

# Sustainable Hybrid Modification of Asphalt Binder Using Styrene-Butadiene-Styrene and Waste Polyvinyl Chloride for Enhanced High-Temperature Performance



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## ABSTRACT

Standard asphalt binders are thermally unstable; thus, modification is required to prevent rutting at high pavement temperatures and under heavy truck axle loads. Using a hybrid styrene-butadiene-styrene (SBS) and waste polyvinyl chloride (PVC) technology, a standard asphalt binder (60/70 penetration grade) was sustainably modified to improve high-temperature performance and rheological stability. Virgin control and nine hybrid mixes containing SBS (2%, 3%, and 4%) and waste PVC (1%, 3%, and 5%) by weight were tested. This hybrid change stiffened the matrix, reducing penetration and increasing softening point, according to conventional tests. Rotational viscosity rose with SBS and waste PVC concentrations, improving flow resistance at mixing and compaction temperatures. PVC concentrations elevated rolling thin film oven (RTFO) mass loss and lowered flash point due to waste polymer thermal instability. PVC's plasticity partially disrupts the SBS's continuous elastic network, decreasing elastic recovery as waste PVC concentration increased. Using the dynamic shear rheometer, a transition from viscous to elastic behavior was observed, with greater  $G^*$  and lower  $\delta$  values. The original and RTFO-aged binders greatly improved in rutting parameter ( $G^*/\sin\delta$ ), indicating increased ageing resistance. In the base performance grade (PG) 64-16 binder, hybrid SBS/PVC raises the high-temperature PG by two to six levels. These findings enhance asphalt binder performance in extreme temperatures and weather, enabling resilient pavement systems and more sustainable, durable, and cost-effective road infrastructure.

**Index Terms:** Polymer Modified Asphalt Binders, Styrene-Butadiene-Styrene, Waste Polyvinyl Chloride, Environmental Sustainability, Dynamic Shear Rheometer

## 1. INTRODUCTION

Asphalt binder is commonly used as a roadway paving ingredient when incorporated into mineral aggregates. Bituminous mixes are utilized in 85% of the roadway pavements worldwide [1]. While the amount of bitumen

in asphalt blend is minimal compared to the aggregate, its properties have a significant influence on the performance of roadways [2].

The rising volume and severity of traffic loads, particularly the increasing number of vehicles with higher axle loads, have significantly affected pavement performance in recent years. This has accelerated pavement deterioration by placing more stress on the pavement [3], [4].

In addition, variation of weather conditions, including cycles of freezing and thawing, extreme heat, and heavy precipitation [5], further contribute to various pavement

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distresses, including rutting, thermal cracking, and fatigue cracking [6], [7]. The most prevalent issue affecting the majority of Iraqi asphalt pavements is rutting [8]. It is defined by the presence of longitudinal depressions within wheel paths that result from progressive shear deformation occurring under conditions of repeated loading [9]. Rutting predominantly takes place when the viscosity of the binder diminishes at elevated temperatures, leading to a decrease in internal shear resistance [10]. To maximize bituminous materials, researchers have concentrated on using cutting-edge designs and technologies. The asphalt binder is altered using a variety of additives and modification techniques to increase the long-term durability of asphalt pavements and lower maintenance costs [11]. These additives include polymers, fillers, fibers, reclaimed rubber, extenders, anti-strip agents, antioxidants, and nanomaterials [12]. One of the most promising methods recently introduced is polymer-modified asphalt (PMAs) binders [13]. There are three main polymer types that are commonly used in asphalt modification, including thermoplastic, elastomers, and reactive polymers. Elastomers represent the largest share of asphalt modifiers (75%), followed by plastomers (15%), crumb rubber (10%), and other additives [14].

Styrene-butadiene-styrene (SBS), which is a copolymer, is one of the most widely used and efficient polymer modifiers that are used in asphalt [15], [16]. A cross-linked SBS structure improves binder elasticity, flexibility, and durability. SBS enhances asphalt viscosity and adhesion to better connect aggregates, making the road surface firmer and more deformation-resistant [17]. PMAs can be expensive to include into road infrastructure. PMAs may cost twice as much as normal bitumen, raising asphalt mix costs by roughly 20% [18].

Bitumen modification using waste thermoplastics is cost-effective. Many sectors employ plastics owing to its formability, low density, durability, and affordability. Polyethylene terephthalate, high-density polyethylene, polyvinyl chloride (PVC), low-density polyethylene, polypropylene (PP), PS, and others are the main types [19], [20]. Plastic's resistance to deterioration, corrosion, and disintegration makes it an environmental problem. For decades, these components have polluted ecosystems without human intervention. Ultimately recyclable, thermoplastics enable a circular economy. Adding plastics to bitumen modification might protect scarce natural resources and decrease landfill waste [21], [22].

PVC is the third most prevalent polymer in the world, behind polyethylene (PE) and PP [23], one viable strategy for

managing the resulting PVC waste is to integrate it into road construction [24]. Furthermore, technical analysis has proven that PVC plays the role of a high-performance modifier by forming a strong three-dimensional structure in the asphalt binder. This microscopic reinforcement significantly enhances the material's resistance to permanent deformation, fatigue, and cracking [25], [26]. The modification of asphalt binders with PVC alters their physical properties, yielding higher penetration resistance and lower thermal flow susceptibility, which are beneficial for maintaining pavement integrity under varying environmental conditions [27]. Salman and Jaleel's study showed that adding waste PVC to (40–50) grade asphalt raises the softening point and reduces heating values. On the other hand, when PVC concentrations rise, the modified binder's penetration, ductility, and flash point all simultaneously decrease [28]. Generally, compound modification can significantly improve key asphaltic properties. Asphalt that has been treated using SBS/PVC reduces the use of SBS and reduces the cost; on the other hand, PVC in asphalt mixtures, either alone or in combination with SBS, can further enhance mechanical properties [29]. Many studies have used a dynamic shear rheometer (DSR) to study bitumen and PMB's dynamic rheology. Rheological characteristics must fall within Superpave's viscoelastic range to correctly imitate road traffic loading circumstances. DSR analysis presents basic characteristics, such as phase angle ( $\delta$ ) and complex shear modulus ( $G^*$ ).

To determine if the asphalt modification improved the binder's resistance to permanent deformation, researchers can analyze DSR data, specifically the rutting factor ( $G^*/\sin\delta$ ). This will prove that the treatment reduces the most frequent pavement distress [30]. Behl *et al.* (2014) noted that incorporating waste PVC into bitumen with a 60/70 penetration grade markedly elevates the  $G^*$  and reduces the  $\delta$ , signifying a shift to a more elastic and robust binder matrix [31]. Arabani and Taleghani (2017) have also corroborated this behavior, demonstrating that an upward trend in the rutting parameter is directly correlated with a rise in PVC concentration by the DSR test [32]. At high temperatures, both modifiers improved binder performance, Jabbar *et al.* (2025) found. Lower-concentration SBS works better. Performance grade (PG) rose from PG 64 to PG 82 with 5% SBS. To increase the grade from PG 64 to PG 76, PVC needed 9%. Although both polymer concentrations increase  $G^*$  and the rutting parameter ( $G^*/\sin\delta$ ), SBS creates a more resilient and flexible network [33]. Ezzat and Abed (2020) found that the SBS/PVC hybrid alteration improved bitumen rheology. Combining PVC's rigidity with SBS's flexibility led to a non-

constant decrease ( $\delta$ ) and substantial improvement (G). The implemented adjustments improved the rutting parameter ( $G/\sin\delta$ ), resulting in increased resistance to permanent deformation at high temperatures. The research found that SBS/PVC hybrid modification increased basic PG 64-16 asphalt grade to superior performance class (PG 82-16 and PG 88-16) depending on polymer concentration [34].

Despite growing polymer modification research, few studies have examined the direct hybrid use of waste PVC and SBS in asphalt binders. Thus, this research examines the physical and rheological characteristics of asphalt binders modified with PVC from door and window construction waste and SBS. This research examines how various polymers synergistically affect binder stiffness and rutting resistance. Combining empirical testing with modern Superpave rheological methods, such as short-term ageing simulations achieves this. These methods determine the High-PG of composed-modified bitumen to validate its appropriateness for severe climates and to encourage the environmentally responsible recycling of waste plastic from industrial processes in the field of pavement engineering.

## 2. MATERIALS AND TESTING PROGRAM

### 2.1. Materials

#### 2.1.1. Asphalt binder

The asphalt binder used in this study was supplied by the Phoenix Refinery near Arbat, Sulaymaniyah, and classified as a 60/70 penetration grade binder. The physical and rheological characteristics of the control asphalt binder are summarized in Tables 1 and 2, respectively, based on laboratory testing conducted in accordance with the relevant ASTM standards.

The measured physical properties demonstrate that the control binder meets the standard requirements for paving-grade asphalt binders. The penetration and softening point values indicate balanced consistency and temperature susceptibility, while the high ductility reflects good flexibility and deformation capacity. In addition, the rotational viscosity (RV) value confirms suitable workability during mixing and compaction processes. The low rolling thin film oven (RTFO) mass loss and retained properties further indicate acceptable short-term aging resistance and thermal stability. Moreover, the rheological evaluation confirms that the binder satisfies the Superpave performance grading requirements for a PG 64-16 asphalt binder based on DSR and BBR testing under original, RTFO-aged, and PAV-aged conditions.

**TABLE 1: Physical properties of control asphalt binder**

Test	Results	ASTM
Penetration (0.1 mm) at 25°C	61	D5
Softening point °C	51	D36
Ductility (cm) at 25°C, 5 cm/min	150	D113
Rotational viscosity (Pa.s) at 135°C	0.407	D4402
Flash point °C	292	D92
Fire point °C	304	D92
Retained penetration % after RTFOT	62.3	D5
Ductility (cm) after RTFOT at 25°C, 5 cm/min	110	D113
RTFO mass loss %	0.35	D2872

RTFO: Rolling thin film oven

#### 2.1.2. Additive material

In this study, two additives were used to develop a hybrid modification: SBS and waste PVC.

SBS, specifically using the commercial product KRATON® D1192 ASM, is a clear linear block copolymer based on styrene and butadiene with bound styrene of 30% mass. It is supplied as powder dusted with amorphous silica. The characteristics of the SBS polymer used in this study are delineated in Table 3. The second additive consisted of waste PVC was sourced from discarded PVC door and window, specially graded to pass through a No.50 sieve.

The selected SBS content (2–4%) and waste PVC dosage (1–5%) were determined based on commonly reported ranges in previous studies on PMAs. These dosages were considered appropriate for improving the elastomeric and plastomeric behavior of the binder while maintaining adequate workability and minimizing excessive stiffness [35], [36].

#### 2.1.3. Mixing process and sample preparation

The hybrid modified asphalt binders were prepared using a high-shear mixer to ensure uniform dispersion of the modifiers. A matrix of formulations was produced by combining SBS polymer (2%, 3%, and 4%) and recycled PVC waste (1%, 3%, and 5%) by weight of the base bitumen. The base asphalt binder was first heated to 165°C until it reached a fluid state and was then transferred to the mixing chamber. SBS was gradually added to the hot binder and mixed at 500 rpm for 15 min to promote initial swelling and dispersion. The temperature was then increased and maintained at approximately 180°C. Subsequently, PVC waste was added gradually, and the mixing speed was increased to 2000 rpm for 45 min to achieve homogeneous distribution of SBS and PVC within the asphalt binder.

**TABLE 2: Rheological properties of base (control) asphalt binder**

Test	Property/parameter	ASTM	Measured value	Testing temperature (°C)	Specification requirement
Original binder	DSR, 10 rad/s, G*/sinδ, kPa	D7175	1.5149	64	Min. 1
			0.7046	70	—
RTFO binder residue	DSR 10 rad/s, G*/sin δ, kPa	D7175	4.4668	64	Min. 2.2
			1.9803	70	—
PAV binder residue	DSR 10 rad/s, G*·sin δ, kPa	D7175	3801.182	25	Max. 5000
			5419.8411	22	—
BBR test	Creep stiffness, MPa	D6648	86.405	-16	Max. 300
			Slope (m-value)	0.349	-16

DSR: dynamic shear rheometer, RTFO: Rolling thin film oven

**TABLE 3: Properties of SBS modifier**

Parameter	Property	Value/unit
Chemical composition	Molecular structure	Linear block copolymer
	Polystyrene content	28.5–32.5% m
	Vinyl content	≥35%
Molecular architecture	Triblock content	≥90%
	Molecular weight	138–162 kg/mol
Mechanical properties	Tensile strength	33 MPa
	Elongation at break	1000%
	300% modulus	4.8 MPa
Physical properties	Specific gravity	0.94
	Melt flow rate, 200 C/5 kg	<1 g/10 min

SBS: Styrene-butadiene-styrene

To minimize possible thermal degradation of PVC and oxidative aging of the asphalt binder, the blending temperature and mixing duration were carefully controlled. The modifiers were added gradually to avoid local overheating and agglomeration. After blending, the modified binders were immediately poured into small containers, covered with aluminum foil, and stored under laboratory conditions before testing to reduce oxidation and contamination.

Compatibility and phase separation are important considerations for hybrid polymer-modified binders because of the differing physical characteristics of SBS and PVC. Therefore, high-shear mixing, controlled blending conditions, and gradual incorporation of the modifiers were adopted to enhance binder homogeneity and minimize the potential for phase separation during laboratory preparation.

**2.2. Testing program**

This study tested hybrid SBS/PVC modified asphalt binders using conventional physical testing and advanced rheological characterization.

All conventional binder tests and DSR measurements were conducted in accordance with the relevant ASTM standard specifications under controlled laboratory conditions to ensure consistency, repeatability, and reliability of the experimental results.

**2.2.1. Physical and rheological characterization**

Penetration and Softening Point testing assessed the original and modified binders’ heat thresholds and consistency. RV was measured at 135°C to evaluate the stiffened matrix’s workability and pumpability.

After measuring viscosity, tensile properties were examined. Exclusive ductility testing determined the virgin asphalt’s baseline stretching capability. Elastic Recovery was employed to better illustrate the SBS/PVC network’s viscoelastic resilience for hybrid modified binders. Safety and thermal stability profiles were determined via Flash and Fire Point testing. Mass Loss was computed during short-term ageing to quantify volatile component evaporation.

All samples were short-term aged in the Rolling Thin Film Oven Test (RTFOT) to simulate short-term field aging conditions. The Pressure Ageing Vessel aged basic asphalt oxidatively. DSR was used to measure the complex shear modulus (G\*) and phase angle (δ) of the original and RTFO-aged binders. The rutting parameter, the main indicator of high-temperature performance, was computed using this data. The hybrid SBS/PVC system was classified as high temperature when the rutting parameter matched the Superpave standard (G\*/sinδ >1 kPa for original binders and ≥ 2.2 kPa for RTFO-aged binders). Finally, the BBR test was performed exclusively on the base binder to establish the first PG classification according to Superpave criteria. The low-temperature performance assessment of the modified binders was not included in the scope of the

present study, since the present study mainly focused on the rutting performance of the SBS/PVC-modified binders at high temperature.

### 3. RESULT AND DISCUSSION

#### 3.1. Conventional Properties for Hybrid Elastomer and Plastomer Polymer Modifiers

Hybrid SBS/PVC modified asphalt physical and rheological properties are shown in Table 4.

The penetration test shows that the hybrid SBS-waste PVC modification strengthens the bitumen matrix. The basic asphalt penetration of 61 dmm was consistently reduced by increasing modifier concentrations.

For the 2% SBS series, increasing PVC from 1% to 5% reduced penetration from 40 dmm to 29 dmm, proving its reinforcing properties. Furthermore, increasing SBS from 2% to 4% decreased penetration from 31 dmm to 22 dmm at 3% PVC. PVC's high-modulus stiffness blocks molecular movement and increases shear resistance, whereas SBS's elastomeric network absorbs the maltene phase [35].

Table 4 confirms the penetration test hardening with the Softening Point Test. A combination of 2% SBS and 3% PVC achieved 70°C, while a combination of 2% SBS and 5% PVC reached 78°C. Creating a rigid, connected network where the polymers' high molecular weight increases internal friction causes this rise. PVC's semi-crystalline structure adds reinforcement and restricts flow at high temperatures, boosting the binder's thermal threshold and decreasing rutting.

A RV test revealed that all modified formulations had greater viscosity than the basic asphalt (0.407 Pa·s). 2% SBS series exhibited a suitable viscosity range (0.95–1.361 Pa·s), but

4% SBS series increased more significantly. Furthermore, all hybrid binders remained within the 3.0 Pa·s Superpave limit.

Based on the elastic recovery test, all hybrid blends are viscoelastic between 44% and 70%. SBS is the main elasticity factor, although the 4% SBS and 1% PVC blend recovered 70%, while the (2% SBS + 5%) PVC and (3% SBS + 3% PVC) formulations recovered 44% and 51%, respectively. As PVC concentrations increase, recovery decreases due to the polymer's inflexible, plastomeric nature. However, the hybrid system balances structural rigidity with elastic responsiveness.

Table 4 shows that the flash point decreased from 1% to 5% waste PVC. After adding PVC, the binder's flash point dropped from 292°C for the base asphalt binder to 283°C at 2% SBS with 1% PVC, and to 251°C at 4% SBS with 5% PVC. Despite the reduction due to PVC thermal breakdown and dehydrochlorination, all hybrid combinations met the 232°C requirement. So, SBS/PVC is safe for pavement construction.

Thermal stability and volatility of hybrid binders are assessed using the mass loss % after (RTFO ageing) test. 2% SBS mixes with 1% and 5% PVC waste had mass loss of 0.4–0.8%, while the modifier concentration increased mass loss, notably at higher PVC concentrations. Briefly ageing waste PVC evaporates the remaining light components, causing that rise. Most blends avoided oxidative hardening and volatile loss during mixing and compaction. This study finds a constant decrease in penetration and a rise in softening point and RV, similar to Mahmoud and Kattan (2023) [37]. However, thermal and elastic characteristics differ. This study's hybrid SBS/PVC binder reduces elastic recovery, lowers flash point, and increases mass loss. Mahmoud and Kattan (2023) discovered that SBS alone enhances elastic recovery and flash point while reducing mass loss [37]. This suggests that although the hybrid approach achieves physical improvement,

**TABLE 4: Conventional test results for hybrid SBS/PVC modified asphalt binders**

SBS %	PVC %	Penetration (0.1 mm)	Softening point (°C)	Viscosity (Pa. s) at 135°C	Elastic recovery (%)	Flash point (°C)	RTFO Mass loss %
2	1	40	61	0.95	50	283	0.4
	3	31	70	1.105	48	275	0.62
	5	29	78	1.361	44	264	0.81
3	1	36	64.5	1.248	55	279	0.52
	3	27	73	1.858	51	268	0.85
	5	24	80.8	2.215	47	259	1.2
4	1	32	71.4	1.65	70	270	0.44
	3	22	82	2.314	61	264	0.73
	5	20	88	2.918	52	251	0.88

SBS: Styrene-butadiene-styrene, PVC: Polyvinyl chloride, RTFO: Rolling thin film oven

the PVC component provides less elastic resilience and more volatility than the standalone SBS modification.

Overall, the results demonstrate that the hybrid SBS/PVC modification significantly improved the conventional properties of the asphalt binder compared to the control binder. Increasing the modifier content generally enhanced binder stiffness and high-temperature resistance, as reflected by lower penetration values and higher softening points. However, excessive PVC content slightly reduced elastic recovery due to the rigid plastomeric nature of PVC.

Among the investigated formulations, the 3% SBS +3% PVC blend exhibited the most balanced overall performance, providing a favorable combination of stiffness, thermal stability, and elastic response. In contrast, the 2% SBS +5% PVC formulation was identified as a promising economical alternative for hot mix asphalt applications, since it achieved satisfactory engineering performance while reducing the required amount of SBS through greater utilization of recycled PVC waste.

### 3.2. DSR Test

A DSR measured  $G^*$ ,  $\delta$ , and the rutting parameter ( $G^*/\sin\delta$ ) under original and RTFO-aged conditions using Superpave testing techniques. The base and hybrid -modified binders (SBS and waste PVC) were tested for permanent deformation resistance at high temperatures.

#### 3.2.1. Structural rigidity and complex shear modulus ( $G^*$ ) enhancement

Figs. 1a and b indicate that hybrid modification greatly enhances complex shear modulus ( $G^*$ ). SBS/waste PVC hybrid binders had higher  $G^*$  values. Compared to the control binder, structural stiffness and load-bearing capacity increased. Stiff reinforcement from waste PVC particles

improves internal friction and structural stiffness, while the swelling SBS component produces an elastomeric network [29], [38]. Thus, hybrid-modified binders resist shear deformation better than unmodified control binders while maintaining high stiffness. By improving its structural components, the hybrid system outlasts traditional asphalt and resists rutting.

#### 3.2.2. Viscoelastic behavior and phase angle ( $\delta$ ) transition

Fig. 2a and b display the phase angle ( $\delta$ ) change for original and RTFO-aged binders. High  $\delta$  values in the control binder indicate viscous behavior and limited elastic recovery at high temperatures. The hybrid alteration significantly reduced  $\delta$  in all samples, indicating a “rubbery” elastic response. As SBS and PVC amounts grew,  $\delta$  values decreased, indicating improved viscoelastic behavior. At higher temperatures, 4% SBS blends with 1%, 3%, and 5% PVC showed the maximum elasticity and lowest phase angle, indicating a robust cross-linked network. The performance of 2% and 3% SBS blends combined with 1%, 3%, and 5% PVC was notably superior to that of the control. This combination effectively transformed the binder from a viscous fluid into a viscoelastic solid, capable of withstanding permanent deformation.

Oxidative stiffening decreases  $\delta$  values for all binders following RTFO ageing. Unlike the control binder, hybrid-modified binders have a more constant viscoelastic response. Compared to the original and aged states, the hybrid system enhances elasticity in the unaged condition and preserves it throughout short-term ageing, resisting oxidative degradation [34].

#### 3.2.3. Rutting resistance ( $G^*/\sin\delta$ ) evolution

Figs. 3a and b show the rutting parameter ( $G^*/\sin\delta$ ) for original and RTFO-aged binders. An integrated analysis of

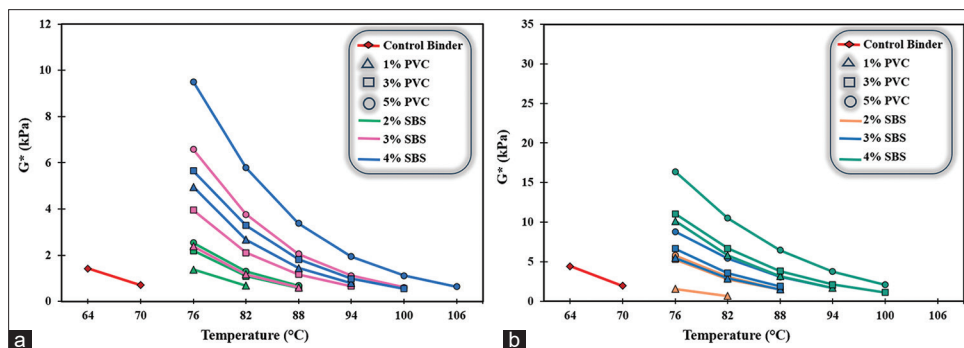


Fig. 1. Complex shear modulus ( $G^*$ ) of base and hybrid styrene-butadiene-styrene/polyvinyl chloride binders: (a) Unaged and (b) rolling thin film oven-Aged.

( $G^*/\sin\delta$ ) for both unaged and RTFO-aged states reveals that the hybrid SBS/PVC alteration enhances the rutting resistance. The control binder passes Superpave at 64°C but fails the minimum requirements at 70°C in both the unaged (1.0 kPa) and RTFO-aged (2.2 kPa) phases, demonstrates the baseline vulnerability of base bitumen. Changing SBS and PVC concentrations in the hybrid modification increases the rutting parameter significantly and non-linearly. Increasing PVC content enhanced the rutting resistance within the 2% SBS group at 76°C.

When PVC concentration increased from 1% to 3%, the binder's stiffness doubled from 1.3881 to 2.5781 kPa. The rutting parameter increases 2.8-fold from 2.5781 to 7.2972 kPa when switching from 2% SBS to 3% SBS at 3% PVC. This trend further accelerated at 4% SBS, when 3% PVC result in 11.0594 kPa. This value is 4.3-fold higher than the 2%SBS and 1.5-fold higher than the 3% SBS hybrids.

2% SBS +3% PVC had better performance than 3% SBS +1% PVC. This shows that PVC significantly increases

( $G^*/\sin\delta$ ) at lower SBS concentrations. These findings show that waste PVC serves as an effective modifier that may significantly decrease the quantity of expensive SBS needed to attain high-stability goals.

3.2.4. High-temperature PG

As shown in Table 5, the DSR test evaluated high-temperature performance using the rutting parameter, and all modified binders showed a higher PG than the original asphalt. When the concentrations of SBS and PVC were increased, a multi-degree rise in high temperature performance was obtained. PG 64-16 was the control asphalt; adding a hybrid modifier of 2% SBS and 1% PVC improved the binder to PG 76-x, a significant two-degree improvement over the base bitumen; increasing the waste PVC content to 3% and 5% effectively improved the high-temperature classification to PG 82-x, which exceeded the control asphalt by three grades. The binder retained a PG 82-x classification at a 1% PVC content at a 3% SBS dosage. When the PVC level was increased to 5%, the modifiers' synergistic impact was most noticeable. This improved the thermal stability to PG 88-x, a four-degree

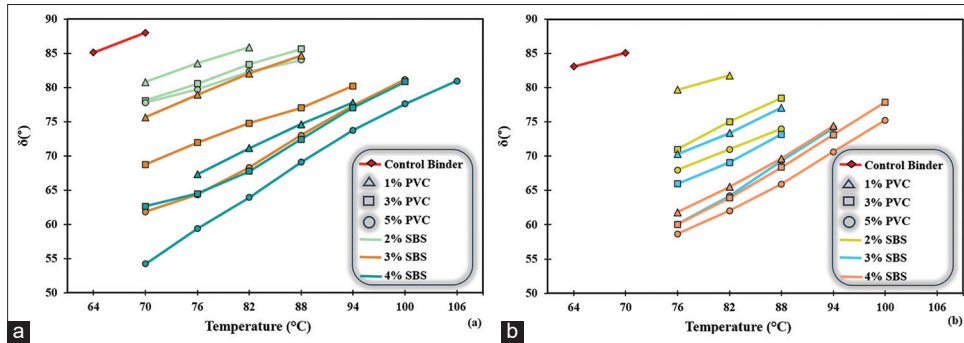


Fig. 2. Phase angle ( $\delta$ ) of base and hybrid styrene-butadiene-styrene/polyvinyl chloride binders: (a) Unaged and (b) rolling thin film oven-Aged.

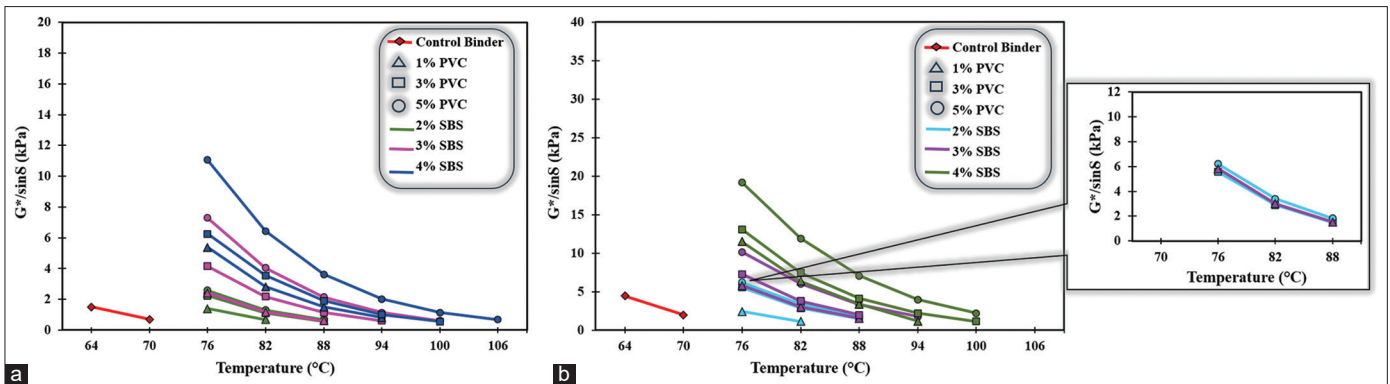


Fig. 3. Rutting parameter ( $G^*/\sin\delta$ ) of base and hybrid styrene-butadiene-styrene/polyvinyl chloride Binders: (a) Unaged and (b) rolling thin film oven-Aged.

**TABLE 5: High-temperature performance grades of original and hybrid SBS/PVC modified asphalt binders**

SBS (%)	PVC (%)	Original pass temperature (°C)	Original G*/sinδ (kPa)	RTFO pass temperature (°C)	RTFO G*/sinδ (kPa)	PG
0	0	67.3	1.51	69.2	4.46	64-16
2	1	78.8	1.388	76.8	2.43	76
	3	82.9	1.099	84.5	2.89	82
	5	84.6	1.31	86.4	3.39	82
3	1	83.5	1.18	84.8	3.01	82
	3	89.9	1.199	87.1	3.81	82
	5	95.3	1.135	92	3.31	88
4	1	92	1.497	92	3.38	88
	3	94	1.007	94.1	2.21	94
	5	101.5	1.133	100	2.2	100

SBS: Styrene-butadiene-styrene, PVC: Polyvinyl chloride, RTFO: Rolling thin film oven

improvement over the unmodified bitumen. At the highest modification level of 4% SBS, the hybrid system reached maximum efficiency.

According to Table 5, samples containing 1%, 3%, and 5% PVC achieved PG 88-x, PG 94-x, and PG 100-x, respectively. Excessive increases in binder stiffness may negatively impact workability, compaction efficiency, and low-temperature flexibility, even if the same high PG grades show increased resistance to rutting and permanent deformation under high-temperature service conditions. According to earlier research, plastomeric modifiers, such as PVC and PE greatly improve stiffness and resistance to deformation; nevertheless, high modifier concentrations may make the material more brittle and vulnerable to thermal cracking at low temperatures. However, by increasing the elasticity and flexibility of the binder, the addition of elastomeric polymers, such as SBS may assist lessen this impact. Therefore, to guarantee long-lasting pavement performance, it is crucial to maintain an ideal balance between rutting resistance, stiffness, flexibility, and workability [39], [40].

#### 4. CONCLUSION

This research evaluates the conventional and rheological properties of 60/70 grade asphalt binders treated with hybrid SBS-waste PVC mixes at various concentrations. Experiment results provide these conclusions:

1. Results from conventional tests indicate that hybrid modification considerably impacts bitumen’s physical qualities. The synergistic interplay between the high-modulus PVC component and the elastomeric SBS network made the hybrid system an effective stiffener. This interaction gradually reduced penetration and significantly raised the softening point. Despite increased RV, all samples were workable. The binder also has good elastic recovery, mass loss limitations, and flash point safety.
2. For rutting resistance, thermal stability, and viscoelastic qualities, the 3% SBS +3% PVC mix showed the greatest optimum engineering performance among the formulations examined. Because it uses less SBS and incorporates more recycled PVC waste, the 2% SBS +5% PVC mix may be more economical and environmentally friendly while maintaining sufficient rheological performance. As a result, both formulations might be considered viable hybrid modification systems according to cost and performance standards.
3. A shift from viscous-dominant to elastic-dominant behavior was confirmed by rheometer (DSR) results of the original binders, which showed a large decrease in phase angle ( $\delta$ ) and a significant rise in complex shear modulus ( $G^*$ ). As the proportion of the modifiers rose, the improvement became more noticeable.
4. All binders showed higher stiffness during RTFO aging, which can be attributed to oxidative hardening; however, hybrid-modified binders outperformed the control binder in terms of viscoelastic balance and structural stability. Improved short-term aging resistance is shown by the decreased susceptibility to aging.
5. For both original and aged binders, the rutting metric ( $G^*/\sin\delta$ ) has shown a significant improvement. A number of hybrid blends showed better resistance to permanent deformation and met Superpave standards at temperatures much higher than the control binder.
6. For both the original and aged states, the rutting parameter ( $G^*/\sin\delta$ ) demonstrated a significant increase in the binder’s internal resistance to permanent deformation. Starting with a PG 64-16 for the control asphalt, the hybrid system effectively raised the high-PG by 2, 3, 4, 5, and even 6 grades, enabling the pavement to withstand severe weather and large traffic volumes.
7. By using plastic waste in pavement applications, the use of waste PVC offers an environmentally beneficial

alternative. In addition to improving the roads' mechanical performance and aging stability, this method provides a long-lasting and sustainable way to build high-performance pavements in hot-climate regions.

Overall, the hybrid SBS/PVC modification strategy enhances stiffness, elasticity, rutting resistance, and aging stability of asphalt binders; hence providing a more effective, durable, and sustainable approach for high-performance pavements which are particularly advantageous in hot-climate regions. However, further investigations are recommended to evaluate the long-term storage stability and phase compatibility of SBS/PVC-modified binders during high-temperature storage conditions. In addition, future studies should assess the low-temperature rheological behavior and thermal cracking resistance of the modified binders using BBR testing and additional Superpave performance evaluations.

## REFERENCES

- [1] H. Li, B. Dong, D. Zhao, P. Guo and J. Zhang. "Physical, rheological and stability properties of desulfurized rubber asphalt and crumb rubber asphalt." *Arabian Journal for Science and Engineering*, vol. 44, no. 5, pp. 5043-5056, 2019.
- [2] Y. O. Hetemoğlu, M. K. Çubuk and M. Gürü. "Improvement in performance characteristics of bitumen and bituminous mixtures by means of polyvinyl acetate". *Construction Materials*, vol. 5, no. 1, p. 9, 2025.
- [3] S. Bhandari, X. Luo and F. Wang. "Understanding the effects of structural factors and traffic loading on flexible pavement performance". *International Journal of Transportation Science and Technology*, vol. 12, no. 1, pp. 258-272, 2023.
- [4] J. C. Pais, S. I. R. Amorim and M. J. C. Minhoto. "Impact of traffic overload on road pavement performance." *Journal of Transportation Engineering*, vol. 139, no. 9, pp. 873-879, 2013.
- [5] Y. Qiao, G. Flintsch, A. Dawson and T. Parry. "Examining effects of climatic factors on flexible pavement performance and service life". *Transportation Research Record Journal of the Transportation Research Board*, vol. 2349, pp. 100-107, 2013.
- [6] A. H. Albayati. "A review of rutting in asphalt concrete pavement". *Open Engineering*, vol. 13, p. 20220463, 2023.
- [7] J. Liu, S. Zhao, L. Li, P. Li and S. Saboundjian. "Low temperature cracking analysis of asphalt binders and mixtures". *Cold Regions Science and Technology*, vol. 141, pp. 78-85, 2017.
- [8] M. M. Hilal and M. Y. Fattah. "Evaluation of modified asphalt binder and mixtures with polyphosphoric acid". *Al-Nahrain Journal for Engineering Sciences*, vol. 26, no. 1, pp. 31-36, 2023.
- [9] H. A. Rondón Quintana, C. A. Zafra and F. Reyes. "Rutting in asphalt mixtures - a review". *Revista Ingenierías Universidad de Medellín*, vol. 22, no. 43, pp. 1-26, 2024.
- [10] Y. Pan, H. Guo, W. Guan and Y. Zhao. "A laboratory evaluation of factors affecting rutting resistance of asphalt mixtures using wheel tracking test." *Case Studies in Construction Materials*, vol. 18, no. 5, p. e02148, 2023.
- [11] A. H. Abed. "Effects of functionalized polyethylene and styrene butadiene styrene polymers on performance grade of local asphalt". *Journal of Engineering*, vol. 18, no. 06, pp. 735-742, 2012.
- [12] S. A. Ghanoon, J. Tanzadeh and M. Mirsepahi. "Laboratory evaluation of the composition of nano-clay, nano-lime and SBS modifiers on rutting resistance of asphalt binder." *Construction and Building Materials*, vol. 238, p. 117592, 2020.
- [13] A. Behnood and M. Modiri Gharehveran. "Morphology, rheology, and physical properties of polymer-modified asphalt binders." *European Polymer Journal*, vol. 112, pp. 766-791, 2019.
- [14] M. Emtiaz, M. N. Imtiyaz, M. Majumder, I. I. Idris, R. Mazumder and M. M. Rahaman. "A comprehensive literature review on polymer-modified asphalt binder." *CivilEng*, vol. 4, no. 3, pp. 901-932, 2023.
- [15] P. Yang, R. Ren, L. Wang and X. Zhang. "Characteristic behavior of asphalt with SBS and PE." In: *Sustainable Construction Materials 2012 - Proceedings of the 2<sup>nd</sup> International Conference on Sustainable Construction Materials - Design, Performance, and Application*. pp. 416-424, 2013.
- [16] L. Zhou, W. Huang, Y. Zhang, Q. Lv, C. Yan and Y. Jiao. "Evaluation of the adhesion and healing properties of modified asphalt binders." *Construction and Building Materials*, vol. 251, p. 119026, 2020.
- [17] J. Huang, Y. Liu, Y. Muhammad, J. Q. Li, Y. Ye, J. Li, Z. Li and R. Pei. "Effect of glutaraldehyde-chitosan crosslinked graphene oxide on high temperature properties of SBS modified asphalt." *Construction and Building Materials*, vol. 357, p. 129387, 2022.
- [18] J. S. Coplantz, M. T. Yapp and F. N. Finn. "Review of Relationships between Modified Asphalt Properties and Pavement Performance." National Research Council, United States, 1993.
- [19] P. K. Gautam, P. Kalla, A. S. Jethoo, R. Agrawal and H. Singh. "Sustainable use of waste in flexible pavement: A review." *Construction and Building Materials*, vol. 180, pp. 239-253, 2018.
- [20] H. Zanjirani Farahani, M. Palassi and S. S. Galooyak. "Rheology investigation of waste LDPE and crumb rubber modified bitumen." *Engineering Solid Mechanics*, vol. 6, no. 1, pp. 27-38, 2018.
- [21] S. Köfteci, P. Ahmedzade and B. Kultayev. "Performance evaluation of bitumen modified by various types of waste plastics." *Construction and Building Materials*, vol. 73, pp. 592-602, 2014.
- [22] A. Sedai, S. Ghimire and J. P. Devkota. "Use of waste plastic as a replacement for bitumen in road construction." *OCEM Journal of Management, Technology and Social Sciences*, vol. 4, no. 1, pp. 94-104, 2025.
- [23] L. Ye, C. Qi, J. Hong and X. Ma. "Life cycle assessment of polyvinyl chloride production and its recyclability in China". *Journal of Cleaner Production*, vol. 142, pp. 2965-2972, 2017.
- [24] D. Wang, A. Baliello, L. Poulikakos, K. Vasconcelos, M. R. Kakar, G. Giancontieri, E. Pasquini, L. Porot, M. Tušar, C. Riccardi, D. L. Presti and A. C. Falchetto. "Rheological properties of asphalt binder modified with waste polyethylene: An interlaboratory research from the RILEM TC WMR". *Resources Conservation and Recycling*, vol. 186, p. 106564, 2022.
- [25] L. You, Z. Long, Z. You, D. Ge, X. Yang, F. Xu, M. Hashemi and A. Diab. "Review of recycling waste plastics in asphalt paving materials". *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 9, no. 5, pp. 742-764, 2022.
- [26] R. Monticelli, A. Roberto, E. Romeo and G. Tebaldi. "Mixed design optimization of polymer-modified asphalt mixtures (PMAs) containing carton plastic packaging wastes". *Sustainability*, vol. 15, no. 13, p. 10574, 2023.
- [27] N. Rahman, M. Ahmeduzzaman, M. A. Sobhan and T. U. Ahmed. "Performance evaluation of waste polyethylene and PVC on hot

- asphalt mixtures". *American Journal of Civil Engineering and Architecture*, vol. 1, no. 5, pp. 97-102, 2013.
- [28] N. Salman and Z. Jaleel. "Effects of waste PVC addition on the properties of (40-50) grade asphalt | MATEC Web of Conferences". *MATEC Web of Conferences*, vol. 162, p. 01046, 2018.
- [29] B. Huang, L. Ma, W. Xu and R. Yang. "Compound modification of asphalt with PVC waste and SBS". *2011 International Conference on Remote Sensing, Environment and Transportation Engineering, RSETE 2011 - Proceedings*, pp. 3946-3949, 2011
- [30] Q. Yang, J. Lin, X. Wang, D. Wang, N. Xie and X. Shi. "A review of polymer-modified asphalt binder: Modification mechanisms and mechanical properties". *Cleaner Materials*, vol. 12, p. 100255, 2024.
- [31] A. Behl, G. Sharma and G. Kumar. "A sustainable approach: Utilization of waste PVC in asphaltting of roads". *Construction and Building Materials*, vol. 54, pp. 113-117, 2014.
- [32] M. Arabani and M. Yousefpour Taleghani. "Rutting behavior of hot mix asphalt modified by polyvinyl chloride powder". *Petroleum Science and Technology*, vol. 35, no. 15, pp. 1621-1626, 2017.
- [33] H. F. Jabbar, M. M. Hilal and M. Y. Fattah. "Assessment of asphalt mixtures enhanced with styrene-butadiene-styrene and polyvinyl chloride through rheological, physical, microscopic, and workability analyses". *Journal of Composites Science*, vol. 9, no. 7, p. 341, 2025.
- [34] E. N. Ezzat and A. H. Abed. "Enhancement rheological properties of asphalt binder modified with hybrid polymers according to superpave system". *Materials Today Proceedings*, vol. 20, pp. 572-578, 2020.
- [35] G. Polacco, S. Filippi, F. Merusi and G. Stastna. "A review of the fundamentals of polymer-modified asphalts: Asphalt/polymer interactions and principles of compatibility". *Advances in Colloid and Interface Science*, vol. 224, pp. 72-112, 2015.
- [36] F. Canestrari, K. Formela, S. Hesp, F. Xu, Y. Zhao and K. Li. "Using waste plastics as asphalt modifier: A review". *Materials*, vol. 15, no. 1, p. 110, 2021.
- [37] A. O. Mahmood and R. A. Kattan. "Improvement of engineering properties of asphalt binder and mixture by using SBS additive material". *Advances in Civil Engineering*, vol. 2023, no. 1, p. 7151175, 2023.
- [38] F. Dong, W. Zhao, Y. Zhang, J. Wei, W. Fan, Y. Yu and Z. Wang. "Influence of SBS and asphalt on SBS dispersion and the performance of modified asphalt". *Construction and Building Materials*, vol. 62, pp. 1-7, 2014.
- [39] A. Calabi-Floody, C. Mignolet-Garrido and G. Valdes-Vidal. "Study of the effect of the use of asphalt binders modified with polymer fibres from end-of-life tyres (ELT) on the mechanical properties of hot mix asphalt at different operating temperatures". *Materials*, vol. 15, no. 21, p. 7578, 2022.
- [40] M. R. Garcez, E. Fontoura, L. A. T. Brito, W. Fedrigo, K. M. Dorneles and G. B. Colpo. "Hard-to-recycle plastic as asphalt modifier: Mechanical performance and potential environmental impacts". *Case Studies in Construction Materials*, vol. 23, p. e05274, 2025.