

STRUCTURAL AND ECONOMIC PERFORMANCE OF SBS POLYMER-MODIFIED ASPHALT UNDER HEAVY TRAFFIC LOAD

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Abstract

This study investigates the structural and economic performance of SBS polymer-modified asphalt under heavy traffic loading, emphasizing polymer interaction, rutting resistance, and moisture durability. XRD analysis revealed enhanced polymer-bitumen interaction, indicating effective integration of SBS into the asphalt matrix. Laboratory evaluations of Dense Bituminous Macadam (DBM) and Bituminous Concrete (BC) demonstrated substantial improvements compared with conventional mixes. At the optimum SBS content of 4%, the Marshall Stability increased by 22.49% for DBM and 30.31% for BC, while the Marshall Quotient (MQ) rose by 31.96% and 10.32% respectively. Percentage improvement was calculated with respect to the control mix values, indicating superior resistance to permanent deformation under traffic loading. Moisture susceptibility assessed using Retained Marshall Stability (RMS), showed significant improvement, indicating enhanced durability under wet conditions. Furthermore, life cycle cost analysis (LCCA) highlighted the economic benefits of SBS modification, including potential reductions in maintenance costs over the pavement lifespan. Overall, the findings demonstrate that SBS-modified asphalt provides enhanced structural performance, durability, and cost efficiency, making it highly suitable for high-traffic highways.

Keywords: Heavy traffic load; Life-cycle cost analysis; Moisture durability; Polymer interaction; Rutting resistance; SBS-modified asphalt

Introduction

Rutting is a major distress phenomenon in bituminous pavements, causing maintenance issues and early structural failure. It reflects the inability of pavements to resist permanent deformation under repeated traffic loads, while fatigue cracking, thermal cracking, and moisture damage further compromise durability (Ziari *et al.*, 2016; Kodippily *et al.*, 2018). Polymer modification has emerged as

an effective approach to enhance binder performance, improving rutting resistance, rheological stability, and moisture susceptibility (Li *et al.*, 2022).

Background Study

SBS is a thermoplastic elastomer exhibiting elasticity at ambient temperatures and thermoplastic

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flow at high temperatures, enabling binders to maintain performance across service conditions (Kumar *et al.*, 2006; Özen, 2011; Lin *et al.*, 2019; Lv *et al.*, 2019). Its incorporation increases stiffness, adhesion, and dynamic stability, thereby enhanced resistance to rutting and moisture-induced damage (Xiao *et al.*, 2019; Vamegh *et al.*, 2020). High-content SBS-modified asphalt demonstrates superior rutting resistance and rheological performance, although aging can reduce its effectiveness, highlighting the need for performance thresholds and proper mixture design (Singh *et al.*, 2020; Han *et al.*, 2023; Rajan *et al.*, 2023; Vamsikrishna & Singh, 2025). SBS with higher molecular weight and optimized dosages (5-7%) significantly reduces non-recoverable creep compliance, thereby improving deformation resistance (Uwanuakwa *et al.*, 2023). Overall, the incorporation of styrene-butadiene-styrene (SBS) consistently improves rutting resistance, as well as the rheological and physical properties, and durability of mixtures under heavy traffic and varying environmental conditions (Vamegh & Ameri, 2021; Yan *et al.*, 2021; Yalcin & Demirbag, 2022).

XRD Analysis of SBS Polymer Systems

X-ray diffraction (XRD) has been widely used to study the microstructure of SBS polymers and composites. SBS-based materials generally show amorphous and semi-crystalline domains, which influence polymer dispersion and mechanical performance (Souza *et al.*, 2008). SBS-W-modified asphalt exhibited better molecular arrangement and fluidity than conventional SBS, improving deformation resistance and fatigue life (Zhuang *et al.*, 2023). Graphene oxide increased SBS crystallinity, forming a more ordered network and enhancing thermal and fatigue performance, while carbon nanotubes reduced crystallinity, improving flexibility (Wang *et al.*, 2021). Overall, XRD effectively reveals the structure, ordering, and dispersion of SBS, which correlate with the performance and durability of modified asphalt.

Lifecycle Economic Evaluation

The use of SBS-modified bitumen enhances pavement durability, reduces maintenance frequency, and minimizes material degradation, collectively resulting in lower life cycle costs. These advantages make it a sustainable and cost-effective choice for long-term infrastructure performance (Chen *et al.*, 2023; Kozel *et al.*, 2024; Zhu, 2024).

Despite extensive studies on SBS-modified asphalt, most research focuses either on binder rheology or mixture rutting performance, with limited evaluation under heavy traffic conditions

that considers both structural and economic aspects. Additionally, the influence of polymer interactions on combined rutting and moisture resistance has not been comprehensively studied, leaving a gap in understanding how optimized SBS content can maximize performance while minimizing cost.

The hypothesis of this study is that by systematically evaluating SBS-modified asphalt under heavy traffic, considering polymer interactions, rutting, and moisture resistance simultaneously, it is possible to identify formulations that deliver enhanced structural durability and cost-effective pavement solutions.

The novelty of this work lies in integrating polymer interaction analysis, rutting resistance, moisture performance, and economic evaluation into a single framework, providing practical guidance for designing high-performance, durable, and economical asphalt pavements under heavy traffic conditions.

Although many studies evaluate SBS-modified asphalt for rutting, moisture resistance, or binder properties individually, there is no integrated approach combining structural performance, durability, and cost-effectiveness for practical pavement design. Developing this framework enables engineers to select optimal SBS dosages and mixture formulations based on real traffic conditions while considering economic constraints, ensuring reliable, durable, and cost-efficient pavements.

Objectives of the Study

1. To investigate the effect of SBS polymer content and interaction on the rheological and physical properties of asphalt binders.
2. To evaluate the rutting resistance of SBS-modified asphalt under simulated heavy traffic conditions.
3. To assess the moisture susceptibility and durability of SBS-modified asphalt mixtures.
4. To perform a comparative economic analysis to identify cost-effective SBS modification strategies.
5. To develop a practical framework for optimizing SBS-modified asphalt mixtures considering structural performance, durability, and economic efficiency.

Materials and Methods

Materials

Selection of Bitumen Grade and Polymer Materials

The selection of a suitable bitumen grade is very important for durable, flexible pavements. In

this study, VG40 was selected due to its higher viscosity and superior performance under heavy traffic and high-temperature conditions. As per the specifications of India's Ministry of Road Transport and Highways (MoRTH, 2013), this grade is recommended for heavily loaded roads in hot climatic regions because it offers improved resistance to rutting and permanent deformation compared to lower viscosity grades. It is also compatible with polymer modification and works effectively with SBS polymer to enhance the strength and overall mechanical performance. Therefore, its use supports current pavement engineering practices for constructing long-lasting and stable road pavements. Figure 1 shows the physical appearance of SBS polymer.



Figure 1. Shows Appearance of SBS (PG-411) Polymer

Aggregate Properties

The aggregates used in this study were procured from Piploda Dwarkadish village, Ujjain district, Madhya Pradesh, located at geographical coordinates of 23.10° N latitude and 75.46° E longitude. The materials were tested in accordance with standards specified by the Bureau of Indian Standards (BIS) (IS 2386) to evaluate their physical and mechanical properties. Specific gravity, bulk density, and water absorption were determined as per IS 2386 (Part III) (BIS, 1963b) to assess density and porosity. Mechanical strength was checked using the Aggregate Impact Value and Los Angeles

Abrasion tests in accordance with IS 2386 (Part IV) (BIS, 1963c). Flakiness and elongation indices were measured as per IS 2386 (Part I) (BIS, 1963a) to study particle shape and interlocking ability. All test results met [Ministry of Road Transport and Highways [MoRTH], 2013]. Table 1 presents the summarized aggregate properties.

Aggregate gradations adopted

Two gradations were used in this study: DBM and BC, in accordance with MoRT&H standards. DBM was selected for the binder course and BC for the surface course, as commonly followed in Indian road construction. The gradations were prepared using the midpoint values of the specified limits, and the curves are shown in Figure 2. Both mixes satisfy well-graded requirements. BC is slightly finer than DBM in the 4.75 mm to 20 mm range, which makes it suitable for the top wearing layer. The well-graded structure helps in better interlocking and overall pavement stability.

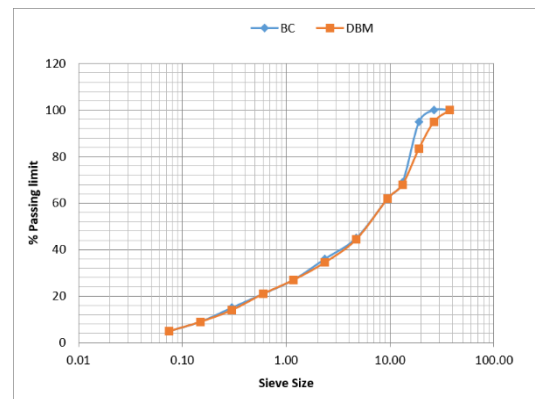


Figure 2. Shows that the aggregates were graded in this study

Methods

Binder Characterization

The properties of VG-40 and SBS-modified binders were evaluated using standard tests to determine consistency, temperature susceptibility, and flow behavior. Penetration IS 1203:2022 (BIS,

Table 1. Aggregate properties determined in accordance with IS 2386 (Part I, Part III, and Part IV) as specified by the Bureau of Indian Standards

Aggregate Properties	Standards	Materials Overview			Specification as per MoRT&H
		Coarse Aggregate	Fine Aggregate	M Sand	
Specific Gravity	IS:2386 (Part-III)	2.762	2.683	2.625	-
Bulk Density (kg/m ³)		1510	1539	1608	-
Water Absorption (%)		0.81	1.14	1.33	Max 2%
Impact test (%)	IS:2386 (Part-IV)	11.57	13.95	-	Max 27%
Abrasion test (%)		14.25	20.24	-	Max 35%
Combined Flakiness	IS:2386 (Part-I)	23	-	-	Combined 35%
Elongation value (%)					

2022a), softening point IS 1205:2022 (BIS, 2022b), and ductility IS 1208-1:2023 (BIS, 2023) tests assessed hardness, thermal response, and flexibility. Absolute viscosity at 60°C IS 1206-2:2022 (BIS, 2022c) and kinematic viscosity at 135°C IS 1206-3:2021 (BIS, 2021) characterized flow resistance at different temperatures. The penetration index (PI) was calculated to quantify temperature sensitivity. Samples were conditioned in a 25°C water bath for 60-90 minutes to ensure uniform temperature and reliable measurements. The PI value in this study was determined using the traditional approach specified in the Shell Bitumen Handbook, as given by equation (1).

$$\text{Penetration Index (PI)} = \frac{1952 - 500 \log \text{Pen} - 20 \times \text{SP}}{50 \log \text{Pen} - \text{SP} - 120} \quad (1)$$

Pen25 denotes the penetration value measured at 25°C, whereas SP represents the softening point of the polymer-modified binder (PMB). The Penetration Index (PI) generally ranges from about -3 to +7. A PI near -3 indicates a binder with high sensitivity to temperature fluctuations, while a value approaching +7 reflects a binder with enhanced thermal stability and significant air-blowing treatment, as described by Read and Whiteoak (2003).

XRD Analysis of SBS Polymer

The microstructural properties of the pure SBS polymer were investigated using a Powder X-ray Diffractometer, a laboratory instrument that analyzes the arrangement of molecules within a sample. The diffractometer was equipped with an SC-70 detector, and measurements were conducted in continuous-scan mode. The receiving slit was set to 1-1/2° and 2.0 mm to optimize resolution and signal intensity. The polymer samples were scanned over a suitable 2θ range, and diffraction patterns were recorded as intensity (counts per second, cps) versus 2θ (degrees) using the instrument software. The XRD analysis of pure SBS allowed the determination of its amorphous or crystalline nature, molecular ordering, and polymer domain size. These microstructural characteristics provide a basis for understanding how SBS is likely to interact and disperse in bitumen when used as a modifier, which can influence rutting resistance, Marshall Stability, and moisture performance in asphalt mixes.

Preparation of Marshall Specimens with SBS-Modified Binder

Marshall Specimens were prepared to evaluate the influence of SBS polymer on the performance of VG-40 bitumen mixtures. SBS was incorporated at 2-10% by weight of the binder. The base bitumen was heated to 125°C to improve workability,

followed by gradual addition of SBS, and mixing continued at 190 °C for 10 minutes to ensure uniform dispersion. Approximately 1200 g of preheated aggregates and filler (180°C) were blended with the modified binder at a trial binder content of 4.5% by aggregate weight. The hot mix was thoroughly blended at 160°C to achieve homogeneity and compacted in preheated Marshall Moulds at 145°C using 75 blows per face. The compacted specimens were cooled, extruded, and tested for Marshall Stability and Flow. This procedure facilitated the assessment of strength and deformation characteristics, enabling identification of the optimum SBS content to improve the durability and rutting resistance of asphalt mixtures.

Marshall Stability Test Procedure and Application

The Marshall Stability test was carried out in accordance with ASTM D6927 (ASTM International, 2015) to assess the load-bearing capacity and deformation characteristics of the bituminous mix. For this purpose, cylindrical samples measuring 102 mm in diameter and 63.5 mm in height were fabricated using a mechanical compactor under controlled temperature and compaction settings. After proper conditioning, each specimen was placed in the Marshall testing frame, where a vertical load was applied at a uniform deformation rate of 50.8 mm per minute until failure. The highest load value obtained during testing was noted as the Marshall Stability, while the corresponding deformation, measured in increments of 0.25 mm, was recorded as the flow value. These parameters were used to assess the mixture's load-bearing capacity and flexibility, providing a basis for optimizing binder content and evaluating the performance of conventional and modified bituminous mixes under simulated field conditions. Figure 3. Measurement of aggregate weight (1200 g), specimen dimensions, and preparation steps including heating, testing, wax coating, and water-bath conditioning.





Figure 3. Shows (a) Dimension measurement; (b) oven heating at 60°C, 120 minutes; (c) Marshall test setup; (d) Wax-coated Marshall Specimens in water bath for conditioning at 60°C for 24 hours

Moisture Susceptibility Evaluation Using Retained Marshall Stability

The Retained Marshall Stability (RMS) test was performed to evaluate the moisture susceptibility of asphalt mixtures. RMS serves as a key indicator of how well bituminous mixes, especially polymer-modified variants containing Styrene-Butadiene-Styrene (SBS), resist moisture-induced damage. For each level of SBS modification, three cylindrical specimens were prepared. The test procedure followed the ASTM D6927 standard (ASTM International, 2015). Conditioned specimens were immersed in a water bath at 60 °C for 24 hours to mimic extended moisture exposure, whereas unconditioned specimens were tested under normal laboratory conditions. Subsequently, all specimens underwent the Marshall Stability test at a constant loading rate of 50.8 mm/min, and the peak load was recorded. The Retained Marshall Stability was calculated as the ratio of the stability of the conditioned specimen to the unconditioned specimen, expressed as a percentage using equation (2).

$$\text{Retained Marshal Stability} = \frac{\text{Marshal stability of conditioned specimen}}{\text{Marshal stability of unconditioned specimen}} \times 100 \quad (2)$$

Higher RMS values indicate greater resistance to moisture-induced weakening, reflecting enhanced durability and adhesion of the asphalt mix.

Life Cycle Cost Analysis (LCCA)

It was carried out to compare the long-term economic performance of conventional VG-40 bitumen and SBS polymer-modified bitumen for a 2 km, six-lane flexible pavement section. The analysis

period was set to 20 years, based on the design life generally adopted for high-volume highways. The procedure for economic evaluation was carried out in accordance with Indian Roads Congress SP:30-2019 guidelines. All costs were estimated in Indian Rupees (Rs million) and converted into present value for proper comparison.

The economic analysis was performed using the Net Present Value (NPV) method, as recommended in IRC SP:30-2019 for pavement economic evaluation. A real discount rate of 4% was used to discount future costs. The NPV was calculated using equation (3) (Walls & Smith, 1998; Qiao *et al.*, 2019):

$$NPV = \sum_{t=0}^T \frac{\sum_{n=1}^N C_t}{(1+i)^t} \quad (3)$$

where, NPV = net present value
 C_t = the cash flow (Cost or benefit) at year t
 i = discount rate per year
 t = time period year

For recurring uniform annual costs such as user cost, the present value was computed using the Present Worth Factor (PWF), given by equation (4) (Indian Roads Congress, 2019):

$$PWF = \frac{(1+i)^n - 1}{i(1+i)^n} \quad (4)$$

PWF = Present Worth Factor, n = number of years (analysis period)

For single future costs occurring at the end of the analysis period (e.g., salvage value), the discount factor was calculated using equation (5).

$$DF = \frac{1}{(1+i)^n} \quad (5)$$

DF = Discount Factor, n = number of years (analysis period)

The initial construction cost was considered at year zero and therefore not discounted. Future maintenance, rehabilitation, and user costs were discounted to present value. The salvage value at the end of the 20th year was treated as a negative cost and discounted accordingly, as per IRC recommendations.

The analysis included all major cost components affecting pavement performance during its service life. Initial construction cost covered binder production (VG-40 or SBS-modified bitumen), aggregate processing, transportation, and paving operations such as laying and compaction.

Maintenance and rehabilitation costs included routine activities such as crack sealing and patch repairs, as well as periodic resurfacing using a 50 mm bituminous overlay. User costs were considered to reflect increased vehicle operating expenses resulting from pavement deterioration. A residual (salvage) value was assigned at the end of the analysis period to represent the remaining recyclable value of the bituminous layers. Cost data were obtained from the standard Schedule of Rates (SoR), Bill of Quantities (BoQ)-based estimates, and published LCCA studies to ensure reliability and transparency.

Results and Discussion

This section presents the test outcomes for bitumen modified with the SBS polymer. Core performance metrics such as bitumen properties are examined alongside mechanical parameters, including Marshall Stability and flow, to assess durability and deformation resistance. Moisture susceptibility is also evaluated to determine behavior under challenging environmental conditions.

Variation in Bitumen Properties

The SBS polymer modification range of 2–10% was chosen to capture the onset of performance improvements and identify the best binder behavior, because literature shows significant gains within this range: 5% SBS gave the best overall balance of stiffness and rutting/low-temperature performance

in binders studied with 3–9% SBS (Riaz *et al.*, 2025), and 6% SBS was found to provide the most favorable mechanical and dynamic properties in asphalt mixtures with 2–7% SBS (Khan *et al.*, 2024), the penetration values exhibit a consistent decline, indicating enhanced stiffness and deformation resistance of the modified binder. This increased rigidity contributes to improved rutting resistance under elevated temperatures and repeated traffic loading, as shown in Figure 4(a). Similarly, the softening point rises with higher SBS content, demonstrating greater thermal stability and reduced susceptibility to deformation at high service temperatures Figure 4(b). The Penetration Index (PI), derived from penetration and softening point values, also increases with SBS addition, confirming improved temperature susceptibility and enhanced durability of the binder, as shown in Figure 4(c). Furthermore, both absolute and kinematic viscosity values increase steadily with polymer modification as shown in Figures 4(d) and 4(e), signifying reduced flowability and enhanced resistance to permanent deformation under heavy traffic and high-temperature conditions. A comparable improvement is observed in ductility test results, Figure 4(f), where the modified binders retain adequate flexibility, indicating that SBS effectively balances stiffness and elasticity, thereby enhancing overall binder performance across varying temperature ranges. Table 2 presents the results of the base binder and the SBS polymer-modified bitumen in terms of their respective properties.

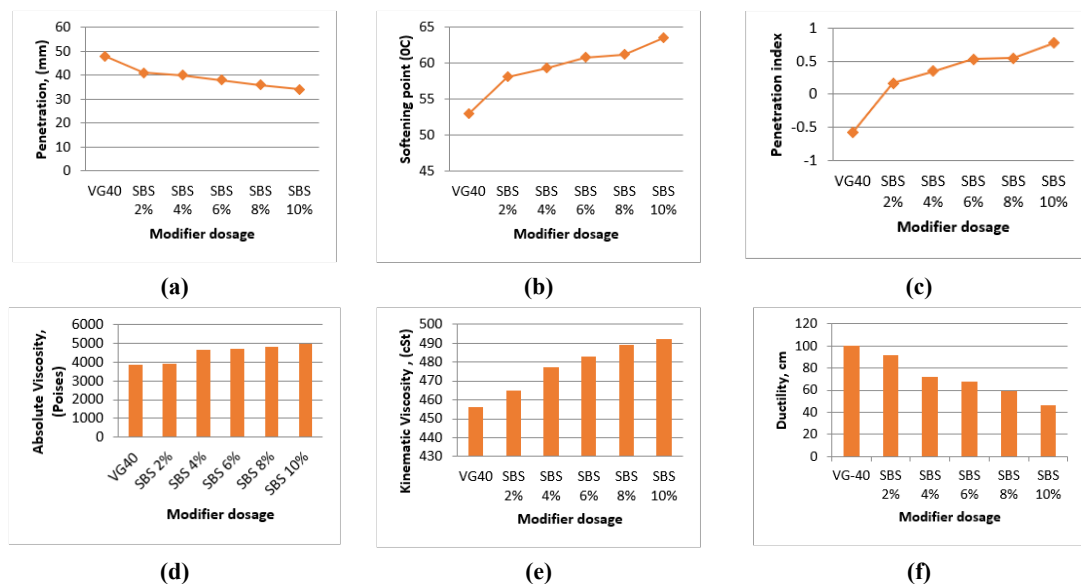


Figure 4. Shows Bitumen properties: (a) penetration; (b) softening point; (c) penetration index; (d) absolute viscosity; (e) kinematic viscosity; (f) ductility

Table 2. Shows Properties of Binder Materials Requirement Specification as per IS 73:2013 (BIS, 2013)

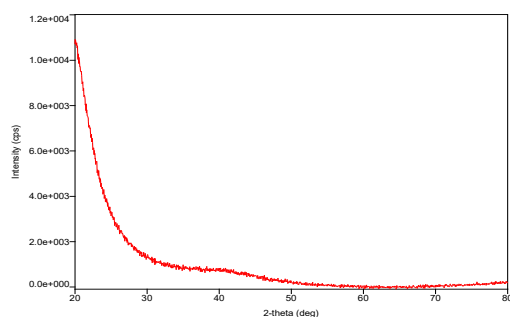
Properties	Modifier dosage (%)						As per IS 73:2013 VG-40 (min.)
	VG-40	2	4	6	8	10	
Penetration, 25°C (mm)	48	41	40	38	37	36	35
Softening point (°C)	53	58.2	59.3	60.8	61.3	63.5	50
Absolute Viscosity, 60°C (Poises)	3851	3912	4640	4725	4831	4956	3600-4800
Kinematic Viscosity, 135°C (cSt)	456	465	478	483	489	493	400
Ductility at 25°C, min	>100	92	72	68	59	46	25
Penetration index	-0.58	0.17	0.35	0.53	0.55	0.91	-

Table 3. Shows XRD analysis of neat SBS polymer powder

S.no.	2- theta(deg)	d (ang.)	Height (cps)	FWHM (deg)	Int. I (cps deg)	Size (ang.)	Rel. int. (a.u.)
1	18.95(15)	4.68(4)	8548(133)	4.58(10)	58914.63003(14)	18.4(4)	100.00

XRD Analysis of SBS Polymer

The XRD pattern of the pure SBS polymer showed a broad diffraction feature at $2\theta \approx 18.95^\circ$ ($d \approx 4.68 \text{ \AA}$) with no sharp crystalline peaks, indicating a predominantly amorphous structure with only short range ordering (Table 3, Figure 5). The broad, low intensity peak and small calculated crystallite size ($\sim 18.4 \text{ \AA}$) are characteristic of flexible block copolymers like SBS, where long range crystallinity is absent and only nano scale ordered domains exist within the polymer matrix; similar broad amorphous peaks near $\sim 19^\circ 2\theta$ have been reported for SBS and related styrene butadiene systems, reflecting a lack of significant crystalline order typical of these materials (Sadri *et al.*, 2024). These largely amorphous and semi ordered structural features are favorable for effective dispersion and interaction within the bitumen matrix, contributing to enhanced binder performance, such as increased Marshall Stability, improved rutting resistance, and greater moisture tolerance in SBS modified asphalt mixes.

**Figure 5. Shows XRD pattern of neat SBS polymer showing intensity versus 2θ ($^\circ$)**

Marshall Mix Design

The bituminous mixtures in this study were designed and evaluated using the Marshall mix design method. As an initial step, trial samples for both Bituminous Concrete (BC) and Dense Bituminous Macadam (DBM) were prepared with a binder content of 4.5%. However, the Marshall Stability and Flow test results at this binder percentage indicated insufficient stability and flow values exceeding the permissible limits prescribed by the Ministry of Road Transport and Highways (MoRTH). Consequently, the optimum binder content was determined as 5.5% for BC and 5.2% for DBM to achieve a balanced combination of strength and flexibility. These revised binder contents yielded stability and flow values within the MoRTH-specified range of 2-4 mm, ensuring satisfactory mix performance. Before testing, the unconditioned specimens were placed in a hot-air oven maintained at 60°C for approximately 120-130 minutes to ensure a uniform temperature. The prepared samples were then tested in accordance with ASTM D6927 (ASTM International, 2015) to determine Marshall Stability, Flow, and Marshall Quotient values. The theoretical maximum specific gravity (Gmm) and bulk specific gravity (Gmb) were determined in accordance with ASTM D2041 (ASTM International, 2007) and ASTM D2726 (ASTM International, 2014), respectively. To assess the moisture sensitivity of the mixtures, the Retained Marshall Stability (RMS) test was performed by placing the conditioned specimens in a water bath at 60°C for 24 hours. The RMS value was determined as the percentage ratio of the stability of the conditioned specimen to that of the unconditioned specimen. For each level of SBS modification, three replicate tests were conducted to

ensure consistency and reliability, and the average values were reported with standard deviations shown as error bars. The Optimum Binder Content (OBC) was defined as the binder percentage that yielded the highest stability, while maintaining flow values within the limits prescribed by MoRTH and satisfying all other Marshall mix design criteria. The increased density and incorporation of larger aggregate sizes contributed to a reduction in optimum asphalt content, thereby lowering material costs, as also noted by Von Quintus and Hughes (2019). This systematic approach ensured reliable mix performance under simulated heavy traffic conditions. The related test outcomes are summarized in Table 4.

Effect of SBS Polymer on Marshall Characteristics

Figure 6 shows the Marshall properties of SBS-modified bitumen: (a) Dense Bituminous Macadam (DBM) and (b) Bituminous Concrete (BC). Stability, flow, and Marshall Quotient (MQ) are presented as mean $\pm$ standard deviation, with error bars indicating variability among three

specimens tested for each binder content. Table 5 reports the corresponding results, where all tests were performed in triplicate, and the values represent the average of three samples.

The addition of SBS polymer improved both stability and MQ while reducing flow, due to better binder elasticity and stronger aggregate-binder adhesion (Jatoi *et al.*, 2025). Among the tested dosages, 4% SBS showed the best performance, achieving high stability with flow within the MoRTH limit of 4 mm, ensuring good load-bearing capacity without excessive deformation. Higher SBS contents increased stiffness, causing flow to exceed limits and potentially reducing flexibility. The percentage increase in Marshall Stability and MQ was calculated relative to the control mix using equation (6).

$$\% \text{ increase} = \frac{\text{Modified Value} - \text{Control Value}}{\text{Control Value}} \times 100 \quad (6)$$

These results indicate that 4% SBS provides the optimal balance of strength, flexibility, and long-term durability for DBM and BC mixes.

Table 4. Shows Outcomes of the Marshall Mix Design Analysis

Mix type	Modifier dosage	Volumetric Properties							
		Gsb	Gb	Gmm	Gmb	OBC (%)	Va (%)	VMA (%)	VFB (%)
DBM	VG40	2.762	1.021	2.519	2.401	5.2	4.68	17.59	73.39
	SBS 2%		1.024	2.524	2.408	5.1	4.59	17.26	73.41
	SBS 4%		1.019	2.526	2.411	5.0	4.55	17.07	73.35
	SBS 6%		1.016	2.529	2.407	4.9	4.82	17.12	71.85
	SBS 8%		1.014	2.533	2.396	4.8	5.40	17.42	68.99
	SBS 10%		1.011	2.536	2.394	4.7	5.59	17.40	67.87
BC	VG40	2.693	1.021	2.507	2.403	5.5	4.15	15.68	73.53
	SBS 2%		1.024	2.512	2.410	5.4	4.06	15.34	73.54
	SBS 4%		1.019	2.514	2.405	5.3	4.33	15.43	71.93
	SBS 6%		1.016	2.517	2.406	5.2	4.41	15.30	71.18
	SBS 8%		1.014	2.521	2.397	5.1	4.91	15.53	68.39
	SBS 10%		1.011	2.524	2.395	5.0	5.11	15.51	67.06

Table 5. Shows the Effect of SBS polymer modification on Marshall Results for DBM and BC

Asphalt type	Modifier dosage (%)	Sample Dimensions (mm)		Marshall Stability (kN)	Flow Value (mm)	Marshall Quotient (kN/mm)
		Diameter	Height			
DBM	VG40	101.38	65.91	12.94	3.13	4.13
	SBS 2%	101.29	66.61	15.61	3.50	4.46
	SBS 4%	100.85	65.18	15.85	2.91	5.45
	SBS 6%	101.23	64.60	13.28	5.58	2.37
	SBS 8%	101.11	66.36	10.63	6.41	1.66
	SBS 10%	101.12	65.72	10.26	6.75	1.52
BC	VG40	100.74	65.26	11.48	2.82	4.07
	SBS 2%	101.39	65.86	13.53	3.17	4.27
	SBS 4%	101.18	66.59	14.96	3.33	4.49
	SBS 6%	101.09	65.86	11.51	6.50	1.77
	SBS 8%	100.59	65.17	10.04	6.58	1.53
	SBS 10%	101.36	66.13	9.79	6.78	1.44

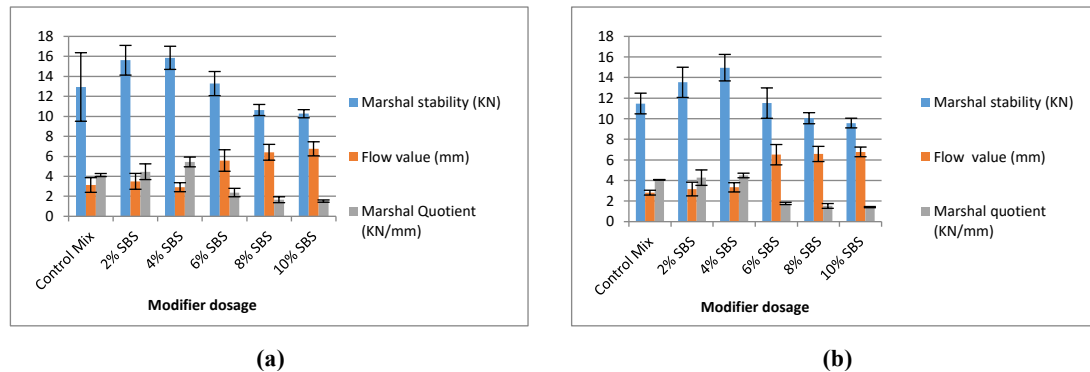


Figure 6. Shows the Marshall properties of SBS-modified bitumen: (a) DBM stability, flow, and Marshall Quotient (mean $\pm$ SD) and (b) BC stability, flow, and Marshall Quotient (mean $\pm$ SD)

Table 6. Shows Retained Marshall Stability (RMS)

Mix type	Modifier dosage (%)	Value of Marshall Stability in kN		Retained Marshall Stability (RMS %)
		Unconditioned	Conditioned	
DBM	VG 40	12.94	10.54	81.45
	SBS 2%	15.61	13.24	84.81
	SBS 4%	15.85	14.65	92.42
	SBS 6 %	13.28	10.72	80.72
	SBS 8%	10.63	8.21	77.23
	SBS 10%	10.26	7.79	75.92
BC	VG 40	11.48	9.68	84.32
	SBS 2%	13.53	12.62	93.24
	SBS 4%	14.96	13.25	88.57
	SBS 6 %	11.51	9.21	80.01
	SBS 8%	10.04	7.89	78.58
	SBS 10%	9.79	7.45	76.09

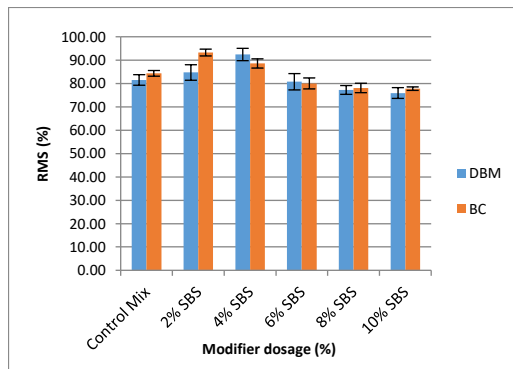


Figure 7. Shows Retained Marshall Stability with SBS Polymer Modification (mean $\pm$ standard deviation)

Retained Marshall Stability (RMS) - Moisture Susceptibility

Moisture can weaken the adhesion between binder and aggregate, leading to stripping and premature pavement failure (Al-Kheetan, 2023). The Retained Marshall Stability (RMS) test evaluates this effect by measuring the strength retained after water conditioning, where values

above 80% (MoRTH standard) are considered satisfactory. Table 6 shows that all SBS-modified mixes exceeded this threshold, indicating improved binder cohesion, better durability, and enhanced rutting resistance compared to unmodified mixes. Figure 7 presents the RMS results for DBM and BC mixes with different SBS contents. Mixes containing up to 6% SBS met the MoRTH standard ($>80\%$ RMS), while higher SBS contents (8-10%) showed a slight decrease in moisture resistance, though they still maintained acceptable performance.

Life Cycle Cost Analysis

The life cycle cost analysis results indicate that although the SBS-modified pavement requires a moderately higher initial investment, it offers superior long-term economic performance. This increase in initial cost is mainly due to the incorporation of polymer in the binder; however, it is effectively compensated by reduced maintenance and user costs over the service life. The total discounted cost values obtained from the analysis are summarized in Table 7, while a comparative representation is provided in Figure 8. The

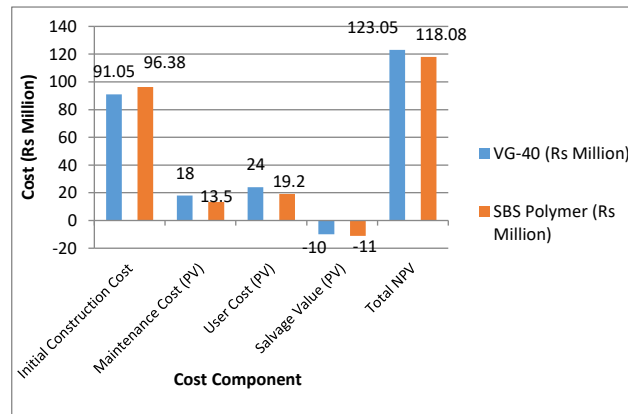


Figure 8. Comparison of Life cycle cost analysis for VG-40 and 4% SBS modified bitumen

Table 7. Life Cycle Cost Results for 2 km, Six-Lane Pavement (20-Year Analysis, 4% Discount Rate) (Babashamsi et al., 2016; Carrick et al., 1996; Santos et al., 2017)

Cost Component	VG-40 (Rs Million)	SBS Polymer (Rs Million)
Initial Construction Cost (Binder & Aggregate)	91.05	96.38
Maintenance Cost (Present Value)	18.00	13.50
User Cost (Present Value)	24.00	19.20
Salvage Value (Present Value)	-10.00	-11.00
Total NPV	123.05	118.08

comparison clearly shows that, despite the higher initial cost, the 4% SBS-modified mix results in a lower overall life cycle cost than the conventional VG-40 mix. This can be attributed to its improved durability and reduced maintenance requirements. Therefore, the use of SBS-modified bitumen is a more economical and sustainable long-term option, particularly under heavy traffic conditions.

The total NPV for the SBS-modified pavement was calculated as Rs118.08 million, compared to Rs123.05 million for the conventional VG-40 pavement. This represents an overall life-cycle cost saving of approximately Rs 4.97 million, corresponding to nearly 4% reduction over the analysis period. The economic advantage becomes more pronounced in the later years of service life, where the cumulative discounted cost of the conventional pavement increases more rapidly due to earlier and more frequent maintenance interventions. The reduction in maintenance cost for the SBS pavement is directly linked to its improved mechanical performance observed in laboratory testing, particularly enhanced resistance to permanent deformation and greater structural capacity under repeated loading, thereby improving rutting resistance compared to conventional VG-40. Furthermore, the lower user cost reflects improved surface conditions over time, resulting in reduced vehicle operating expenses. These findings confirm that the mechanical performance benefits of polymer modification translate into measurable

economic gains when evaluated at the system level. Overall, the results substantiate that for high-traffic six-lane highway corridors, SBS polymer-modified bitumen offers superior life cycle economic efficiency despite its higher initial construction cost. The study highlights the importance of performance-informed LCCA in infrastructure decision-making and supports the adoption of polymer-modified binders for long-term sustainable pavement development.

Conclusions

The study comprehensively evaluated the structural and economic performance of SBS-modified asphalt for Dense Bituminous Macadam (DBM) and Bituminous Concrete (BC) pavements under heavy traffic conditions. The results indicate that SBS polymer modification significantly enhances the mechanical performance of asphalt mixtures. Both Marshall Stability and Marshall Quotient values increased with SBS incorporation, reflecting improved rutting resistance, load distribution, and resistance to permanent deformation. Similarly, Retained Marshall Stability (RMS) values were higher in polymer-modified mixes, demonstrating superior moisture resistance and durability, which is particularly important for pavements in regions with heavy rainfall. XRD analysis confirmed effective polymer-bitumen interactions, explaining the

observed improvements in stiffness, deformation resistance, and thermal stability. Among the tested dosages, 4% SBS was identified as the optimal content, providing the best balance between strength, flexibility, and compliance with national specifications. While higher SBS contents further increased stiffness, they adversely affected flow and moisture performance, underscoring 4% SBS as the most efficient and practical formulation for field applications. Economic evaluation using life-cycle cost analysis revealed that incorporating 4% SBS-modified bitumen used in DBM and BC layers reduces long-term maintenance, extends pavement service life, and lowers overall costs, making it a cost-effective strategy for high-traffic highways. In summary, this study confirms that incorporating SBS polymer significantly enhances the structural integrity, rutting resistance, and overall durability of asphalt mixtures. The modified binder not only improves mechanical performance but also offers notable economic benefits. Among the tested formulations, 4% SBS by weight of VG-40 was identified as the optimum dosage, providing the best balance between performance and cost. These findings offer valuable guidance for developing high-performance, long-life flexible pavements capable of withstanding heavy traffic and adverse environmental conditions.

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Author Contribution

Arvind Singh Gaur: Conceptualization, Methodology, Investigation, Data Collection, Formal Analysis, Validation, Writing – Original Draft. Imran Ahmad Khan: Supervision, Conceptualization, Methodology, Validation, Writing – Review & Editing.

Ethic Approval and Consent to Participate

Not applicable, as this study did not involve human participants, animals, or biological samples.

Declaration of Generative AI Use

The authors declare that no Generative AI tools were used in the preparation of this manuscript.

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