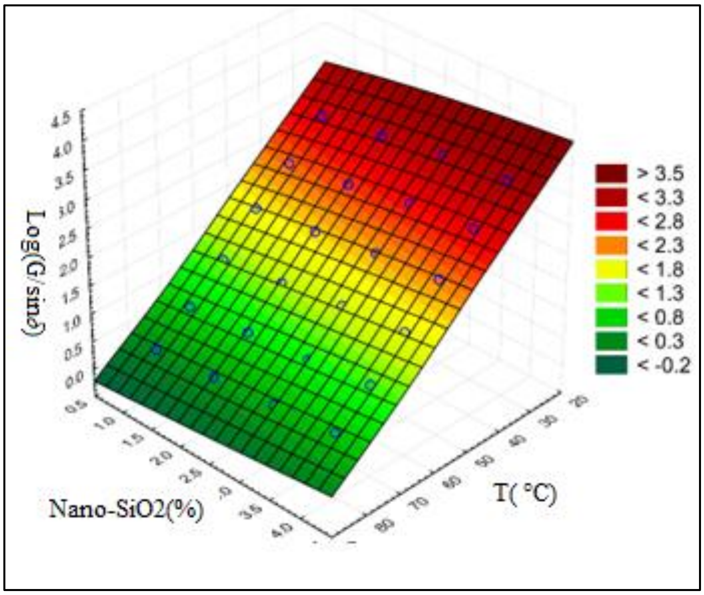

Fig. 3. Change in log ($G^*/\sin\delta$) with temperature and Nano-silica content for non-aged bitumen.

Table 7. The DSR test ($G^*/\sin\delta$) results at test temperatures and different compounds for short-term aging bitumen

	Temperature (°C)	Bitumen 60/70	Rheological behaviour $G^*/\sin\delta$ (kPa), Bitumen 60/70 + SBS				Rheological behaviour $G^*/\sin\delta$ (kPa), Bitumen 60/70 + 4.5% SBS + Nano-SiO_2			
			2.5%	3.5%	4.5%	5.5%	1%	2%	3%	4%
Rheological behaviour $G^*/\sin\delta$ (kPa)	40	65.352	161.254	260.350	346.920	630.350	464.456	650.620	1,100.250	1,320.256
	50	18.93	48.580	81.070	114.320	185.190	155.620	209.620	315.850	399.520
	60	3.576	14.075	28.083	26.058	50.500	36.510	52.556	79.156	108.210
	70	1.049	3.689	6.420	9.062	15.160	12.640	15.266	19.465	26.900
	80	0.304	1.314	2.090	3.250	4.256	4.090	5.592	7.250	9.250

Furthermore, the study reveals that bitumen samples modified with 5.5% SBS exhibit the highest parameter values ($G^*/\sin\delta$) compared to other formulations at temperatures ranging from 40 to 80 °C. The addition of Nano-silica to SBS polymer-modified bitumen further enhances the parameter values ($G^*/\sin\delta$). across the same temperature range, thereby improving rutting resistance and high-temperature performance. Notably, increasing the Nano-silica content from 1% to 4% results in a continuous increase in ($G^*/\sin\delta$). This enhancement is attributed to the increased mixed modulus and reduced phase angle resulting from

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Nano-silica's interaction with bitumen and SBS polymer components. Nano-silica nanoparticles facilitate strong adhesion with bitumen and polymer compounds through absorption, thereby minimizing phase angle (δ) and reducing viscosity loss, which enhances the high-temperature performance of modified bitumen samples.

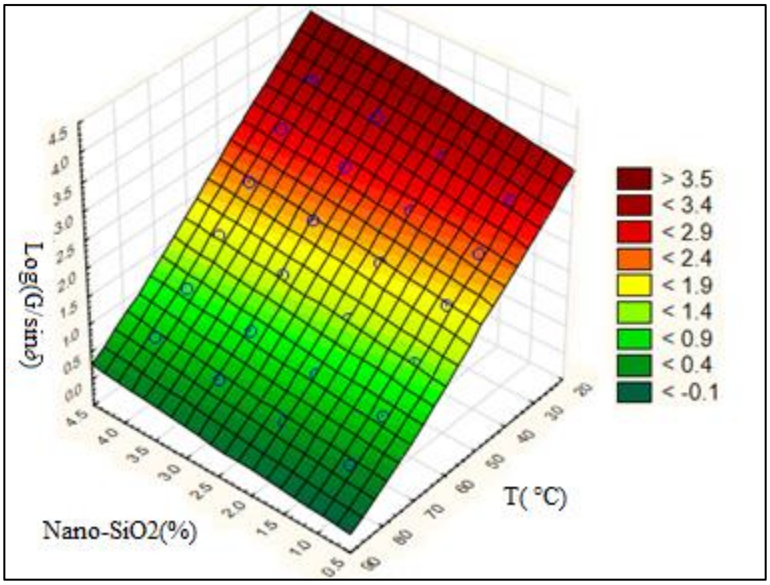

Fig. 4. Change in log(G∗/sinδ) with temperature and Nano-silica content for aged bitumen.

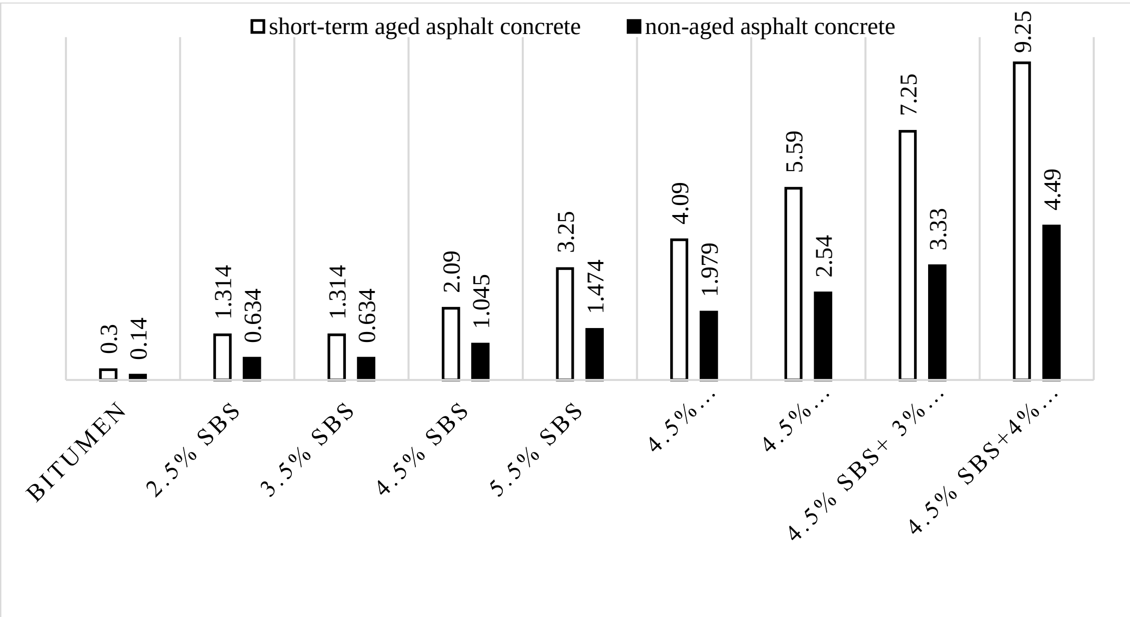

Fig. 5. Change in (G∗/sinδ) for both non-aged and short-term aged bitumen samples at 80 °C.

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According to the findings, bitumen compositions containing 4% Nano-silica exhibit the highest parameter values (G*/sinδ) compared to other formulations at temperatures ranging from 40 to 80 °C. Fig. 5 illustrates the changes in (G∗/sinδ) for both non-aged and short-term aged bitumen samples at 80 °C.

According to the SHRP A-407 guidelines, a minimum parameter value of G∗/sinδ of 1 kPa is required for non-aged bitumen, and 2.2 kPa for short-term aged bitumen. Based on these criteria, bitumen compositions containing 4.5% and 5.5% SBS polymer, as well as those combining 4.5% SBS polymer with varying amounts of Nano-silica, meet these standards at 80 °C. These formulations demonstrate adequate rutting resistance and high-temperature performance, as their G∗/sinδ values exceed the specified thresholds. The addition of Nano-silica further improves the viscoelastic properties of SBS-modified bitumen, ensuring compliance with SHRP A-407 requirements even under high-temperature conditions.

4.3 Rotational viscosity

The rotational viscometer test provides a method to measure the viscosity of bitumen by rotating a rod within a chamber. This test assesses the torque required to maintain a constant rotational speed at a specified temperature, thereby determining the shear stress at the rod surface using Equation 5.

$$\tau_b = T/(2\pi_i^2 l) \tag{5}$$

where τ_b represents the shear stress.

The results of rotational viscosity tests, conducted according to the AASHTO T-316 standard, are depicted in Fig. 6. These tests encompass both dual formulations of bitumen and SBS polymer compounds, as well as triple compositions incorporating bitumen, SBS polymer, and Nano-silica. The figures illustrate how viscosity values vary across different formulations, providing insights into how additives like SBS polymer and Nano-silica influence the flow properties of bitumen under standardized testing conditions.

As shown in Fig. 6, the cyclic viscosity of bitumen increases steadily with the addition of SBS and Nano-silica. This phenomenon arises from forming three-dimensional networks within the bitumen matrix, facilitated by the long, branched chains of SBS polymer and the dispersion of Nano-silica particles. These networks enhance the stiffness of the bitumen, reducing its fluidity and consequently increasing viscosity.

However, excessive viscosity can pose challenges during the asphalt mixing and compaction processes. According to SHRP A-407 guidelines, bituminous materials intended for asphalt production must exhibit rotational viscosity values below 3 Pascal-seconds at 135 °C to ensure practical usability. Notably, formulations containing SBS and 4% Nano-silica meet this criterion, demonstrating controlled viscosity levels suitable for effective asphalt mixture production.

4.4 Dynamic creep test results

The dynamic creep test, conducted according to BS EN 12697-25:2005 standard, is crucial for assessing the high-temperature performance of asphalt mixture samples. Asphalt samples, prepared using the Superpave mix design method and compacted with a gyratory compactor, were subjected to dynamic creep testing using a Universal Testing Machine (UTM). According to the standard, asphalt specimens measuring 150 mm in diameter and 60 mm in height, with a specified air voids content of 7%, were tested under unsaturated conditions at stress levels of 200 kPa and 450 kPa, and at temperatures of 50 °C and 60 °C. The UTM device measured both the numeric modulus and cumulative permanent deformation for all design combinations. Fig. 7 illustrates the cumulative permanent strain values of the asphalt mixtures after 10,000 loading cycles under a stress level of 200 kPa, at temperatures of 50 °C and 60 °C. These results provide insights into the rutting resistance and durability of the asphalt mixtures under simulated high-temperature conditions, aiding in the evaluation of their suitability for practical applications in pavement construction.

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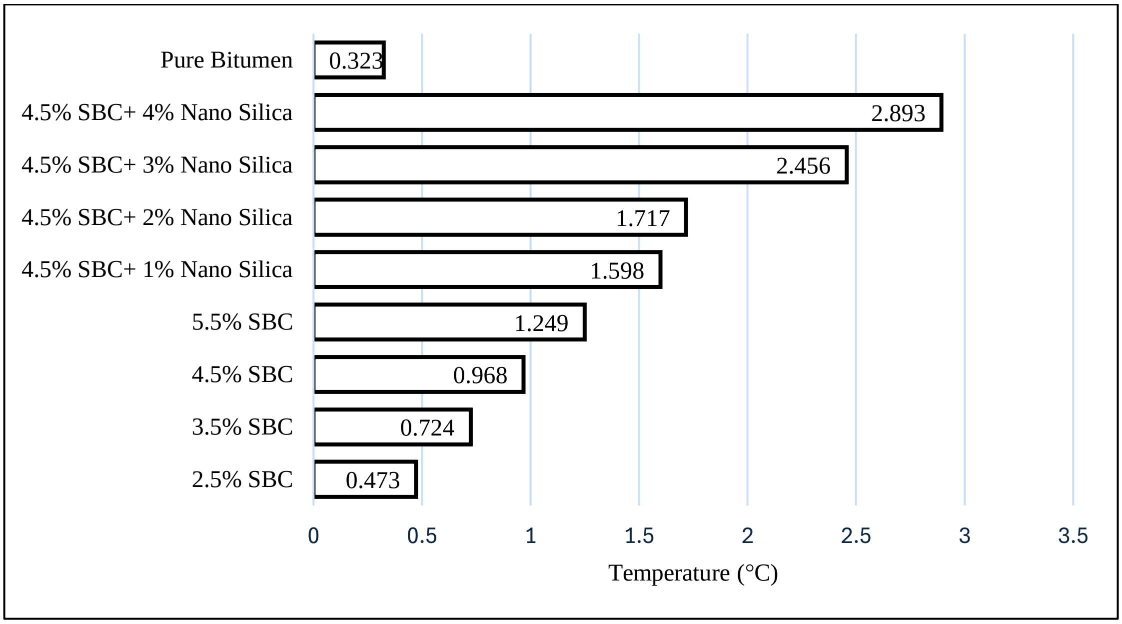

Fig. 6. Viscosity (135 °C) in various triple compounds of bitumen, nano and polymer.

The dynamic creep test results highlight the significant impact of combining SBS polymer with Nano-silica in reducing cumulative strain and enhancing the rutting resistance of asphalt samples. Nano-silica particles enhance adhesion between bitumen and aggregates by adsorbing onto aggregate surfaces, thereby improving the overall strength of the asphalt mixture against applied stresses, and reducing permanent cumulative strain.

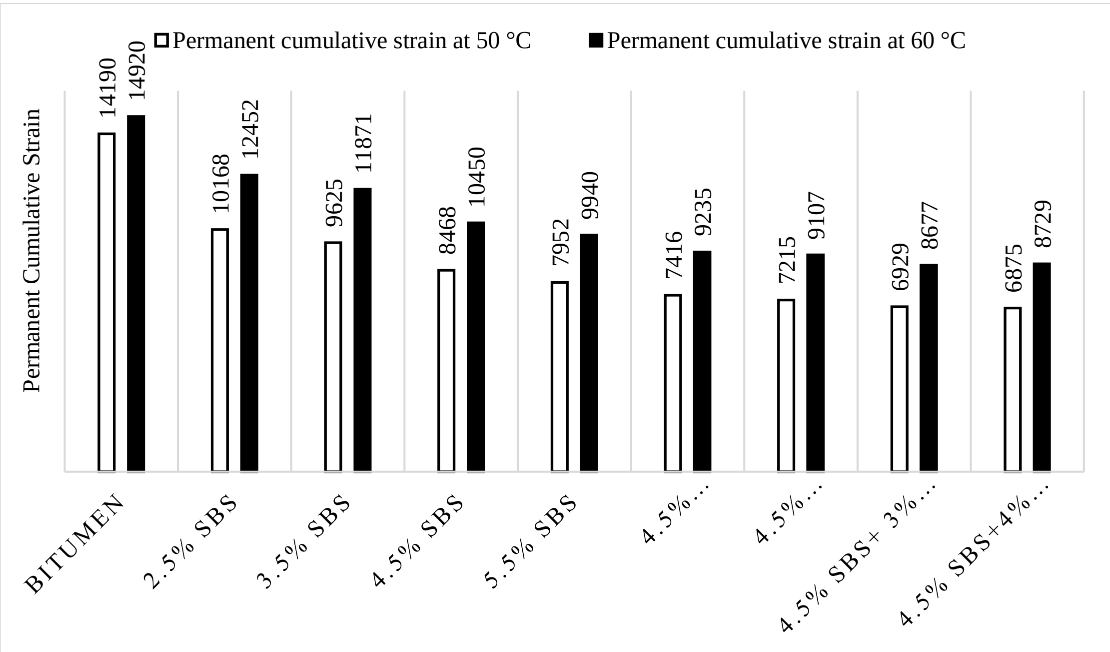

Fig. 7. Permanent cumulative strain of asphalt mixtures in the 10,000th loading cycle at a stress level of 200 kPa and temperatures of 50 °C and 60 °C.

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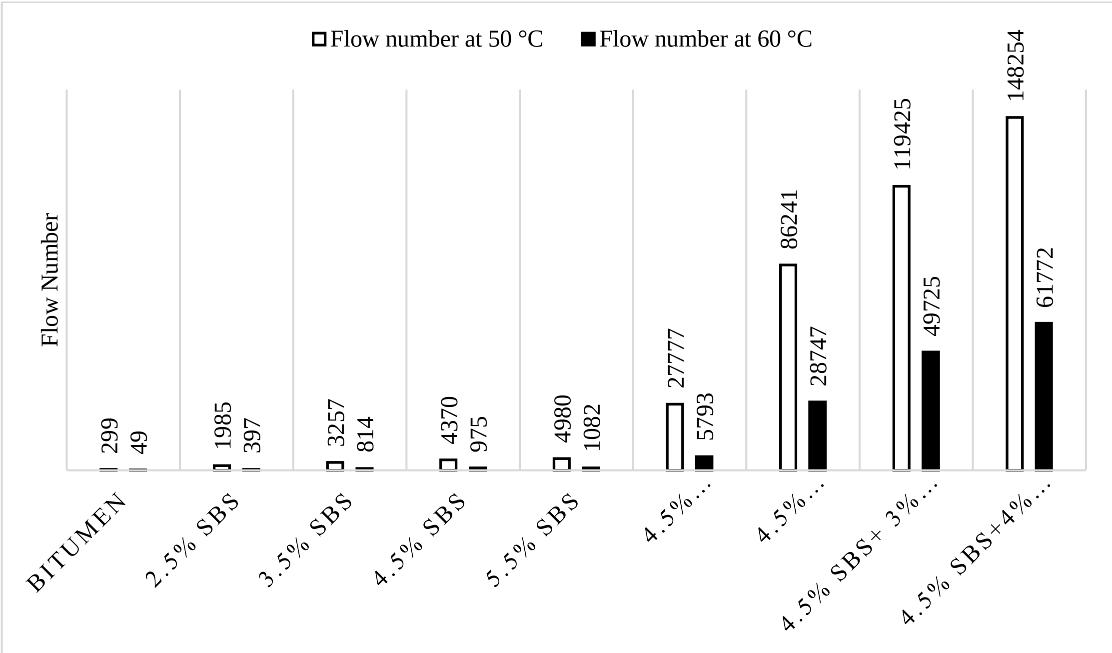

Fig. 8. Psychic number of asphalt mixtures at a stress level of 450 kPa and at temperatures of 50 °C and 60 °C according to the dynamic creep test.

Specifically, the combination of 4.5% SBS polymer and 4% Nano-silica demonstrates substantial benefits, reducing cumulative strain by 51% and 41% compared to the control sample with pure bitumen at temperatures of 50 °C and 60 °C, respectively. These results underscore the effectiveness of SBS polymer and Nano-silica in enhancing the durability and performance of asphalt mixtures under high-temperature conditions.

Fig. 8 illustrates the flow rates of asphalt mixtures under a stress level of 450 kPa and temperatures of 50 °C and 60 °C. The flow rates, influenced by the cumulative strain results from the dynamic creep test, show significant increases with the addition of SBS polymer and Nano-silica. In particular, the sample containing 4.5% SBS polymer and 4% Nano-silica exhibits flow rates 1,260 times higher at 50 °C and 495 times higher at 60 °C compared to the sample with pure bitumen.

5 CONCLUSION

This study investigated the synergistic effects of Nano-silica on SBS polymer-modified bitumen, focusing on their combined impact on bitumen's rheological properties at high temperatures and the rutting potential of asphalt mixtures. The conclusions drawn from this research are summarized as follows:

(i) Polymer-bitumen compositions exhibit significant phase separation issues with the addition of SBS polymer, where the bitumen phase separates from the polymer phase by more than 24 °C, complicating asphalt mixture performance. However, the addition of 1% Nano-silica effectively resolves this stability concern in polymer-bitumen blends.

(ii) The results from the rotational viscometer tests indicate that both SBS and Nano-silica polymers increase the viscosity of bitumen. Specifically, the rotational viscosity of pure bitumen increased by 300% with 4.5% SBS and by 500% with 4.5% SBS and 1% Nano-silica,

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compared to pure bitumen. Importantly, all tested compounds met the SHRP A-407 criteria for viscosity.

(iii) The addition of SBS to pure bitumen results in a continuous increase in the G*/sinδ parameter across temperatures ranging from 30 °C to 80°C, at a constant frequency of 10 radians per second. This enhancement signifies improved resistance to deformation and better high-temperature performance of the modified bitumen samples. Furthermore, the incorporation of Nano-silica into SBS-modified bitumen further improves its high-temperature performance. At 80 °C, the G*/sinδ values were 0.148 for pure bitumen, 1.474 for 4.5% SBS-modified bitumen, and 492/4 for the composition with 4.5% SBS polymer and 4% Nano-silica under non-aged conditions.

(iv) The dynamic creep test results conducted separately at 50 °C and 60 °C for asphalt mixtures demonstrate that the addition of SBS polymer to base bitumen, and subsequently Nano-silica to SBS-modified bitumen, significantly reduces cumulative permanent strain and increases asphalt flow rates. These outcomes indicate enhanced performance of the modified asphalt mixtures at high temperatures, thereby reducing the risk of rutting failure.

The findings of this research show that by adding SBS polymer and Nano-silica to bitumen greatly increases the resistance of the asphalt mixture. This issue can significantly increase the life of asphalt roads in hot weather areas. Therefore, in tropical regions, the unevenness of the asphalt road is reduced, and the safety of drivers increases.

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CONFLICT OF INTEREST

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

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Methodology: M. Mirshekarian Babaki
Formal analysis: M. Mirshekarian Babaki
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REFERENCES

1. Rezaei, S., Ziari, H., & Nowbakht, S. (2016). High-temperature functional analysis of bitumen modified with composite of nano-SiO_2 and styrene butadiene styrene polymer. *Petroleum Science and Technology, 34*(13), 1195-1203. https://doi.org/10.1080/10916466.2016.1188112

2. Zhang, J., Simate, G. S., Lee, S. I., Hu, S., & Walubita, L. F. (2016). Relating asphalt binder elastic recovery properties to HMA crack modeling and fatigue life prediction. *Construction and Building Materials*, *111*, 644-651. https://doi.org/10.1016/j.conbuildmat.2016.02.175

3. Wang, Y., Sun, L., & Zhou, J. (2015). Pavement performance evaluation of recycled styrene-butadiene-styrene-modified asphalt mixture. *International Journal of Pavement Engineering*, *18*(5), 404-413. https://doi.org/10.1080/10298436.2015.1095296

4. Wen, G., Zhang, Y., Zhang, Y., Sun, K., & Fan, Y. (2002). Rheological characterization of storage-stable SBS-modified asphalts. *Polymer Testing*, *21*(3), 295-302. https://doi.org/10.1016/s0142-9418(01)00086-1

5. Bulatović, V. O., Rek, V., & Marković, K. J. (2014). Effect of polymer modifiers on the properties of bitumen. *Journal of Elastomers and Plastics*, *46*(5), 448-469. https://doi.org/10.1177/0095244312469964

6. Liang, M., Liang, P., Fan, W., Qian, C., Xue, X., Jian, S., & Gao, N. (2015). Thermo-rheological behavior and compatibility of modified asphalt with various styrene-butadiene structures in SBS copolymers. *Materials and Design*, *88*, 177-185. https://doi.org/10.1016/j.matdes.2015.09.002

7. Galooyak, S. S., Goli, A., & Zanjirani, H. (2015). Performance evaluation of nano-silica modified bitumen. *International Journal of Transportation Engineering*, *3*(1), 55-66. https://doi.org/10.22119/IJTE.2015.13377

8. Galooyak, S. S., Dabir, B., Nazarbeygi, A. E., & Moeini, A. (2010). Rheological properties and storage stability of bitumen/SBS/montmorillonite composites. *Construction and Building Materials*, *24*(3), 300-307. https://doi.org/10.1016/j.conbuildmat.2009.08.032

9. Habbouche, J., Boz, I., Diefenderfer, B. K., Smith, B. C., & Adel, S. H. (2021). State of the practice for high polymer-modified asphalt binders and mixtures. *Transportation Research Record*, *2675*(7), 235-247. https://doi.org/10.1177/0361198121995190

10. Huang, W., & Tang, N. (2015). Characterizing SBS modified asphalt with sulfur using multiple stress creep recovery test. *Construction and Building Materials*, *93*, 514-521. https://doi.org/10.1016/j.conbuildmat.2015.06.041

11. Jahromi, S. G., & Khodaii, A. (2009). Effects of nanoclay on rheological properties of bitumen binder. *Construction and Building Materials*, *23*(8), 2894-2904. https://doi.org/10.1016/j.conbuildmat.2009.02.027

12. Shafabakhsh, G., Mirabdolazimi, S. M., & Sadeghnejad, M. (2014). Evaluation the effect of nano-TiO_2 on the rutting and fatigue behavior of asphalt mixtures. *Construction and Building Materials*, *54*, 566-571. https://doi:10.1016/j.conbuildmat.2013.12.064

13. Arabani, M., Haghi, A. K., & Tanzadeh, R. (2012). Laboratory study on the effect of nano-SiO_2 on improvement fatigue performance of aged asphalt pavement. In *Proceedings of the 4th International Conference on Nanostructures* (*ICNS4*), Kish Island, Iran. https://www.researchgate.net/publication/351357111_Laboratory_study_on_the_effect_of_Nano-SiO₂_on_improvement_fatigue_performance_of_aged_asphalt_pavement

https://doi.org/10.24191/jsst.v4i2.85

14. Eisa, M. S., Mohamady, A.., Basiouny, M. E., Abdulhamid, A., & 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

15. Shi, X., Cai, L., Xu, W., Fan, J., & Wang, X. (2018). Effects of nano-silica and rock asphalt on rheological properties of modified bitumen. *Construction and Building Materials*, *161*, 705-714. https://doi.org/10.1016/j.conbuildmat.2017.11.162

https://doi.org/10.24191/jsst.v4i2.85