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Performance evaluation of asphalt mixture using styrene-butadiene-styrene additive

Tuan Anh Nguyen [1*], Van Long Nguyen[2], Ngoc Quang Le[3]

[1]*Big Data Research for Infrastructure & Green Engineering Research Group (BRIDGE), University of Transport Ho Chi Minh City*

[2]*Civil and Environmental Engineering in Sustainable Development Research Group (CESD), University of Transport Ho Chi Minh City*

[3]*Project Management Board for Construction Investment of Transport, Civil and Industrial Works of Kien Giang Province*

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ABSTRACT

This study investigates the influence of Styrene-Butadiene-Styrene (SBS) polymer modification on the performance characteristics of AC 12.5 asphalt concrete mixtures using Vietnamese aggregate materials. While SBS has demonstrated effectiveness in enhancing asphalt mixture properties globally, comprehensive assessments under Vietnamese conditions with local materials remain limited. Experimental specimens were fabricated with SBS contents of 0% (control), 3%, 5%, and 7% by weight of bitumen, with a constant optimal bitumen content of 5.0%. Performance evaluation was conducted through Marshall stability tests, indirect tensile strength measurements, and Hamburg Wheel-Tracking Device (HWTD) rutting resistance assessments. Results indicate that SBS modification significantly enhances mechanical properties, with optimal performance observed at 5% SBS content. At this concentration, Marshall stability at 60°C increased by 11.1% (15.0 kN vs. 13.5 kN), indirect tensile strength at 25°C improved by 96.4% (2.20 daN/cm^2 vs. 1.12 daN/cm^2), and rutting resistance exhibited a remarkable 57.7% reduction in rutting depth (3.31 mm vs. 7.82 mm) after 15,000 loading cycles at 50°C. The research confirms that SBS modification at 5% content represents an optimal balance between enhanced performance and practical application for AC 12.5 mixtures under Vietnamese conditions, thereby establishing a scientific basis for the implementation of polymer-modified asphalt in Vietnamese road construction practice.

1. Introduction

Asphalt concrete is a predominant material used in highway pavement construction due to its flexibility, load-bearing capacity, ease of application, and reasonable cost. However, asphalt pavements are susceptible to damage from traffic loads, increasingly harsh

* Tuan Anh Nguyen. Big Data Research for Infrastructure & Green Engineering Research Group (BRIDGE), University of Transport Ho Chi Minh City
Email*:* tuananh.nguyen@ut.edu.vn

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environmental conditions, and aging processes. The durability and service life of asphalt concrete pavements can be enhanced through the use of various additives [1], [2], [3], [4], [5], [6], [7], [8], [9], [10]. These studies have focused on improving the mechanical properties of asphalt concrete mixtures, including rutting resistance, crack resistance, and durability under environmental factors and operational loads.

Among the methods of asphalt modification, the use of polymers has been proven to be one of the most effective approaches to enhance pavement performance. Lesueur et al. [7] conducted a comprehensive review of modification mechanisms in asphalt mixtures, establishing the fundamental principles behind additive incorporation. Styrene-Butadiene-Styrene (SBS) is one of the most extensively researched and widely used polymer additives in this field. Zhang et al. [11] conducted a comprehensive evaluation of performance test methods for SBS-modified asphalt. Their results indicated that the addition of SBS significantly improves high-temperature performance and reduces the temperature sensitivity of asphalt binders while increasing viscosity at high temperatures. Depending on the base asphalt type, the impact of SBS can vary. The softening point of SBS-modified asphalt increased from 5.7% to 26.4% for SK70# base asphalt and from 21.2% to 46.6% for SK90# base asphalt when SBS content increased from 4.5% to 6%.

Mirzaiyanrajeh et al. [12] performed a comprehensive evaluation of the properties and performance of asphalt mixtures with binders modified by Reactive Isocyanate and SBS. Their study revealed that both modifiers improved the characteristics of the control mixture regarding rutting resistance and fatigue cracking but might negatively affect thermal cracking resistance. Notably, when combining both Reactive Isocyanate and SBS, the resulting mixture showed a good balance between rutting performance, fatigue cracking, and maintenance of thermal cracking resistance.

Determining the optimal SBS content is a critical factor in asphalt concrete mixture design. Mahmood and Kattan [13] conducted research on the impact of SBS on the engineering properties of asphalt binders and mixtures. Their results showed that increasing SBS content leads to decreased penetration and increased softening point, viscosity, and elastic recovery. This study identified 3% as the optimal SBS content for asphalt mixtures, providing the highest tensile strength ratio (TSR) and rutting parameter values while upgrading the asphalt binder from PG58-22 to PG76-16.

Despite international studies demonstrating the effectiveness of SBS in improving asphalt concrete properties, directly applying these results to Vietnamese conditions presents numerous challenges due to differences in material sources, climatic conditions, and technical standards. Phuc [9] evaluated the performance of Korean modified asphalt binders under Vietnamese conditions, focusing primarily on rheological properties and temperature sensitivity. However, comprehensive assessments of SBS effectiveness for asphalt concrete mixtures using local materials remain lacking.

Furthermore, the absence of specific guidelines on optimal SBS content for Vietnamese conditions creates difficulties for designers and contractors in applying this additive. International studies indicate that optimal SBS content can range from 3%

to 5%, depending on material sources and usage conditions, but there are no precise recommendations for Vietnamese materials and conditions. Moreover, performance evaluation tests of SBS-modified asphalt concrete in Vietnam are limited, resulting in insufficient experimental data for assessing the economic and technical effectiveness of this solution.

Particularly, under Vietnamese traffic conditions with increasing vehicle loads and harsh tropical monsoon climate, rutting is one of the most common and serious distresses in asphalt concrete pavements. Finding effective solutions to enhance rutting resistance is an urgent need to improve quality and extend the service life of pavements, reduce maintenance costs, and enhance traffic safety.

Based on the above reasons, this paper focuses on evaluating the effectiveness of SBS additive for AC 12.5 asphalt concrete mixtures using Vietnamese materials through Marshall tests, indirect tensile strength tests, and rutting resistance assessments. The study uses different SBS content levels (0%, 3%, 5%, 7%) to determine the specific effects of the additive on the mechanical properties of the mixture and identify the optimal content for Vietnamese conditions. The research results will provide scientific and technical foundations for applying SBS additives in asphalt concrete pavement construction in Vietnam, contributing to improving the quality of transportation infrastructure and reducing maintenance costs.

2. Experimental material

2.1. Material selection and characterization

The experimental program utilized locally sourced materials to ensure applicability to Vietnamese construction practices. For this investigation, materials were selected from regional quarries in southern Vietnam: coarse aggregates from Antraco quarry (An Giang province), fine aggregates from Tan Chau quarry (An Giang province), and mineral filler from Tra Duoc quarry (Kien Giang province). Petrolimex 60/70 bitumen was used as the binder. All these materials complied with TCVN 13567-1:2022 [14] requirements. Following supplier recommendations, SBS modifier was incorporated at four different content levels (0% as control, 3%, 5%, and 7%) by weight of Petrolimex bitumen 60/70.

The SBS modification process consisted of the following sequential steps:

- The 60/70 penetration grade bitumen was heated to 160-170°C and maintained at this temperature for approximately 1.5 hours to achieve proper liquefaction;
- Precise quantities of the heated bitumen and SBS additive were measured according to the designated modification percentages (3%, 5%, and 7% by weight of bitumen);
- The SBS additive was gradually incorporated into the heated bitumen while maintaining a temperature of 175-180°C;
- The blend was continuously mixed using a high-shear mixer operating at 3,500 rpm for 30 minutes to ensure homogeneous dispersion of the polymer throughout the bitumen matrix;
- Upon completion of the mixing process, the SBS-modified bitumen was extracted for subsequent testing and specimen preparation.

2.2. Mix design and specimen preparation

The AC 12.5 asphalt mixture was designed following the Marshall methodology with attention to achieving optimal volumetric properties. A densegraded aggregate structure with a nominal maximum aggregate size of 12.5 mm was employed for both the unmodified control mixture and the SBS-modified variants. The aggregate gradation used in this study is presented in Figure 1, which illustrates the particle size distribution within the specified control points.

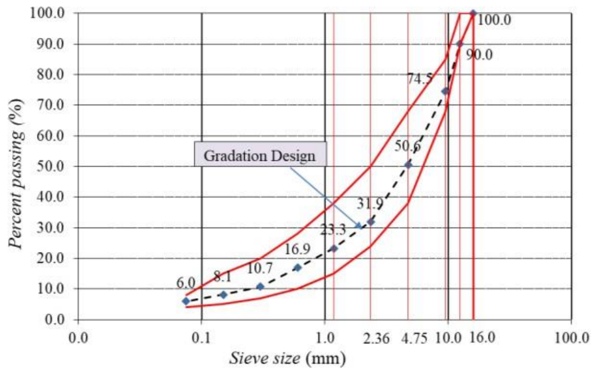

Figure 1. Aggregate gradation showing particle size distribution for AC 12.5 mixture.

To determine the optimal bitumen content, compacted AC 12.5 specimens were tested at various bitumen content levels. Based on the test results, the optimal bitumen content was determined to be 5.0% by weight of the AC 12.5 mixture for both unmodified and SBS-modified formulations.

Subsequently, SBS additive was added at contents of 3%, 5%, and 7% by weight of bitumen to produce AC 12.5 mixtures. The AC 12.5 mixtures with different SBS contents were prepared into specimens to compare Marshall stability, indirect tensile strength, and rutting resistance according to the Hamburg Wheel-Tracking test.

3. Marshall test

The Marshall test was conducted according to TCVN 8860-1:2011 [15]. Specimens were compacted with an air void content of 5.04%. Prior to stability testing, all specimens underwent thermal conditioning in a water bath maintained at a constant temperature of 60°C for a duration of 40 minutes. Following thermal conditioning, each specimen was immediately transferred to the Marshall testing apparatus and subjected to compression loading at a constant deformation rate of 50 mm/minute until failure occurred. The test setup is illustrated in Figure 2, and the comprehensive test results are summarized in Table 1.

The test results in Table 1 show that when using SBS additive at contents of 3%, 5%, and 7%, the stability of the AC 12.5 asphalt concrete mixture is significantly improved. The data clearly shows that SBS improves the mechanical strength of the asphalt mixture. As SBS content increases from 0% to 7%, Marshall stability values consistently rise from 13.5 kN to 15.3 kN. However, the rate of improvement varies significantly at different SBS concentrations. When increasing SBS content from 3% to 5%, stability improves by 1.1 kN (from 13.9 kN to 15.0 kN), representing an 8.1% increase. In contrast, further increasing SBS from 5% to 7% only yields a 0.3 kN improvement (from 15.0 kN to 15.3 kN), just a 2.0% increase. This pattern demonstrates that while SBS consistently enhances stability, the benefits diminish significantly beyond 5% concentration.

This finding corresponds with the research by Mahmood and Kattan [13], which found that increasing SBS content leads to improved performance characteristics, though in their study, 3% was identified as the optimal content. The difference in optimal content between their study and the current research may be attributed to differences in the base materials used. Similarly, Arif et al. [1] reported that 4% SBS content provided optimal performance characteristics for their tested materials, further indicating that optimal SBS content is dependent on the specific materials used. Marshall stability after 24 hours of water conditioning follows a similar pattern, increasing from 11.6 kN (0% SBS) to 12.1 kN (3% SBS) and 13.2 kN (5% SBS), then plateauing at 13.2 kN (7% SBS). The retained stability ratio after 24 hours compared to the initial value exceeds the minimum requirement of 80% for all samples, ranging from 86.3% (0% SBS) to 88.6% (7% SBS). This improvement in moisture resistance aligns with the general findings of polymer modification effects described by Lesueur et al. [7] in their review of modification mechanisms in asphalt mixtures.

Flow values exhibit a non-linear relationship with SBS content. The flow remains constant at 3.2 mm for both 0% and 3% SBS, decreases to 2.9 mm at 5% SBS, then increases slightly to 3.1 mm at 7% SBS. All values remain within the specified range of 1.5-4.0 mm. The volumetric properties (air void content, voids filled with bitumen, and voids in mineral aggregate) show minimal variation across different SBS concentrations, with all values remaining within required limits. This consistency indicates that SBS modification primarily affects the mechanical properties rather than the volumetric characteristics of the mixture.

4. Indirect Tensile Strength Test

The indirect tensile strength test was conducted according to TCVN 8862-2011 [16]. Prior to testing, cylindrical specimens were thermally conditioned in a precision-controlled water bath maintained at 25°C for a duration of 30 minutes to ensure uniform temperature distribution throughout the sample. Following thermal conditioning, the specimens were immediately transferred to the Marshall testing apparatus and subjected to diametrical compression at a constant loading rate of 50 mm/minute until failure occurred. This loading configuration induces tensile stresses perpendicular to the loading plane, simulating tensile conditions commonly experienced in pavement structures. The experimental setup is illustrated in Figure 2, and the comprehensive test results are presented in Table 2.

Table 1. Marshall test results.

No.	Test parameter	Unit	SBS content by weight				Requirement
			0%	3%	5%	7%	
1	Marshall stability at 60°C	kN	13.5	13.9	15.0	15.3	≥ 8.0
2	Marshall stability at 60°C/24h	kN	11.6	12.1	13.2	13.2	-
3	Retained Marshall stability at 60°C after 24 hours compared to initial value	%	86.3	87.1	88.3	88.6	≥ 80
4	Flow	mm	3.2	3.2	2.9	3.1	1,5–4
5	Air void content	%	4.43	4.58	4.39	4.46	4–6
6	Voids filled with asphalt	%	71.1	70.4	71.3	71.1	-
7	Voids in mineral aggregate	%	15.3	15.5	15.3	15.4	

Table 2. Indirect tensile strength test results.

Parameter		**SBS additive content**									
		0%	**3%**			**5%**			**7%**		
Sample ID			**Sample 1**	**Sample 2**	**Sample 3**	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 1**	**Sample 2**	**Sample 3**
Sample dimensions	Diameter (cm)	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
	Height (cm)	8.52	8.45	8.42	8.46	8.21	8.26	8.25	8.02	8.05	8.03
Failure load (kN)		1.52	1.79	1.76	1.80	2.86	2.88	2.87	2.42	2.39	2.43
Indirect tensile strength (daN/cm^2)		1.12	1.34	1.32	1.34	2.20	2.20	2.19	1.90	1.87	1.91
Average indirect tensile strength (daN/cm^2)		1.12		1.33			2.20			1.89	

Figure 2. Indirect tensile strength test.

The test results in Table 2 show a significant influence of SBS additive on the indirect tensile strength of the AC 12.5 asphalt concrete mixture. For the control sample (0% SBS), the average indirect tensile strength is 1.12 daN/cm^2, lower than the samples with SBS. When SBS content increases to 3% and 5%, the average indirect tensile strength increases to 1.33 daN/cm^2 (18.8% improvement) and 2.20 daN/cm^2 (96.4% improvement), respectively, demonstrating a substantial enhancement in the indirect tensile capacity of the mixture.

However, when SBS content increases to 7%, the average indirect tensile strength decreases to 1.89 daN/cm^2, which is 14.1% lower than at 5% SBS, though still 68.8% higher than the control mixture. This clear reduction indicates a threshold effect, where excessive SBS content begins to compromise the tensile properties of the mixture.

This pattern showing a clear peak in performance at a specific SBS concentration is consistent with findings in polymer modification research. The consistency of test results within each SBS concentration group in the current study (as evidenced by the minimal variation between samples 1, 2, and 3 at each concentration level in Table 2) provides high confidence in the observed performance trends and confirms the identified threshold effect at 5% SBS content. The significant improvement in tensile strength at 5% SBS concentration (96.4% higher than the control mixture) demonstrates the polymer's effectiveness in enhancing the mixture's resistance to tensile failure at elevated temperatures (60°C). This improvement can be attributed to the SBS polymer network formation within the bitumen, which provides enhanced elasticity and cohesion at high temperatures. The subsequent decline in performance at 7% SBS content suggests potential issues with the polymer-bitumen interaction at higher concentrations. Previous studies in polymer modification have shown that excessive polymer content can potentially lead to phase separation or inadequate dispersion within the bitumen matrix [7], though microscopic analysis would be needed to confirm the specific mechanism in this case. Based on the consistent experimental data, it can be concluded that for indirect tensile strength under the testing conditions employed (60°C), there is a clear optimal SBS content of 5% for the AC 12.5 mixture using Vietnamese materials.

5. Wheel tracking test

Based on the analysis of Marshall and indirect tensile strength test results as presented above, and to optimize costs, the authors conducted a comparative test of rutting resistance for AC 12.5 mixtures using 0% and 5% SBS additive by weight of bitumen. An experimental study was conducted to assess the resistance of asphalt concrete to rutting using the Hamburg Wheel Tracking Device (HWTD), following the methodology outlined in Decision 1617/QĐ-BGTVT [15]. The tests were performed on sample plates measuring 320 × 260 × 50 mm at a temperature of 50°C (Figure 3). The rut depth in the tested plates was recorded after 15,000 loading cycles.

Figure 3. Hamburg wheel-tracking test.

The test results in Table 3 show that using SBS additive at 5% content significantly improves the rutting resistance of the AC 12.5 asphalt concrete mixture. The average rut depth of the control sample is 7.82 mm, while this value for the sample using 5% SBS is 3.31 mm, a reduction of more than 57%. This substantial improvement in rutting resistance is consistent with findings from Le et al. [4], who reported that additives like carbon nanotubes significantly enhanced rutting resistance at high temperatures for asphalt mixtures.

Table 3. Hamburg Wheel Tracking test results.

Test parameter		SBS additive content (%)	
		0	**5**
Rut depth (mm)	Left wheel path	7.98	2.68
	Right wheel path	7.66	3.94
	Average	**7.82**	**3.31**

This remarkable enhancement in rutting resistance can be attributed to the polymer network formed by SBS within the bitumen matrix, which increases the stiffness and elasticity of the binder at elevated temperatures. As noted by Zhang et al. [11], SBS modification significantly improves high-temperature performance of asphalt binders by increasing viscosity, which directly translates to enhanced rutting resistance in the mixture.

The level of improvement observed in this study (57.7% reduction in rutting depth) exceeds the improvements reported by Nguyen et al. [5] when using Rediset LQ-1200 additive, highlighting the particular effectiveness of SBS in addressing rutting problems under Vietnamese conditions. This demonstrates that using SBS additive is an effective solution to enhance the rutting resistance of asphalt concrete pavements, especially for roads subjected to heavy traffic loads and harsh climatic conditions like those found in Vietnam.

The combination of improved Marshall stability, enhanced indirect tensile strength, and significantly reduced rutting propensity at 5% SBS content provides compelling evidence for the optimal performance of this modification level for AC 12.5 mixtures under Vietnamese conditions. This optimal content balances the mechanical performance benefits with economic considerations, offering a practical solution for improving asphalt pavement durability in Vietnam.

6. Conclusions

The experimental results demonstrate that incorporating SBS polymer into AC 12.5 asphalt concrete mixtures significantly enhances the mechanical properties of the material under Vietnamese conditions. This study has identified 5% SBS content as providing the optimal balance of performance enhancement across multiple parameters. The key findings are:

- Marshall Stability: The addition of 5% SBS content increases Marshall stability at 60°C by 11.1% (from 13.5 kN to 15.0 kN) compared to the control mixture, while further increases to 7% SBS yield diminishing returns with only 2.0% additional improvement. The retained stability after water conditioning also improves, reaching 88.3% at 5% SBS content, well above the minimum requirement of 80%.

- Indirect Tensile Strength: A substantial improvement of 96.4% in indirect tensile strength at 60°C was observed at 5% SBS content (2.20 daN/cm^2 versus 1.12 daN/cm^2 for the control mixture). The clear decline in performance at 7% SBS content (1.89 daN/cm^2) confirms the existence of an optimal threshold at 5% SBS for this parameter.

- Rutting Resistance: The incorporation of 5% SBS results in a remarkable 57.7% reduction in rutting depth (3.31 mm versus 7.82 mm for the control mixture) after 15,000 loading cycles at 50°C. This significant improvement in rutting resistance is particularly valuable for Vietnamese road conditions, which are characterized by heavy traffic loads and high temperatures.

These findings collectively demonstrate that SBS modification at 5% content represents an optimal balance between enhanced performance and practical application for AC 12.5 mixtures under Vietnamese conditions. The improvements in high-temperature stability, tensile strength, and rutting resistance would contribute to increased pavement durability, extended service life, and reduced maintenance costs in Vietnam's transportation infrastructure.

It is worth noting that SBS content exceeding 5% may lead to adverse effects on certain mechanical properties due to potential phase separation or inadequate dispersion within the bitumen matrix. This observation aligns with the established principles of polymer modification in asphalt mixtures and underscores the importance of proper dosage control in practical applications.

Future research should extend this study through long-term field performance evaluations under Vietnamese climate and traffic conditions, microstructural analysis to investigate SBS-bitumen interaction mechanisms at varying concentrations, and fatigue performance testing at intermediate temperatures. Additional investigations on the combined effects of SBS with other additives (such as anti-aging or adhesion-promoting agents) could optimize mixture performance while potentially reducing required SBS content, enabling development of more precise specifications for SBS-modified asphalt mixtures in Vietnamese road construction practice.

Contributions of authors in this article

Nguyen Tuan Anh: Methodology, Data management, Formal analysis, Validation, Visualization, Feedback on peer review, Writing – original manuscript. **Van Long Nguyen**: Data compilation, Data analysis, Verification, Writing – original manuscript. **Ngoc Quang Le**: Methodology, Supervision, Manuscript Editing.

Declaration of competing interest and dedication to copyright

The authors declare the absence of any potential conflicts of interest from this study and affirm that the paper has not been previously published.

Data available

Data will be provided upon request.

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