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Laboratory Study on the Combined Effect of Novolac and SBS Polymers on the Physical and Mechanical Properties of Hot Mix Asphalt

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Abstract: With the growing need for sustainable and long-lasting paving materials, researchers have turned to innovative additives to improve the performance of bitumen and asphalt mixtures. Conventional bitumen often fails under heavy traffic loads and harsh climatic conditions, necessitating modification. This study aimed to improve the performance of bitumen and hot mix asphalt (HMA) by co-modifying them with a 4% styrene-butadiene-styrene (SBS) polymer and varying ratios of novolac resin. The results offered that the optimum ratio was 2% Novolac with 4% SBS. The physical and mechanical properties were evaluated through penetration tests, softening point, penetration index, dynamic shear rheometer (DSR), Marshall Stability tests, indirect tensile strength (ITS), tensile strength ratio (TSR), and wheel tracking. The modified mixture offered an improvement in penetration index from -1.89 to +1.3, a 38.7% increase in stability, a 40.9% increase in indirect tensile strength (ITS), and a 66.2% increase in moisture resistance. In comparison, the depth of permanent deformation was reduced by 58%. These results indicate significant improvements in stability, moisture, and deformation resistance, making it a promising option for developing more efficient asphalt mixtures. It also aligns with sustainable construction goals by reducing the need for frequent maintenance and extending pavement life.

Keywords: Mechanical performance, Modified bitumen binder, Novolac, Styrene butadiene styrene (SBS)

Introduction

Flexible pavement can be considered the most widely used types of pavement worldwide. Approximately 90% of the world's highways use asphalt pavement. It consists of approximately 95% mineral aggregate and 5% bituminous binder, which is compacted using an asphalt mixture. It consists of asphalt concrete, a granular base, and sub-layers, typically resting on a base layer (Chang et al., 2020). However, the performance of asphalt pavements deteriorates severely due to increased axle loads and traffic volume, as well as wear, fatigue, and cracking caused by low temperatures (Al-Nawasir & Al-Humeidawi, 2023b). These drawbacks reduce highway lifespan and increase maintenance costs. Furthermore, these drawbacks are related to the viscosity, strength, elasticity, and average plastic deformation of the bitumen binder (Liang et al., 2015). Therefore, efforts have focused on enhancing highway durability and structural strength through improved structural designs, enabling them to withstand heavy loads and adapt to modern transportation demands. (Al-Nawasir & Al-Humeidawi, 2023b; Khudhair & Kadhim, 2018).

It's important to note that asphalt mixtures are notably affected by properties and characteristics of the bitumen binder, particularly its elasticity, viscosity, cohesion, and stability. It has been concluded that developing the performance commonly used in highway and airport runway construction by enhancing the binder the essential and active component of the asphalt mixture is a relatively effective method for improving the mechanical performance nds. For this reason, bitumen stabilization has become increasingly important to maintain pavement

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load-bearing capacity, strengthen the bond between the bitumen and aggregate, and prevent pavement damage due moisture (Fini et al., 2012; Mehmood et al., 2025). In recent years, asphalt modifiers such as polymers have been increasingly used to improve highway strength and address the challenges of increased traffic and high temperatures. SBS (styrene-butadiene-styrene) is widely available, making it one of the most common flexible polymers (Stelescu et al., 2022). The choice of polymer depends on several factors, including highway location, available local resources, environmental friendliness, and cost (Ziari et al., 2015). Phenolic resins have been considered for use as asphalt modifiers because they increase durability and rigidity in harsh weather conditions, possess high thermal stability, have a strong molecular structure, and exhibit good bonding with asphalt. Novolac is an example. It is worth noting that when formaldehyde reacts with a phenolic compound in an acidic medium, it produces novolac, which exhibits high resistance to aging and oxidation (Al-Humeidawi et al., 2018). There are very few studies that have demonstrated the combined impact of SBS and Novolac on the mechanical and physical characteristics of asphalt. Although SBS and Novolac have excellent properties when used as asphalt modifiers, most research has focused on studying each material individually, creating a knowledge gap in understanding their combined effect. This study has a specific objective: to determine the effect of SBS and Novolac individually, and then their combined effect, on the characteristics of modified asphalt. Laboratory experiments were conducted using typical testing methods to measure permeability, softening point, ductility, and rheological performance. The results may contribute to the development of stronger and more thermally stable asphalt, particularly in areas with high traffic and temperatures. The study also provides a sustainable approach by enhancing binder performance and extending pavement service life.

Materials and Experimental Design

Aggregates

This investigation used local sources to obtain aggregates from Badura quarries in western Iraq with a (NMAS) of 12.5 mm. The aggregate grade used in the mix design was the average for the Iraqi standard (see Table 1). Limestone dust was used as mineral filler. It mostly passes through Sieve No. 200 (0.075 mm). Table 3 shows physical characteristics of this limestone dust. Crushed aggregate with acute angles and rough surfaces was used; crushed sand was used. Tests were conducted on coarse and fine aggregates according to ASTM standards to ensure that the aggregates met the specifications shown in Table 2. All tests were conducted in the laboratories of Al-Qadisiyah University. Figure 1 shows the physical appearance of aggregates used in mixture.

Table 1. Grading of aggregates employed in the surface layer (SCRB, 2003)

Sieve size	mm	Specification limits SCRB (%)	Passing for selected Gradation (%)
3/4	19	100	100
1/2	12.5	90-100	95
3/8	9.5	76-90	83
No.4	4.75	44-74	59
No.8	2.36	28-58	43
No.50	0.3	5-21	13
No.200	0.075	4-10	7

Table 2. Characteristics of coarse and fine aggregates

Property	ASTM Designation	Coarse aggregate	Fine aggregate
Bulk Specific Gravity	C127,128(ASTM, 2015b)	2.57	2.6
SSD Specific Gravity	C127,128(ASTM, 2015b)	2.61	2.64
Apparent specific gravity	C127,128(ASTM, 2015b)	2.68	2.81
Absorption %	C127,128(ASTM, 2015b)	1.67	1.94
Los Angeles Abrasion %	C131(ASTM, 2014b)	20.4	---

Table 3. Physical characteristics of limestone dust

Physical characteristics	Result
Specific gravity(g/cm^3)	2.6
Specific surface area, m^2/kg	389
%Passing sieve No.200	95

Figure 1.Coarse and fine aggregates used in HMA

Bitumen Binder

The present study conducted tests at Highway Laboratory at Al-Qadisiyah University on pure asphalt with a permeations grade of 40-50, sourced from the Nasiriyah Refinery in southeastern Iraq, according to ASTM standards, to determine its properties. These included: penetration (a measure of asphalt hardness), softening point, ductility (the ability of asphalt to stretch before breaking), and flash point (the temperature at which asphalt ignites). According to these tests, the outcomes show summarized in Table 4, which shows the physical properties of the asphalt used (see Fig. 2).

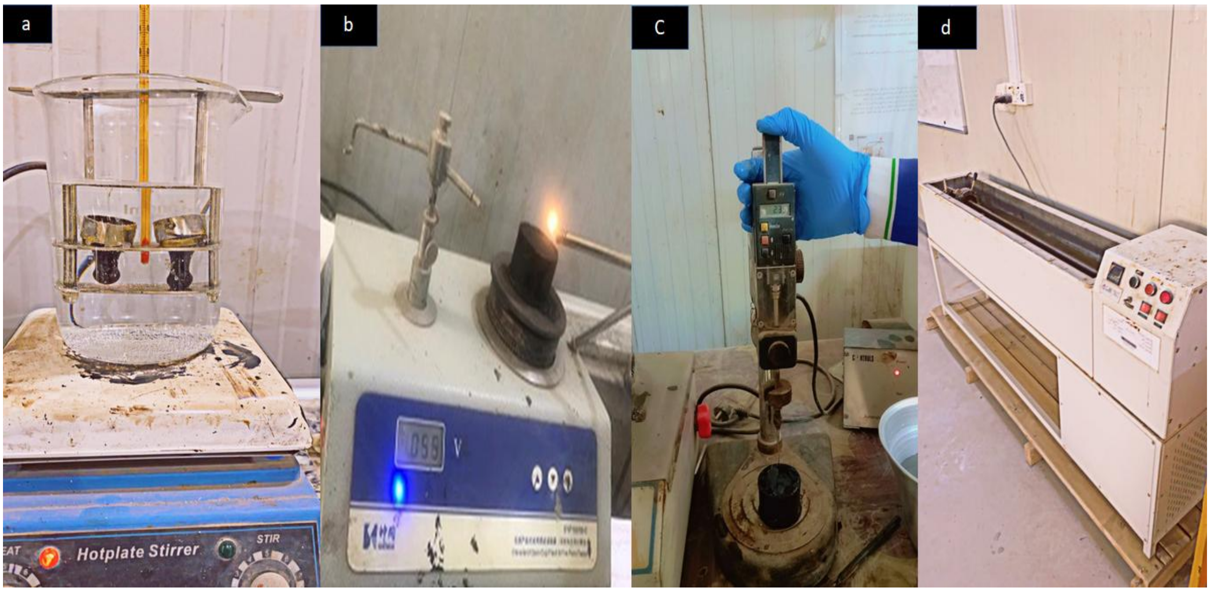

Figure 2. Asphalt test: (a) Softening point, (b) Flashpoint, (c) Penetration, (d) Ductility

Table 4. Physical properties and test of asphalt cement

Property	Standard (ASTM)	Results	Requirement
Penetration (0.1mm) 25°C	ASTM D5(ASTM, 2013b)	46	40-50
Softening point (°C)	ASTM D36(ASTM, 2014)	48	-
Flash point (°C)	ASTM D92(ASTM, 2002)	287	>232
Ductility (cm)	ASTM D113(ASTM, 2007)	>100	>100
Specific gravity at 25°C	ASTM D70(ASTM, 2009a)	1.036	-
Viscosity at 135 °C (C.P)	ASTM D4402(ASTM, 2015)	642.5	-
at 165 °C (C.P)		166	

Styrene-Butadiene-Styrene (SBS)

SBS is a triblock copolymer obtained from the local market in Iraq and supplied by Kraton Polymer Company. It is in the form of small white particles. Due to its elastic properties, it was used in this study as a bitumen modifier. This polymer is popular because of the elastic characteristics that increase the viscosity of asphalt. The study offered that adding SBS to asphalt leads to an increase in the rheological performance (Davidson et al., 2014). In addition, laboratory tests have shown that adding SBS to pure asphalt reduces the bitumen's susceptibility to changes in high temperatures, reducing pavement deformations. SBS gives bitumen flexible, rubber-like properties, which help it withstand heavy traffic loads and high temperatures. It also has a low cracking coefficient, resulting in highways requiring less maintenance and lasting longer (Al-Nawasir & Al-Humeidawi, 2023a).

Novolac Resin

Sawari General Chemical Industries Company used novolac, a type of phenol-formaldehyde resin produced through acid-catalysed polymerisation of phenol with formaldehyde, such as hydrochloric acid or sulfuric acid, where the ratio of formaldehyde to phenol is less than 1:1. Due to the deficiency of formaldehyde, novolac remains a thermosetting resin and requires the addition of a hardening agent to form a cross-linked structure. Hexamethylenetetramine, also known as hexamine, is usually used as a hardening agent, as it decomposes at temperatures above 90°C, releasing formaldehyde, which reacts with the phenolic group in novolac to initiate the cross-linking process, forming a solid, thermosetting polymer network. Studies have shown that using novolac is a great choice for improving the asphalt mixtures behavior, especially when combined with recycled materials. It has improved bitumen's rheological properties and enhanced its thermal and mechanical stability, leading to improved resistance to permanent deformation (AL-Ghurabi & Al-Humeidawi, 2023). Figure 3 illustrates the physical forms of the two additives used in this study. Novolac appears as a brownish powder (1), while SBS is in the form of white granules (2).

Figure 3. Physical forms of asphalt modifiers: (1) Novolac powder and (2) SBS granules

Sample Preparation

Asphalt mixtures were made using the standard Marshall Design method, with 75 blows applied to both sides of the cylindrical specimens. Depending on the results of the preliminary tests, the optimum asphalt content (OAC) of 5.1% was determined. hot mixtures asphalt samples were produced using a 5.1% asphalt content to ensure uniformity throughout the investigation.

To modify the bitumen binder with polymers, the bitumen binder was first heated to approximately 160°C. Novolac resin was added at ratios of 1, 2, 3, 4, and 5% by weight of pure asphalt, along with 10% hexamine by weight of novolac as a hardening agent. The mixing process involved using a high-shear mixer (2500 rpm) for half an hour. Then, at 180°C, we added SBS (4% by weight of the asphalt) and mixed it with the novolac in the high-shear mixer for one hour. Following this, the mixture was placed (60°C) for two hours to ensure homogeneity and prevent segregation. To further confirm homogeneity, we repeated the process under the same temperature and time conditions, as shown in Figure 4. According to previous laboratory studies and research, the choice of novolac (2%) and SBS (4%), or different concentrations, affects elasticity, plasticity, other physical properties, and permeability, all of which reflect the sensitivity to temperature.

Figure 4. Preparation of polymer blend to enhance bitumen properties

Experimental Procedure

Conventional Bitumen Binder Tests

Bitumen was modified with 4% SBS and percentages novolac resin. Conventional and real-world tests, such as penetration, softening point, and ductility, were carried out on the bitumen.. (ASTM, 2007) was performed for Bitumen, Reliable elasticity and extensibility by ductility test. the penetration test was used to measure hardness of bitumen (ASTM, 2013b; Al-Nawasir & Al-Humeidawi, 2023a).

The Temperature Susceptibility

An important rheological property of bitumen binder is thermal-resistance (resistance to permanent deformation), which is critical in Polymer Modified Bitumen PMB. Thermostability measured for example, by the penetration index (PI) refers to the rate at which bitumen binder properties change with temperature. The PI is a numerical indicator of the binder sensitivity to temperature variations. Knowing the PI of a particular material allows one to predict its performance for a specific application. Bitumen binders with higher penetration values also referred to as soft grades are typically used in cold regions, while those with lower penetration values known as hard grades are applied in hot climates. Regardless of the type, bitumen exhibits thermoplastic behavior: it softens when heated and hardens when cooled (Al-Haddad, 2020; Ohinola OA, 2012). Higher PI values indicate lower temperature susceptibility. Standard asphalt cement ranges in PI from -2 to +2. The findings of the softening point and penetration tests are used to derive the temperature susceptibility indicator values. One often uses Eq. (1) to get PI (READ et al., 2015).

$$PI = (1952-500 \log (pen25)-20\times SP)/ (50 \log (pen25)-SP+120)$$

Pen25 is the penetration at 25 °C and SP is the softening point of unmodified and modified bitumen binder**.**

Rheological Properties

These properties cannot be assessed by conventional physical tests alone, as bitumen binders are subjected to many thermal and mechanical stresses in service due to climatic and traffic loads. However, such problems become more severe when the binder is modified by adding polymers such as (SBS) or resins such as novolac that alter the binder's viscoelastic behaviour to a high degree. Therefore, conventional tests such as penetration and softening point are insufficient to represent the real performance of binders under a wide range of service conditions.

Traditionally, binder characterisation has been based on empirical tests, like the penetration test. Nonetheless, these tests are not able to replicate the stress-strain states that prevail in the field and also do not reflect the fundamental mechanical behavior of the binder (Read & Whiteoak, 2003). Bitumen is a complex material that shows a combined viscoelastic response, where the elastic (recoverable) and viscous (non-recoverable) behavior are significantly influenced by temperature and loading frequency (Read & Whiteoak, 2003; Yusoff et al., 2010). The interaction of all these combined properties is known as the rheological properties of the binder and plays a vital role in long-term pavement performance prediction. These properties can be better evaluated. One of the most important types of instruments that can deliver G and δ is (DSR). G is overall deformation resistance of binder material and δ is ratio of elastic to viscous properties of binder. Phase angle provides great significance in understanding the behaviour of bitumen binder, where low phase angle (0°) indicates elastic behaviour and high phase angle (90°) indicates the viscous behaviour (Asphalt Institute, 2014; Kök et al., 2013). This test aimed to evaluate the development of properties and the degree of permanent deformation resistance. According To (AASHTO,2013) prior to this test, the samples were placed in a rotary kiln (RTFOT) at (163°C ,85 minutes). The process was then repeated under the same conditions. The results offered a change in mass, which was used to confirm the validity of the results under real-world conditions and to determine the oxidation susceptibility of the binder. This provided insight into the extent to which properties of modified bitumen binders were affected (Ameri et al., 2018; Walubita et al., 2020; Zhang et al., 2021).

Marshall Stability and Flow Test

The results of this test were the stability-to-flow ratio (kN) (Marshall's modulus), determining the stability and HMA flow rates. Different asphalt content ratios (4, 4.5, 5, 5.5, and 6) were used in an analyzer according to the Marshall test (ASTM-D6927,2015). The Marshall's modulus measures resistance of mixtures to surface wear and tear and permanent changes. The soaking process lasted for half an hour (at 60°C), and compaction rate after soaking was 50.8 mm/min (Bostancioğlu & Oruç, 2016; Yilmaz et al., 2011). See Figure 5.

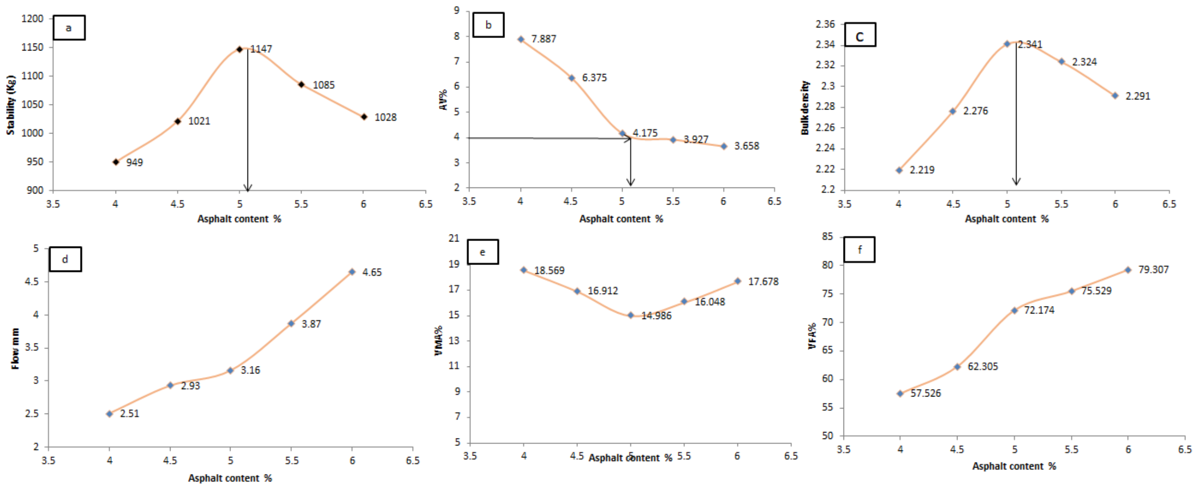

Figure 5. The relationship between asphalt content and mix properties: (a) Stability, (b) Air Voids (AV), (c) Bulk Density, (d) Flow, (e) Voids in Mineral Aggregate (VMA), and (f) Voids Filled with Asphalt (VFA)

Indirect Tensile Strength (ITS) Test

This was tested to ASTM-D4867. It is designed to measure the tensile fracture failure at an intermediate level pavement temperature of an asphalt mixture. The ITS test is carried out by imposing a linear compressive load acting uniformly across the diameter of the sample (see Fig. 7). The specimen is calculated by measuring the maximum load at the failure point, and the equation is used to calculate the ITS.

$$ITS = (2000 \times P) / (\pi \times t \times d)$$

ITS= Tensile strength by indirect method (KPa), P= Applied force (N), t= Denotes the vertical dimension of the sample (mm), d= Diameter of the tested sample (mm)

According to ASTM D 4867, the air void content of specimens used in ITS testing should range between 6% and 8%. This study achieved a 7% air void content through blows. Blows were set at three levels using a Marshall hammer: 35, 55, and 75. Three specimens were tested for each trial, and the air void content was determined. A graph was then constructed showing the relationship between the number of blows and the percentage of air voids, as shown in Fig. 6. This graph indicates that 47 blows achieve a 7%.

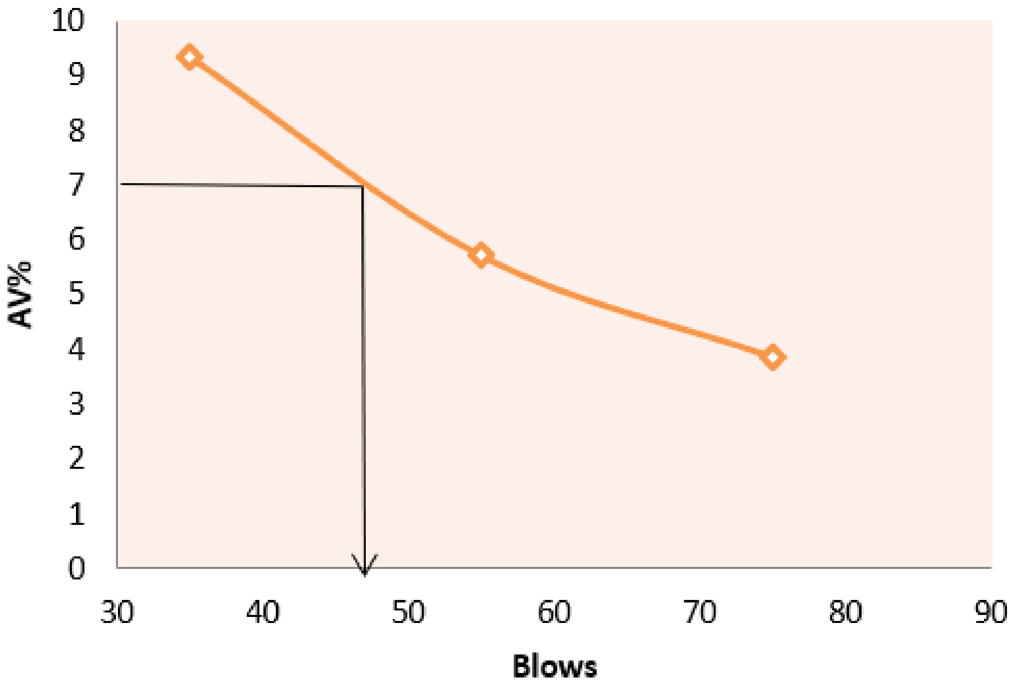

Figure 6. Relationship between number of blows and air voids

Figure 7**.** Laboratory tests of ITS devices and specimens at the University of - Al- Qadisiyah

Tensile Strength Ratio (TSR)

The researchers intended to reduce moisture damage, a major issue with asphalt mixtures. To assess this, they used (TSR), comparing with the tensile strengths of conditioned and unconditioned samples, and evaluating pavement deterioration due to moisture exposure. The pavement can be affected by wetness and geomaterial segregation, causing water to penetrate the pavement and leading to damage from environmental effects, such as scaling and perforation. Specimens: Two sets of specimens were fabricated. Three were immersion bath conditioned (60 °C for 24 h) (first set), three were not immersion bath conditioned (second set). All samples were then tested for tensile strength, and a value of TSR was obtained. ASTM D4867 indicates an acceptable product with a TSR value of 80% or more. If the TSR is below 80%, it is considered susceptible to moisture damage, so some modification should be done to improve the durability and performance of the asphalt mixture. The equation is used to calculate the TSR.

TSR% = (Swet /Sdry) ×100

Where: TSR stands for the Tensile Strength Ratio, Sdry indicates the mean tensile strength obtained from the unconditioned (control) specimens, and Swet denotes the mean tensile strength of samples conditioned under moist environments.

Wheel Tracking Test (WTT) for Rutting Performance

The WTT is the most prevalent and standard method for evaluating the rutting resistance of a mixture (permanent deformation due to traffic loading and moisture). This test estimates the rate of permanent strain and the extent of hardening in an asphalt mixture under cyclic loading. The deformation is measured by repeatedly rolling a loaded wheel at a constant speed and load over a rectangular indentation of a compacted asphalt sample (50, 180, 340 mm). The number of passes and the load value are determined based on the highway traffic design. Figure 8 shows the WTT equipment in the Highway Laboratory at Al-Qadisiyah University. The samples were compacted under mechanical compression, and three different load levels (700, 800, 900, and 1000 kN) were tested to determine the optimum compression load that achieves a 7% air void ratio. The air void ratio of sample after applying different loads was calculated and based on the results; a graph was drawn to illustrate relationship between the applied load and the air void ratio. A load of 870 kN was found to be optimal, which is the required ratio to achieve a 7% air void ratio according to WTT requirements (see Figure 8). The test was conducted using a wheel that applied a load of 700 N, equivalent to 157 lb to the surface at 10,000 revolutions, according to (EN 12697-22:2003). Due to the viscoelastic nature of bitumen, asphalt mixture deforms when subjected to traffic stresses. It must be mentioned that when loads are removed, only a very small percentage of the deformation remains as a permanent deformation, while a very large part of the deformation that occurred returns to its original state (Tahami et al., 2018).

Figure 8. Conducting the (WTT) to evaluate the performance of modified asphalt mixtures

Results and Discussion

Conventional Bitumen Test Results

Table 5 presents the results show that binder stiffness increases significantly with the addition of SBS, and the penetration depth decreases to 32.5 mm. This is attributed to the reduced plasticity and improved cohesion of the material, resulting from the SBS particles forming a polymer network within the asphalt. Furthermore, the softening point, a measure of bitumen's properties and stability as a binding agent at high temperatures, rises to 61°C, leading to improved resistance to thermal deformation. SBS has the potential to enhance the thermal transition of bitumen from its solid to liquid state, indicating better performance at high temperatures and a reduction in deformation under heavy traffic loads (Al-Humeidawi Basim H, 2018; Wang et al., 2021) . The penetration decreased (41) to (16), and softening point increased (49) to (59) with the addition of Novolac. The elongation value decreased from 100 to 1 cm, indicating a decrease in the bitumen's flexibility (see Fig. 9). The changes upon adding Novolac are as follows:

- A significant decrease in penetration occurs when a mixture of Novolac and SBS at (4%) is applied.
- A penetration value of 12 is achieved when a mixture of Novolac at (3%) and SBS at (4%) is applied.

mixture of Novolac at (2%) and SBS at (4%) provides optimal performance and makes the bonding material highly suitable for hot weather. Other changes are also observed: flexibility decreases as elongation decreases, which in turn decreases progressively with the addition of Novolac. The elongation decreases from 58 to 17 cm, and the softening point reaches (73°C).

Table 5. Physical properties of the modified bitumen binder

Test	Asphalt (40-50)	SBS%	Novolac with 10% hexamine					Novolac+SBS		
		4	1	2	3	4	5	1+4	2+4	3+4
Penetration	46	32.5	41	34.6	29	21	16	29.4	24.1	12
Softening point	48	61	49	51.5	53	56	59	66	71	73
Ductility	>100	67	100	87.5	53.5	27	15	58	46	17
Flash point	289					>300				

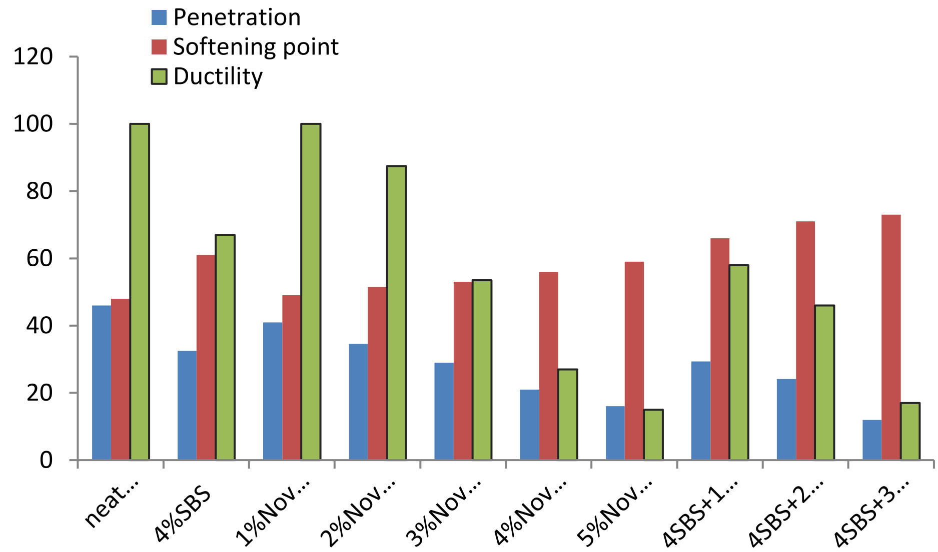

Figure 9. Effect of novolac and SBS modifiers on the physical properties of bitumen binder

Heat Sensitivity Test Results of Bitumen

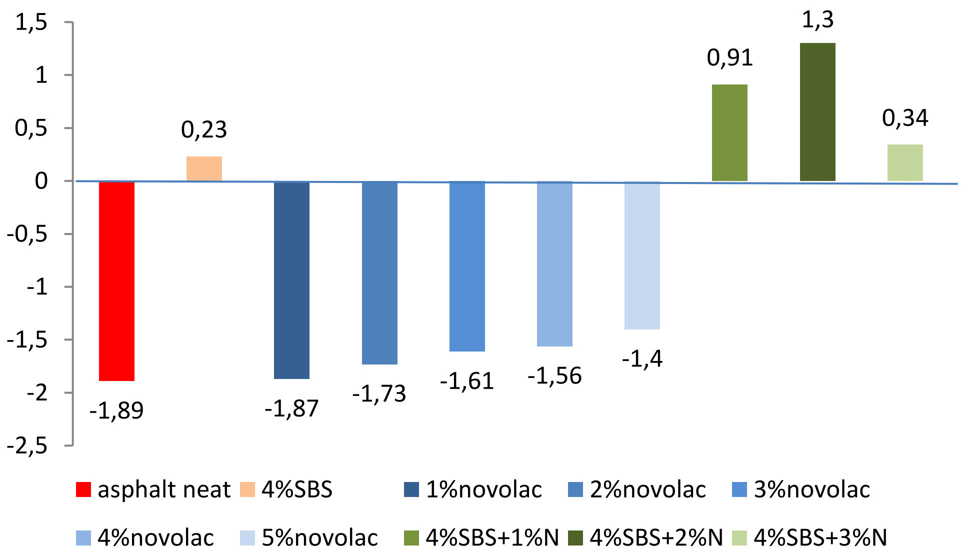

Figure 10.Penetration index of the modified and unmodified binder

To determine the effect of heat on bitumen, the penetration index (PI) was used. The results offered that pure asphalt is sensitive to heat, with a penetration index of (PI = -1.89) (see Fig 10), To reduce its sensitivity to heat, SBS was added at a rate of (4%), resulting in a (PI = 0.23). Different percentages of novolac were also added, yielding varying results. However, it was found that combining novolac at (2%) with SBS at (4%) provides the best thermal performance. When novolac is used at (3%) and SBS at (4%), the efficiency decreases (PI = 0.34). It is due higher increase in softening points than the reduced penetration causing a lower PI value. These results indicate a reduction in the binder thermal resistance to brittleness (Bala et al., 2017). The above results confirm that incorporation of novolac results in increased thermal stability of bitumen, especially when combined with SBS. According to these results, it can be said that SBS is the most effective component in lowering bitumen temperature sensitivity, and this impact is magnified by blending SBS with novolac when blended in certain ratios, when it comes to bitumen high temperature performance.

DSR Test Results of Modified Binder

The increases in G∗ and decreases in δ with the increase in additive content confirm the above fact. The increment of G* is attributed to the additive, which stiffens the bitumen and enhances the resistance to deformation. Lower phase angle values indicate a transition from viscoelastic towards more elastic behaviour. This is because incorporating the polymer increases the elastic properties and the phase angle decreases compared to the unmodified asphalt. To this end, these rheological changes are of significance since it has been established in literature that producing minimal permanent deformation in the bitumen binder when subjected to stress is one of the key performance parameters (Gong et al., 2021; Kök et al., 2013; Rahi et al., 2015).

In this research, the rheological behaviour of the bitumen binder was evaluated together with its resistance to thermal ageing (during high-temperature mixing and paving phases) in a short-term ageing simulation (via RTFO). (DSR) test was used to evaluate the rutting resistance of the binder represented by G*/sin δ index, a measure of rutting resistance based on stiffness and viscoelastic response of the binder at high temperature. It was tested at 76°C, simulating the typical pavement surface conditions in Central and Southern Iraq. A modified version of one of the binders, incorporating 4% styrene–butadiene–styrene (SBS) and 2% novolac (by weight of bitumen) was tested. The results offered that the G*/sin δ values exceeded the required Superpave specifications, with the bond yielding (7.40) kPa before RTFO aging and (15.51) kPa after RTFO aging (see Fig 11). These results confirm that the bitumen's performance in hot weather conditions improves when modified with SBS-Novolac. Furthermore, this interaction between the two materials and the effect of RTFO enhances the polymer network, increases the bond's stiffness and strength, and imparts high resistance to deformation.

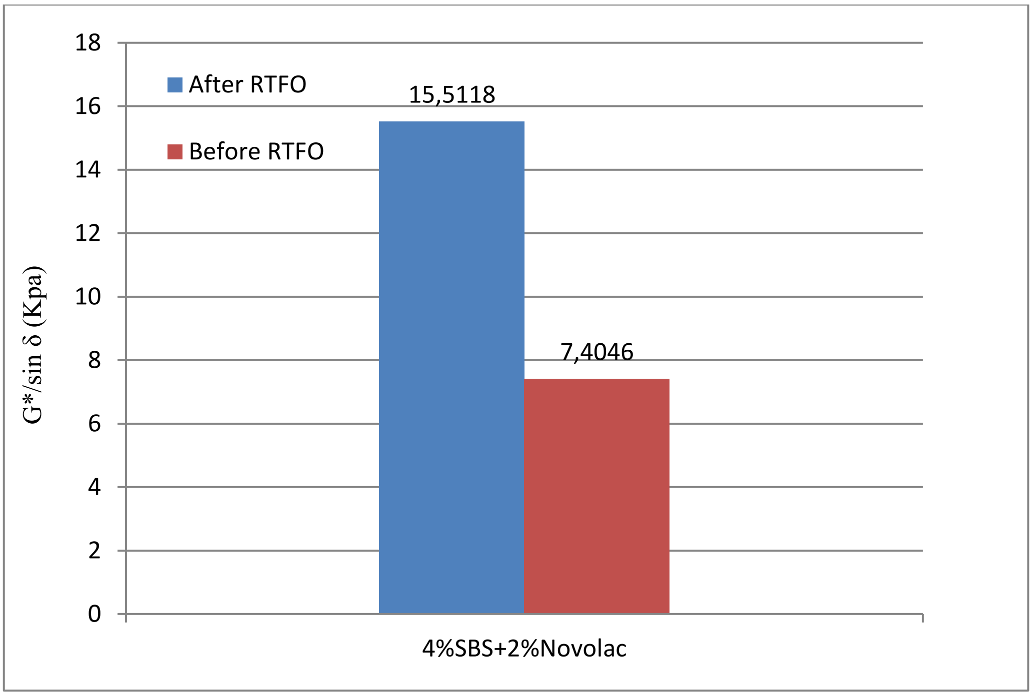

Figure11. DSR G/sin (δ) values at 76°C before and after RTFO aging for binder modified with 4% SBS and 2% novolac

RTFOT Mass Change Test Results

Various studies have indicated the effect of polymers when used to modify bitumen, particularly SBS, on short-term aging behavior of bitumen. This was demonstrated through rotary thin-film oven (RTFO) tests, where thermal and oxidative stability was observed to be significantly improved. For example, bitumen binders modified with SBS exhibited good resistance to network deterioration during the RTFO test (Yu et al., 2019). Likewise (Chen et al., 2021) Using both the RTFO and PAV tests, it was found that SBS binders, when subjected to repeated aging cycles, maintain stable rheological and chemical properties. In this study, bitumen binders were subjected to short-term aging according to AASHTO T 240, "Effect of Heat and Air on a Moving Film of Bitumen binder (RTFO Test)." This test simulates the oxidative aging that occurs during mixing and paving at high temperatures with continuous airflow, by placing a thin layer of bitumen binder in a closed chamber. A test was performed at 163 ± 0.5 °C and for 85 ± 1 min, at 4000 ± 200 ml/min. Per Superpave specifications, the allowable change in mass is +1.00% max. As expected, there was a slight mass loss of −0.070% for the unmodified binder (caused by overheating during short-term aging, which results in the loss of lighter components due to their volatilization) as indicated in the test results. In contrast, the modified binder containing 4% SBS and 2% novolac exhibited a positive mass change of 0.053%, indicating lower volatilization and enhanced thermal stability (see Table 6). Both values fall within the acceptable limits defined by AASHTO T240, confirming the suitability of these binders for pavement applications. Furthermore, the superior performance of the modified binder highlights the effectiveness of the SBS–novolac combination in mitigating oxidative degradation during short-term aging.

Table 6. Mass change of bitumen binders after RTFO aging according to AASHTO T 240

Binder Type	RTFO Mass Change (%)
Neat Asphalt	-0.07
4%SBS+2%Novolac	0.053

Note: All results fall within the 1% RTFO mass change limit defined by AASHTO T240

Marshall Stability and Flow Results

Novolac was mixed at a rate of (2%), SBS at a rate of (4%), and hexamine at a rate of (10%) by weight of Novolac. The results offered that combining SBS with Novolac improves overall mechanical performance of the mixture, as the strength upon combination reached (1637 kg) Figure 12 shows the Marshall test results where the improvement is (38.7%) when compared to an unmodified mixture .The hardening of novolac leads to interlocking chains between the aggregate and binder, resulting in increased binder strength (Al-Gurah & Al-Humeidawi, 2023). While the flow results offered variations in the behavior of the mixes when using SBS, resulting in a decrease in flow from 3.2 to 2.9, addition of 4% novolac increased flow to 3.6, due to increased novolac content. The composite mix recorded a flow of 3.1, reflecting a good balance between stiffness and flexibility (see Fig 13).

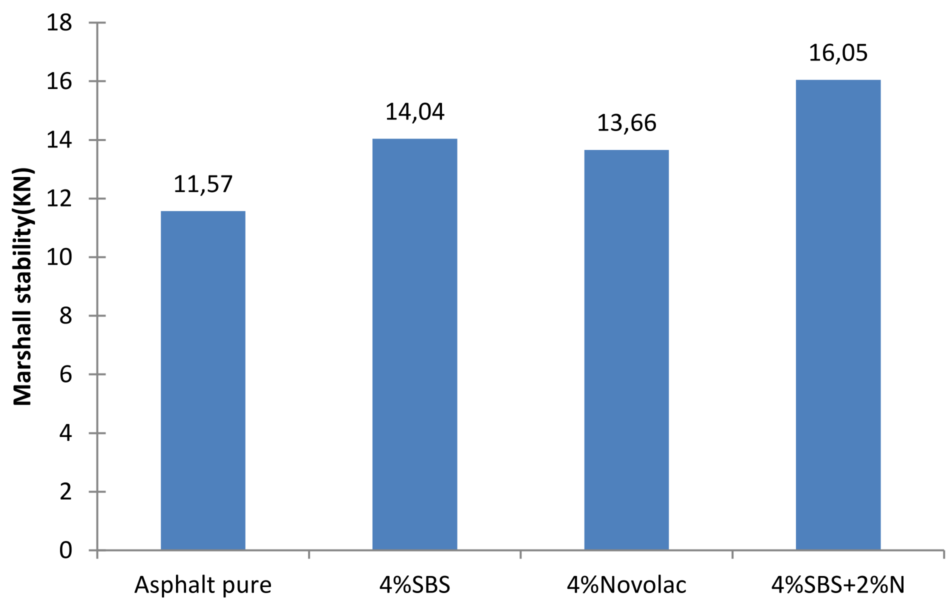

Figure 12. Effect of novolac and SBS on Marshall stability.

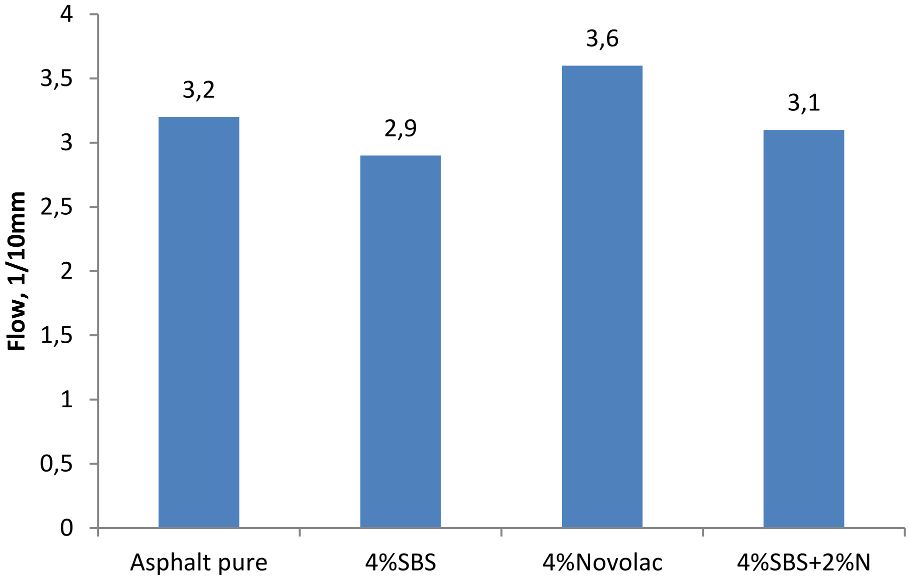

Figure 13. Results of the Marshall flow test for HMA with novolac and SBS.

Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR)

The experiment was performed on samples containing 4% novolac by weight of bitumen and 10% by weight hexamine, which was determined based on physical tests), and on samples composed of a mixture of 4% SBS and 2% novolac; samples containing 4% SBS were used. The results offered that samples containing a mixture of 4% SBS and 2% novolac had the highest indirect tensile strength, reaching 1709 kPa for the unconditioned state and 1587 kPa for the conditioned state (see Fig 14). The TSR value reached 92.9%, indicating enhanced moisture resistance (see Fig 15). Compared to the unmodified asphalt mix, this represents a 40.9% increase in ITS and a 66.2% improvement in moisture resistance. The results displayed that the combination of Novolac with SBS developed the cohesion and elasticity of the bitumen, and the adhesion between the bituminous binder and the aggregate in asphalt mix, which greatly increased its moisture resistance and thus improved the performance of the mixes in humid environments. In Humid atmospheric conditions, the stability of the mixture depends on the particles added to the SBS.(Al-Humeidawi et al., 2016; Taki et al., 2019).

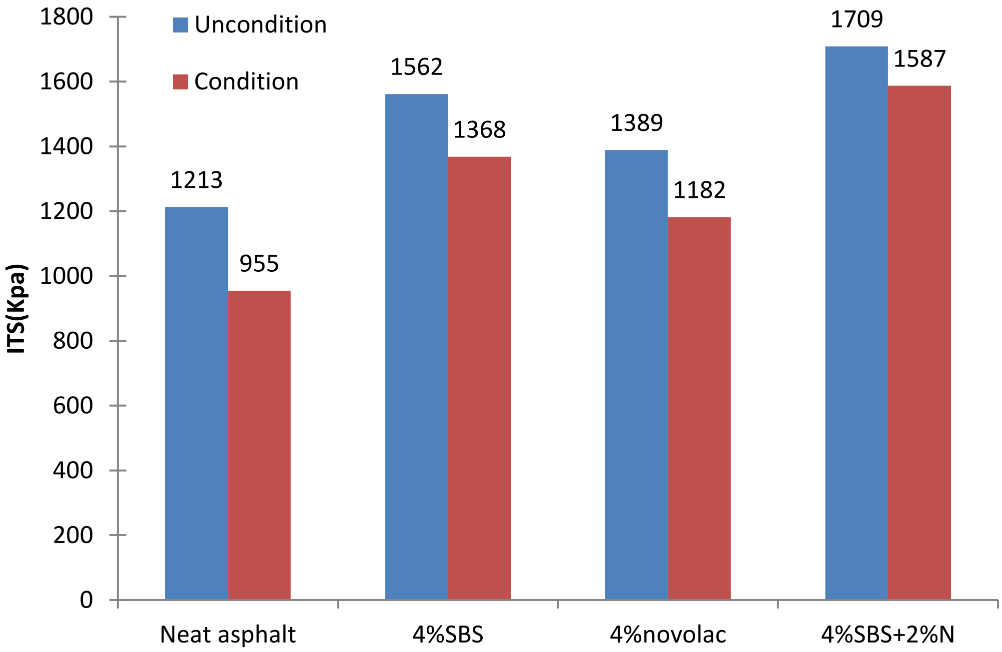

Figure 14. Effect of asphalt modification on indirect tensile strength (ITS)

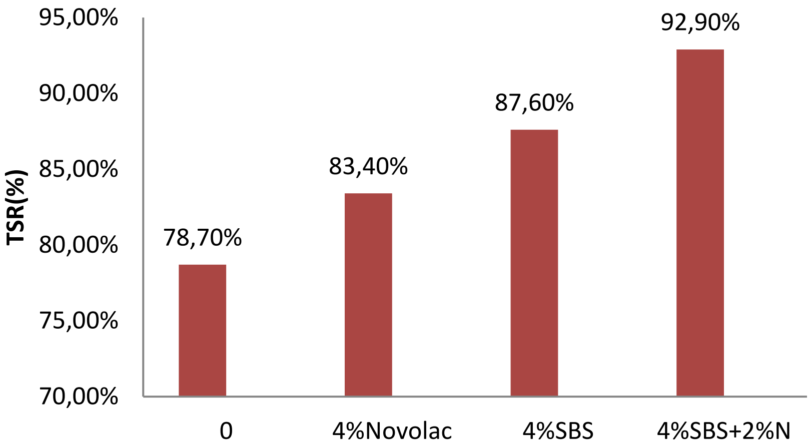

Figure 15. Impact of novolac and SBS modification on tensile strength ratio (TSR)

Wheel Track Test

As heavy vehicles increasingly travel on highways, they experience permanent deformation, which in turn causes damage, increases maintenance costs, and also degrades safety. Therefore, this test indicates this deformation. The end result of the WTT, which show the rut depth as a job of cycle number up to 10,000 cycles, were obtained in accordance to EN 12697-22:2003 at a load of 700 N (157 lbf), and are presented in Figure 16. One thing noted is the reduction in rut depth with the use of novolac. The reason for this is that the bitumen binder is more cohesive, which enhances cohesion and improves the adhesive effect between the aggregate particles. It was also concluded that the softening point increases and the heat sensitivity decreases, thus leading to improved crack resistance of HMA due to the use of the polymer (Al-Gurah & Al-Humeidawi, 2023). We note that the rut depth was reduced when using 4% novolac. The depth of erosion reached (9.8) mm compared to (10.6) mm when using SBS. Mixing Novolac (2%), which adds stiffness to the bitumen, with SBS, which adds flexibility to the bitumen, reduces the amount of permanent deformation. This is due to the balance that occurred between flexibility and stiffness, as the depth of denting decreased to (6.8) mm. (see Fig 17).

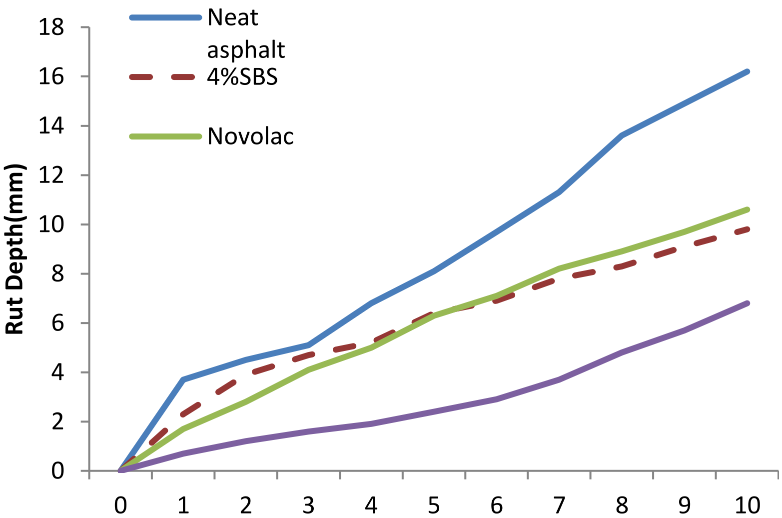

Figure 16. Effect of asphalt modification on rut depth under wheel tracking test.

Conclusions

The present work examined the impact of modifying bitumen using a combination of SBS polymer and novolac resin to produce high-performance and sustainable asphalt mixtures. Based on the laboratory findings, the key findings of this study are as follows:

Figure 17. Effect of rut depth under wheel tracking test on asphalt samples

- The combination of SBS and novolac significantly enhanced the properties of bitumen, as evidenced by an increased softening point, improved thermal stability, and reduced penetration values.
- The synergistic effect of the two modifiers improved binder flexibility and stiffness balance, leading to higher resistance to cracking and rutting under repeated loading conditions.
- The modified binders exhibited better moisture resistance, indicating improved adhesion between bitumen and aggregate, which extends pavement life and minimizes moisture-induced damage.

In a nutshell, the SBS novolac resin mixture combines the flexibility of the former with the rigidity of the latter, producing a bitumen binder with improved mechanical and durability properties. Therefore, this approach of modification promises a sustainable and economical solution to traditional additives, aligning with contemporary pavement design trends that emphasize durability and minimal maintenance. Moreover, this study opens the door for implementing such modified binders in real field conditions, particularly in hot climate zones. Despite a slight increase in initial cost, the extended pavement life and reduction in maintenance costs justify the use of these additives. Further research is recommended to evaluate long-term aging, large-scale production feasibility, and environmental impact. Therefore, further investigations into fatigue resistance and low-temperature performance, particularly via Bending Beam Rheometer (BBR) testing, are recommended. Field trials and life-cycle cost analyses are also necessary to validate these findings and assess large-scale applicability.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflict of interest.

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