Evaluation of the Strength and the Moisture Sensitivity of the HMA Mixture with RAP

Osamah H. Chafat[1]*, Basim H. Al-Humeidawi[2], Alaa H. Abed[3]

Authors affiliations:
1*) Department of Civil Engineering, Collage of Engineering, Al-Nahrain University, Baghdad, Iraq.
osamah.civ23@ced.nahrainuniv.edu.iq

2) Roads and Transport Department, College of Engineering, University of Al-Qadisiya, Al-Diwaniyah province, Iraq.
Basim.alhumeidawi@qu.edu.iq

3) Civil Engineering Department, Collage of Engineering, Al-Nahrain University, Baghdad, Iraq.
alaa.h.abed@nahrainuniv.edu.iq

Paper History:

Received: 11th Mar. 2025

Revised: 25th Mar. 2025

Accepted: 13th Apr. 2025

Abstract

Moisture-induced damage in asphalt pavements, is defined by adhesive failure at the binder-aggregate interface and decreased mechanical integrity, severely reduce pavement durability. The research examines the mechanical properties and moisture sensitivity of hot mix asphalt (HMA) enhanced with styrene-butadiene-styrene (SBS) polymer and including reclaimed asphalt pavement (RAP). Laboratory assessments, including indirect tensile strength (ITS) and tensile strength ratio (TSR) tests, were performed on conventional HMA, SBS-modified HMA (4% SBS), and SBS-modified HMA contained 20% RAP. The results indicated that SBS modification significantly improved mechanical and moisture resistance properties, where unconditioned ITS specimens increased by 37.1% and TSR value enhanced by 13.5%. The incorporation of RAP decreased ITS value by about 21 % relative to pure SBS-modified HMA; nevertheless, the SBS+RAP combination still show higher ITS and TSR values than conventional HMA.

Keywords: Indirect Tensile Strength (ITS), Polymer Modified Bitumen (PMB), Moisture Induced Damage, Tensile Strength Ratio (TSR), Reclaimed Asphalt Pavement (RAP)

تقييم قوة وحساسية الرطوبة لخليط HMA مع RAP

اسامه حسن جفات، باسم حسن الحميداوي ، علاء حسين عبد الحافظ

الخلاصة

التدهور الناتج عن الرطوبة في أرصفة الأسفلت، والذي يتميز بالفشل اللصقي عند واجهة الرابط-الركام وانخفاض التكامل الميكانيكي، يقوض بشكل كبير متانة الأرصفة. تبحث الدراسة في الخصائص الميكانيكية وحساسية الرطوبة لأسفلت الخلط الساخن (HMA) المعزز ببوليمر ستيرين-بوتادين-ستيرين (SBS) والذي يتضمن الرصف الأسفلتي المعاد تدويره (RAP). تم إجراء تقييات مخبرية، بما في ذلك اختبارات القوة الشد غير المباشرة (ITS) ونسبة القوة الشد(TSR) ، على الأسفلت الساخن التقليدي(HMA) ، والأسفلت الساخن المعدل بـ SBS (4% SBS)، والأسفلت الساخن المعدل بـ SBS باستخدام ٢٠٪ من الرصف الأسفلتي المعاد تدويره (RAP). أشارت النتائج إلى أن تعديل SBS حسّن بشكل ملحوظ الخصائص الميكانيكية ومقاومة الرطوبة: زادت قوة الشد غير المشروطة بنسبة ٣٧,١٪، وتحسنت نسبة الشد إلى الشد بنسبة ١٣,٤٩٪، وذلك بفضل شبكة بوليمرية متقاطعة جسديًا زادت من التماسك والمرونة وتوزيع الإجهاد. إدخال RAP خفض ITS بنسبة ٢٠,٩٪ مقارنةً بالأسفلت المعدل بـ SBS النقي؛ ومع ذلك، فإن مزيج SBS+RAP لا يزال يتجاوز أداء الأسفلت التقليدي) زيادة بنسبة ٨,٤٪ فيITS ، و٨٥,٥٢٪ في(TSR ، مما يشير إلى توافق جزئي على الرغم من الصعوبات التي يسببها الرابط القديم.

1. Introduction

Asphalt pavements suffer greatly from moisture deterioration, which reduces their overall effectiveness in a number of nations. Water damage manifests in roadways using asphalt concrete (AC) separating, diminished mix durability, and reduced service life. AC stripping occurs when water seeps into the asphalt cement and aggregate particles, weakening the adhesive bond. [1].

The process of moisture damage has been defined through two primary steps: (a) water transport, which refers to the mechanisms by which liquid or vaporized water infiltrates the asphalt mixture, the asphalt binder, or the mastic, ultimately reaching the asphalt binder-aggregate interface; and (b) system response, which encompasses alterations in the internal structure that diminish the mixture's load-bearing capacity. Throughout the years, six distinct micro- or macro-scale processes clarify the mechanisms by which water deteriorates asphalt mixtures: separation, displacement, hydraulic scour, pore pressure-induced degradation, spontaneous emulsification, and environmental effects on the aggregate-asphalt system. It is evident that the overall damage from water must be ascribed to several factors, and more investigation is required to understand the adhesion between asphalt and aggregate.[2].

According to literature, the hydrophilic characteristic of silanol groups makes acidic aggregate asphalt mixes prone to moisture degradation and cutting, therefore, materials like granite and gravel, which are high in silica increase this degradation. Pavement structures generally make heavy use of locally accessible rocks, which leads to the frequent usage of acidic materials[3]. Most often, liquid antistripping agents (ASA) such as cationic surface-active amines, amides, fatty polyamines, and substituted imidazoline are employed to reduce moisture damage. The exact process by which ASA improves asphalt-aggregate adhesion is unclear, although it is known that it does so[4]. Rock asphalt, styrene-butadiene styrene (SBS), double rock composite, silane coupling agents, and silane are among the asphalt modifiers that have been shown to improve water resistance [5].

Both pavement design and material selection have a role in reducing the possibility of stripping in asphalt pavements [6]. In order to speed up the process of water removal from the pavement structure, granular courses with strong drainage capabilities are usually used together with impermeable surface layers [7]. Several Iraqi case studies suggested that asphalt pavement moisture degradation may be restricted, occurring only in places where water and/or vapors were oversaturated due to unfavorable subsurface drainage [8]. Regardless of drainage conditions, asphalt pavement stripping may occur in poorly designed mixes made from not suitable materials. According to [9], acidic aggregates including granite, gravel, and quartz were shown to be more likely to strip asphalt when used in asphalt mixes. Use of the antistripping agent (ASA) is the quickest and most dependable way to improve the asphalt mixture's resistance to moisture [10]. Many different types of commercial liquid asphalt admixtures are now staples in asphalt batching plants. Improved asphalt moisture resistance was also seen polymer modified bitumen (PMB) with plastic, SBS, hydrated lime, and other materials [11] .

Researchers have been trying to evaluate the moisture sensitivity of asphalt mixes using recently established laboratory tests [12]. There are three types of tests: (a) tests for asphalt mix components (bitumen, gravel, filler, etc.); (b) tests for loose mixtures; and (c) tests for pavement mixtures that have been packed down. At first, loose asphalt mixes were used for tests in the lab, such as the hot water test and the static soaking test. [13]. Improved methods of evaluating compacted asphalt mixes were subsequently developed, which included comparing the strengths of compacted specimens both before and after moisture conditioning in order to determine the mixes' sensitivity to moisture. [14].

Improved Lottman test (AASHTO T283) adopted the indirect Tensile Strength Ratio (TSR) as the criterion for assessing moisture resistance, acknowledging that freeze-thaw cycles may significantly exacerbate moisture damage [4]. The evaluation of moisture deterioration alongside rutting performance was performed using the asphalt pavement analyzer (APA) test and the Hamburg wheel-tracking test. [15]. The TSR method is still used to evaluate asphalt mixtures by the majority of US states. A recent study by NCHRP RRD 316 provided evidence of using Gibbs surface free energy (SFE) to assess aggregate and asphalt adhesion and moisture resistance. [16]. The surface energy values of asphalt binders and aggregates may be quantified using methods such as the Wilhelmy plate device, sessile drop technique, sorption device, inverse gas chromatography, atomic force microscopy, and micro calorimetry. The energy ratio reflecting the compatibility of an asphalt-aggregate combination may be computed to assess moisture resistance [17]. Certain research used a novel approach to assess the influence of additives and aging on the surface free energy of asphalt binders [18].

This research aims to investigate moisture-related degradation in asphalt pavements and to create solutions to alleviate its detrimental impact on pavement durability. The study goals include characterization of the moisture susceptibility of asphalt mixes and assessment of the efficiency of material changes, particularly the incorporation of polymer additives and reclaimed asphalt pavement (RAP), in improving resistance to water-induced degradation. This subject is crucial since moisture damage is a primary factor in pavement deterioration, compromising the asphalt-aggregate connection via stripping and thus diminishing pavement durability. Enhancing moisture resistance is essential for pavement durability, particularly as moisture degradation occurs via several processes at the binder–aggregate interface, requiring a comprehensive knowledge of adhesion and protective strategies. This study evaluates asphalt mixtures modified with SBS polymer, including blends containing 20% RAP, to assess performance of HMA under moisture conditioning. Parameters such as ITS and TSR were utilized to quantify enhancements in durability.

2. Raw Materials

2.1. Asphalt Cement

The penetration grade of used bitumen binder was (40-50). The physical properties and tests of the used asphalt cement are illustrated in Table 1.

Property	Test method	Test results	SCRB specification

	(ASTM)		
Penetration at 25 °C, (0.1 mm)	D 5	42	(40-50)
Ductility at 25 °C,	D 113	104	>100
Flash point, (°C)	D 92	315	Min.232
Softening point, (°C)	D 36	53	---------
Rotational Viscosity @ 135 °C, Pa. Sec	D 4402	0.762	MAX.3pa.sec
Rotational Viscosity @ 165 °C, Pa. Sec	D 4402	0.175	MAX.3pa.sec
%Solubility in trichloroethylene	D 2042	99.69	Min. 99%
Storage stability.	D 7173	1.21	MAX. 4

Table (1): Physical properties and tests of the used asphalt cement.

2.2. Aggregate

Crushed aggregates were used, this type of aggregate is commonly and locally used in asphalt paving industry. Coarse aggregate particles tend to have a dark color and sharp edges, while fine aggregate particles consist of stone screens. It consists of resilient grains, solid, devoid of clay and other harmful substances. Table 2 presents the test results for coarse and fine aggregates.

Table (2): Physical characteristics of course and fine aggregates.

Property	Test method (ASTM)	Coarse aggregate	Fine aggregate	SCRB
Bulk Specific Gravity	C 127 C 128	2.622	2.632	-------
Apparent Specific Gravity	C 127 C 128	2.651	2.670	-------
Percent Water Absorption	C 127 C 128	0.732	1.420	-------
Soundness Test by Sodium Sulfate Solution	C 88	2.06	-------	12% Max.
Percent Wear (Loss Angeles Abrasion)	C 131	17	-------	30% Max.
Percent Flat and Elongated Particles	D 4791	1.5	-------	10% Max.
Passing sieve No.200, %	C 117	1.09	2.68	----
Deleterious Materials, %	C 142	0.40	2.6	3% Max.
Fractured faces, %	-	97	-------	*90% Min.*
%Sand Equivalent	D 2419	-------	47	*45% Min.*

2.3. Mineral Filler

This research used hydrated lime filler materials that pass-through sieve No. 200 (0.075 mm). Table 3 illustrates the properties of the mineral filler.

Table (3): Properties of the Mineral Filler.

Property	Test method	Test results	Standard Specification No. 807/2004
Bulk Specific Gravity	ASTM C127, 128	2.70	…….
Apparent Specific Gravity	ASTM C127, 128	2.751	…….
Cao + MgO %	Reference Guideline No. 337/1991	92.65%	Min. 85%
MgO%		0.2%	Max. 5%
Fe_2O_3%		0.285	…….
Al_2O_3%		0.8	…….
SiO2%		2.965	…….
Oxides%		4.05	Max. 5%
SO3%		0.29	…….
Loss of ignition		1.24	…….
Activity (CaO)		89.725	…….
Co_2 %		2.36	Max. 5%
Slaking time		11.5	5-15 minutes

2.4. Polymers

SBS polymer was used to enhance the properties and performance of bitumen binder under different traffic loads and environmental conditions. SBS particles shown in Figure 1, are linear block copolymer composed of styrene and butadiene, with a 31.5% styrene content by mass. It enhances flexibility, impact characteristics, wear resistance, and is easily processed[19]. The chemical composition of the polymer was determined through an AT-FTIR test.

Figure (1): Polymers used in asphalt modification:

2.5. Polymer modified bitumen (PMB)

PMB incorporates 4% SBS called PMB-SBS is used as a modified bitumen at this study. The composition comprises and mixed with a high-shear mixer.

In order to clarify the reasons on differences in moisture susceptibility for different HMA specimens contained PMB-SBS, the chemical composition for these specimens were investigated using FTIR analysis. Figure 2 displays the FTIR results for the net bitumen and PMB.

The results show that all binders have absorption peaks around wavenumbers of 1600 cm-1, 1460 cm-1, 1400 cm-1, 1375 cm-1, 1175 cm-1, 1125 cm-1, 110 cm-1, 1100 cm-1, 1000 cm-1, 985.8 cm-1, 900 cm-1, 700, 592.91 cm-1, and 557.38 cm-1.The above functional groups are represented by the absorption peaks: hydroxyl groups, aromatics, aliphatic hydrocarbons, carbonyls, sulfoxides, butadiene, polyaromatics[19-22].

The test results for all asphalt binder types utilized in the research adhered to standard procedures aligned with international specifications and the AASHTO M320 specification. The asphalt performance grade (PG), rotational viscosity (RV) and other properties of net bitumen and PMB as shown in Table 4.

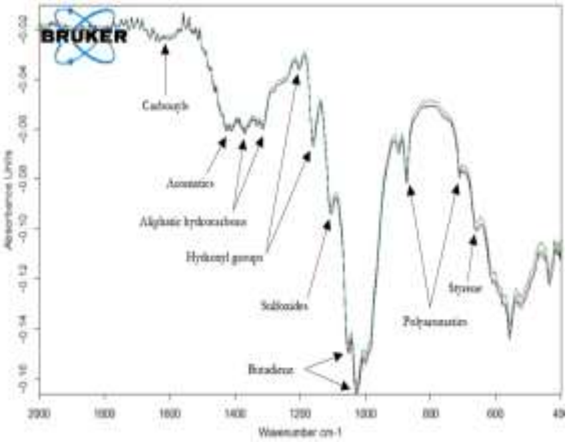

Figure (2): FTIR spectroscopic results for all PMB

Table (4): Asphalt performance grade (PG) and properties of PMBs test Results.

Property		Test method	Test results: Net asphalt	Test results: 4%SBS
Original Binder				
(G*/sin δ) min. 1.00 kPa, AASHTOM320		AASHTO T315	1.9084 @ (70)C°	1.1721 @ (82)C°
			0.8752 @ (76)C°	0.6326 @ (88)C°
After RTFOT (Test Method AASHTO T240)				
(G*/sin δ) min. 2.20 kPa, AASHTOM320		AASHTO T315	3.1020 @ (70)C°	2.2743 @ (82)C°
			1.5499 @ (76)C°	1.1422 @ (88)C°
After PAV @ 110C (AASHTO R28)				
Creep Stiffness Test @ -10C°	S value mpa, max 300 MPa,	AASHTO T313	72	130
	m value, min. 0.300		0.401	0.361
PG		AASHTOM 320	70-10	82-10
RV @ 135 °C MAX. 3 pa.sec		ASTM D 4402	0.76 Pa. Sec	1.791
RV @ 165 °C, MAX. 3pa.sec		ASTM D 4402	0.175Pa. Sec	0.460
Storage stability, MAX. 4		ASTM D 71713	1.4	0.9
%Solubility in trichloroethylene Min. 99%		ASTM D 2042	99.69	99.81
%Elastic recovery, MIN. 75%		AASHTO T 301	77	81

3.Aggregate gradation

Aggregate gradation with NMAS of (12.5) mm was used in this work as shown in Figure 3. The coarse and fine aggregates were sieved according to Superpave requirements for the 12.5 mm NMAS gradation.

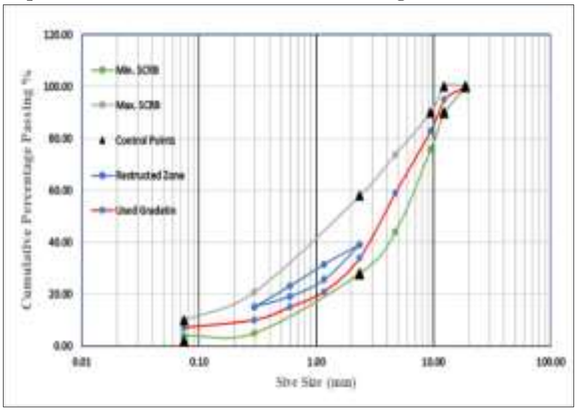

Figure (3): Asphalt Mixture Gradation with Superpave Specification Limits for 12.5mm, NMAS.

4.Design Binder Content for HMAs Mixtures

There are many design methods proposed by different institute or agencies to design HMA. At this study Superpave design method was adopted HMA using different percentage of asphalt binder ranging between (4%-5%), whereas two samples were prepared for each asphalt percent (eight for each mixture). The design (optimum) binder contents are 4.8%, 4.9%, and 4.95% for control, 4% PMB-SBS, and 4% PMB-SBS with 20% RAP mixtures, respectively.

5. Test Method and Preparation of Specimens

AASHTO 283 procedure is followed for conducting moisture sensitivity evaluations. Before the test, six Superpave specimens shown in Figure 4, were prepared, which included the suggested aggregate mix and binder at the design binder content, compacted to a height of 95±5 mm with an air void percentage of 7.0% ± 0.5%. There are two categories for these specimens, half of the specimens were tested as dry specimens (unconditioned), and the other half were tested as wet specimens (conditioned) after completing a freeze-thaw cycle to condition the moisture and achieve partial saturation. After the conditioning phase was over, the specimens were subjected to indirect stress until they break. After that, ITS values for unconditional and condition specimens were determined. The mixture is considered to have passed the test (satisfactory)if the retained strength ratio, which measures the average strength of the conditioned subset relative to the control subset, is equal to or greater than 80% [23]. Thirty specimens were used for this section in total. Number of samples and percent of saturation are shown in Table 5.

Figure (4): Prepared Sample for Moisture Damage.

Table (5): Number of samples and percent of saturation.

Property	AASHTO Test method	Test results		
		Net asphalt	4%SBS	4%SBS +RAP
Number of samples	T 283	6	6	6
Percent of saturation	T 283	73	72	74

6. Results and Discussions:

6.1. Indirect Tensile Strength (ITS) test results

Figure 5 displays the ITS results for three different types of HMAs: conventional HMA (Control), HMA with 4% PMB-SBS, and HMA with 4% PMB-SBS + 20% RAP. The results illustrate that the ITS value of unconditioned samples for the control mix is 819 kPa, while the PMB-SBS mix achieves 1123 kPa, indicating about 37 % increase in tensile strength. The ITS value of 4% PMB-SBS + RAP is 888 kPa, showing an 8.4% rise relative to the control, although that it shows about 21% drop compared to the 4% PMB-SBS. In other words, adding RAP, which may contain older, harder bitumen, could decrease some of the benefits of adding SBS, even though SBS makes the mixture stronger.

ITS value for condition specimens is 662 kPa of the control mix, whereas for SBS-modified mix achieve 1029 kPa, indicating an increase of around 55.5%. The ITS of 4% PMB-SBS + RAP is 760 kPa, which is 14.8% higher than the control and 26.1% lower than the SBS-only combination. This shows how the aged properties of RAP affect conditioned strength. The results show that PMB-SBS has better mechanical integrity compared to bitumen that has not been modified. It is more resistant to moisture degradation and tensile stresses.

The molecular basis for these increases is shown in Figure 2, which shows the FTIR spectra of every asphalt binder. In contrast to the net bitumen, the PMB-SBS displays supplementary absorption peaks at about 699 cm^{-1} and 966 cm^{-1}, which are associated with SBS's polystyrene and polybutadiene phases. The existence of these peaks signifies the establishment of a physically crosslinked polymer network inside the bitumen matrix. This polymer network enhances cohesion, elasticity, and viscoelastic recovery, hence improving tensile strength. Molecular interactions make the stress more evenly distributed throughout the asphalt mixture. This makes the pavement last longer and prevents cracks from forming.

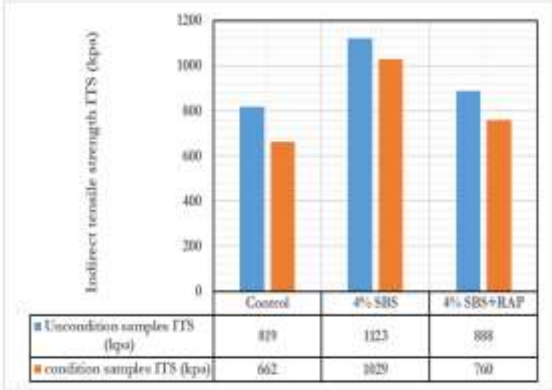

Figure (5): Indirect tensile strength test results.

6.2. Tensile Strength Ratio (TSR) results

As an indication of moisture susceptibility, Figure 6 displays the TSR results for many mixtures that comprised different types of bitumen. The TSR value for 4% PMB-SBS is significantly higher at 91.6%, compared to 80.72% for the control, indicating a 13.49% improvement in moisture resistance. The use of SBS improves the binder's adhesion and cohesion, mitigating moisture-related degradation and thus elevating the TSR. The 4% SBS+RAP combination has a reduced TSR of 85.52%, which surpasses the control but is lesser to the SBS-only mixture. The reason for this drop might be the old binder in RAP, which might not work as well with the SBS, making the polymer less useful overall.

The FTIR spectral data shown in Figure 2, illustrate there is a differentiate in the molecular compositions of unmodified bitumen and 4% SBS-MA. The spectrum of the SBS-MA exhibits extra absorbance peaks absent in the spectra of the unmodified bitumen. The peaks, particularly noticeable at around 1600 cm^{-1} and 1700 cm^{-1}, are ascribed to aromatic and carbonyl groups, respectively, which are indicative of the styrene and butadiene constituents in SBS. These polymers are recognized for their capacity to increase the elasticity and thermal stability of binders, hence enhancing adhesive qualities and resistance to thermal and oxidative degradation.

The rise in TSR value for the PMB-SBS indicate a significant enhancement in the quality and resilience of the asphalt mixture against moisture-related damage. The SBS-modified mixture works better because of the molecular interactions found in the FTIR test results.

Adding SBS changes the bitumen matrix to make a stronger network that resists water stripping better than conventional HMA. Furthermore, the incorporation of RAP, while it reduces the TSR in comparison to the SBS-only combination, still yields a greater TSR than the control. This means that even though RAP adds an older, probably stiffer binder that might not mix well with SBS, the whole change is still better than mixing the two substances the same way.

The incorporation of SBS significantly improves the moisture resistance of asphalt, shown by the elevated TSR and confirm by FTIR molecular analysis indicating the integration of polymer chains inside the bitumen matrix. This integration strengthens the binder, increases its viscoelastic properties, and makes it more resistant to outside forces, which makes the pavement last longer.

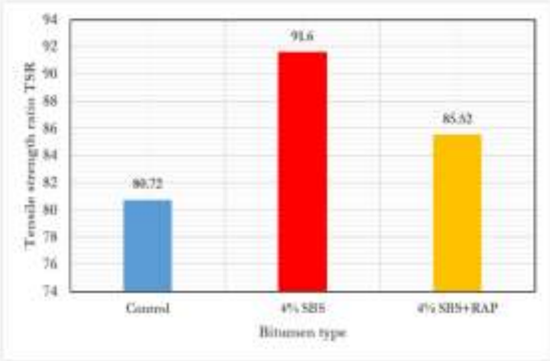

Figure (6): Relationship between the tensile strength ratio and the bitumen types.

7.Conclusions

The research assessed moisture damage for different HMA mixes contained PMB-SBS and RAP compared with conventional HMA. The research indicates that PMB-SBS, significantly enhances the resilience of hot mix asphalt (HMA) for mechanical stress and water exposure.

The SBS-modified HMA demonstrated the greatest ITS and TSR, with unconditioned ITS values rising by 37.1% (1123 kPa compared to 819 kPa for the control) and TSR enhancing by 13.49% (91.6% compared to 80.72% for the control). The improvements are due to the creation of a physically crosslinked polymer network, which enhances cohesion, elasticity, and stress distribution, as shown by FTIR spectroscopy.

Incorporating 20% RAP into SBS-modified HMA resulted in a 20.9% reduction in performance compared to pure SBS; nevertheless, the SBS+RAP combination still exceeded the control, exhibiting an 8.4% increase in ITS and a TSR of 85.52%. While there may be some compatibility between SBS and an aged binder in RAP, the oxidative aging process in RAP decreases the strength of the polymer network.
The FTIR investigation indicated that SBS was incorporated into the bitumen matrix. Significant absorbance peaks were observed at 699 cm^{-1} for polystyrene and 966 cm^{-1} for polybutadiene. These peaks indicate interactions between polymer and bitumen that improve viscoelasticity and adhesion, reducing moisture-induced stripping. Conversely, unmodified bitumen exhibited an absence of these polymeric characteristics, leading to reduced intermolecular forces.

8. References:

[1] A. E. A. E.-M. Behiry, "Optimisation of hot mix asphalt performance based on aggregate selection," Int. J. Pavement Eng., vol. 17, no. 10, pp. 924-940, 2016. https://doi.org/10.1080/10298436.2015.1043634

[2] S. Caro, E. Masad, A. Bhasin, and D. N. Little, "Moisture susceptibility of asphalt mixtures, Part 1: mechanisms," Int. J. Pavement Eng., vol. 9, no. 2, pp. 81-98, 2008. https://doi.org/10.1080/10298430701792128

[3] S. Aldagari, M. R. Kakar, M. O. Hamzah, M. N. Akhtar, and D. Woodward, "Enhanced sustainability at the bitumen-aggregate interface using organosilane coating technology," Constr. Build. Mater., vol. 359, p. 129500, 2022. https://doi.org/10.1016/j.conbuildmat.2022.129500

[4] R. Xiao, Fundamental Investigation of Interaction between Moisture and Asphalt-Aggregate Systems, 2022.

[5] S. Shi, J. Zhang, Y. Li, H. Wang, and L. Chen, "Enhancing asphalt-based waterproof materials for building cement substrates: Modifications, construction, and weathering resistance," Constr. Build. Mater., vol. 441, p. 137537, 2024. https://doi.org/10.1016/j.conbuildmat.2024.137537

[6] R. Xiao, P. Polaczyk, and B. Huang, "Mitigating stripping in asphalt mixtures: pretreatment of aggregate by thermoplastic polyethylene powder coating," Transp. Res. Rec., vol. 2678, no. 4, pp. 776-787, 2024. https://doi.org/10.1177/03611981231186598

[7] T. M. Hashim, M. Z. Al-Mulali, F. F. Al-Khafaji, A. A. A. Alwash, and Y. A. Ali, "An experimental comparison between different types of surface patterns of permeable interlocking concrete pavement for roadway subsurface drainage," Case Stud. Constr. Mater., vol. 17, p. e01227, 2022. https://doi.org/10.1016/j.cscm.2022.e01227

[8] D. Krupnik, Ground-Based Hyperspectral Imaging at Various Scales, Univ. Houston, 2019.

[9] D. Zhang, P. Yu, Z. Liu, Z. Liu, H. Chen, and Y. Gao, "Influence of acidity and alkalinity of water environments on the water stability of asphalt mixture: Phase I-molecular dynamics simulation," Constr. Build. Mater., vol. 411, p. 134466, 2024. https://doi.org/10.1016/j.conbuildmat.2023.134466

[10] R. Xiao, Y. Ding, P. Polaczyk, Y. Ma, X. Jiang, and B. Huang, "Moisture damage mechanism and material selection of HMA with amine antistripping agent," Mater. Des., vol. 220, p. 110797, 2022. https://doi.org/10.1016/j.matdes.2022.110797

[11] A. Sassani, A. Lawal, and O. Smadi, Guidebook for Application of Polymer-Modified Asphalt Overlays: From Decision-Making to Implementation, Iowa State Univ., Inst. Transp., 2024.

[12] Y. D. Wang, J. Liu, and J. Liu, "Integrating quality assurance in balance mix designs for durable asphalt mixtures: State-of-the-art literature review," J. Transp. Eng., Part B: Pavements, vol. 149, no. 1, p. 03122004, 2023. https://doi.org/10.1061/JPEODX.PVENG-957

[13] S. Haider, I. Hafeez, S. B. A. Zaidi, M. A. Nasir, and M. Rizwan, "A pure case study on moisture sensitivity assessment using tests on both loose and compacted asphalt mixture," Constr. Build. Mater., vol. 239, p. 117817, 2020. https://doi.org/10.1016/j.conbuildmat.2019.117817

[14] D. Movilla-Quesada, A. C. Raposeiras, E. Guíñez, and A. Frechilla-Alonso, "A Comparative Study of the Effect of Moisture Susceptibility on Polyethylene Terephthalate-Modified Asphalt Mixes under Different Regulatory Procedures," Sustainability, vol. 15, no. 19, p. 14519, 2023. https://doi.org/10.3390/su151914519

[15] R. W. Bazuhair and M. A. Alqahtani, "An Assessment of Testing and Conditions Protocol to Evaluate Asphalt Mixtures," Eng., Technol. Appl. Sci. Res., vol. 13, no. 4, pp. 11119-11123, 2023. https://doi.org/10.48084/etasr.6003

[16] T. Bagchi, Evaluation of Compatibility between Asphalt Binders and Mineral Aggregates, Arkansas State Univ., 2020.

[17] A. Alfalah, Evaluating the Impact of Oxidation on Moisture Resistance of Asphalt Components and Mixtures, Rowan Univ., 2023.

[18] M. R. Kakar, M. O. Hamzah, M. N. Akhtar, and D. Woodward, "Surface free energy and moisture susceptibility evaluation of asphalt binders modified with surfactant-based chemical additive," J. Clean. Prod., vol. 112, pp. 2342-2353, 2016. https://doi.org/10.1016/j.jclepro.2015.10.101

[19] M. Bilal, Performance Evaluation of Styrene-Butadiene-Styrene (SBS) Modified Asphalt Mixtures using Dynamic Modulus Test, Mil. Coll. Eng. (NUST) Risalpur Cantt, 2022.

[20] Z.-g. Feng, H.-j. Bian, X.-j. Li, and J.-y. Yu, "FTIR analysis of UV aging on bitumen and its fractions," Mater. Struct., vol. 49, pp. 1381-1389, 2016. https://doi.org/10.1617/s11527-015-0583-9

[21] V. Mouillet, F. Farcas, and S. Besson, "Ageing by UV radiation of an elastomer modified bitumen," Fuel, vol. 87, no. 12, pp. 2408-2419, 2008. https://doi.org/10.1016/j.fuel.2008.02.008

[22] S. Weigel and D. Stephan, "The prediction of bitumen properties based on FTIR and multivariate analysis methods," Fuel, vol. 208, pp. 655-661, 2017. https://doi.org/10.1016/j.fuel.2017.07.048

[23] S. Weigel, M. Gehrke, C. Recknagel, and D. A. Stephan, "Identification and quantification of additives in bituminous binders based on FTIR spectroscopy and multivariate analysis methods," Mater. Struct., vol. 54, no. 4, p. 171, 2021. https://doi.org/10.1617/s11527-021-01763-1

[24] T. NCHRP, Evaluation of Indirect Tensile Test (IDT) Procedures for Low-Temperature Performance of Hot Mix Asphalt, 2004.