Improving the Functional Properties of Asphalt Binder via Triple-Component Polymer Modification: An Analysis of Stability and Rheological Behavior

Taher M. Rasheed
Department of Chemical Engineering, College of Engineering, University of Duhok Polytechnic, Duhok, Iraq
taher.rasheed@dpu.edu.krd

Sherwan M. Simo
Department of Petroleum Engineering, College of Engineering, University of Zakho, Zakho, Iraq | Engineering Researcher Center, University of Zakho, Kurdistan Region, Iraq
sherwan.simo@uoz.edu.krd

Mevan M. Mustafa
Department of Petroleum Engineering, College of Engineering, University of Zakho, Zakho, Iraq
mehvan.mustafa@uoz.edu.krd (corresponding author)

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ABSTRACT

This research explores the improvement of asphalt binder performance through a novel three-component polymer modification that combines Styrene-Butadiene-Styrene (SBS), Ethylene-Vinyl Acetate (EVA), and Dibenzoyl Peroxide (DBP). The study addresses the longstanding issue of phase separation in polymer-modified asphalt, a challenge exacerbated by Iraq's extreme climatic conditions and heavy infrastructure demands. The work focuses on enhancing the rheological, physical, and chemical stability of 40/50 penetration grade asphalt, aiming to strengthen its resistance to aging, deformation, and thermal deterioration. The results reveal that the combined use of SBS, EVA, and DBP produces a strong synergistic effect—boosting elasticity, stiffness, and high-temperature performance while minimizing rutting and fatigue. The most effective and economical blend was determined to be 2.5 wt.% SBS+EVA with 0.3 wt.% DBP. The analytical evaluations, including Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and Energy-Dispersive X-ray Spectroscopy (EDX), confirmed successful chemical interaction among the additives, resulting in a more uniform polymer-asphalt structure. This method offers a promising solution for creating long-lasting, sustainable asphalt binders that can withstand heavy traffic and harsh environmental stresses.

Keywords-polymer-modified asphalt; rheological properties; phase stability; Styrene-Butadiene-Styrene; Ethylene-Vinyl Acetate; Dibenzoyl Peroxide

I. INTRODUCTION

Asphaltic materials are complex organic compounds widely used in industrial applications, especially in construction and infrastructure. They are generally classified into two types: natural asphalts, found near crude oil deposits, and industrial asphalts, produced through the fractional distillation of crude oil at 300°C-350°C. Industrial asphalts are valued for their consistent properties and are commonly used in road paving, roofing, and waterproofing. Research focuses on improving their performance and sustainability through various modifications and additives [1]. Asphalt binder, a vital element in the construction and performance of asphalt pavements, continues to be a central subject of investigation in roadway engineering. Chemically, it is a high-molecular-weight hydrocarbon material comprising four fundamental fractions: asphaltenes, resins, saturates, and aromatics [2].

Each of these components contributes to the binder's overall behavior, influencing characteristics such as stiffness, adhesion, and temperature susceptibility [3]. The rheological behavior of asphalt binder, which determines its deformation and flow under different loads and temperatures, is crucial for performance. Complex viscosity, reflecting both elasticity and viscosity, quantifies these properties. Optimizing rheological performance enhances pavement durability, reduces maintenance, and ensures long-term integrity, especially under heavy traffic and extreme conditions [4].

The asphalt binder evaluation typically involves measuring key physical and rheological characteristics, including softening point, penetration, and viscosity [5]. These characteristics are vital for designing asphalt mixtures that endure traffic loads and environmental factors. Conventional asphalt binders, though viscoelastic, often underperform under heavy traffic, loads, and extreme weather. This has driven greater attention toward polymer-modified binders, which offer enhanced elasticity, lower stress, temperature susceptibility, and improved resistance to rutting and fatigue, while also considering the cost-effectiveness of incorporating such additives to alter the asphalt properties [6].

Polymers are synthetic macromolecules made of repeating units called monomers, typically derived from crude oil and natural gas. These monomers link through polymerization to form long chains mainly composed of carbon, along with elements like hydrogen, oxygen, nitrogen, and chlorine. The structure and composition of polymers influence their properties, such as strength, flexibility, and viscosity, making them widely used in various industries depending on the properties of asphalt and applications [7]. Polymer-modified binders have demonstrated outstanding performance in high-stress environments, including heavily trafficked intersections, airports, weigh stations, and racetracks [8].

In advanced asphalt paving applications, polymer-modified asphalt has gained widespread use owing to its well-established performance advantages [9]. Of the many polymers employed to modify asphalt, SBS remains the most widely used, followed by materials such as Ground Tire Rubber (GTR), Styrene-Butadiene Rubber (SBR), EVA, polyethylene, polyvinyl acetate (PVAc), polymethyl methacrylate (PMMA), cyanoacrylate, and several others [10].

Phase separation is a common issue in modified asphalt, especially with polymers like SBS or EVA and crosslinkers like DBP. It occurs due to incompatibility between the polymer and asphalt binder, resulting in distinct polymer-rich and asphalt-rich phases over time [11].

Phase separation reduces the uniformity, stability, and performance of modified asphalt. To address this issue, strategies include utilizing compatibilizers, optimizing mixing conditions, choosing compatible polymers, and adding stabilizers like sulfur or reactive polymers to promote bonding and prevent separation [12]. This study aims to enhance the performance of 40/50 penetration grade asphalt through a novel triple-component modification employing SBS, EVA, and DBP. The work addresses the persistent problem of phase separation in polymer-modified asphalt, particularly under Iraq's extreme climate and heavy traffic. By employing DBP as a crosslinker, the research introduces a new strategy to improve compatibility, rheology, and stability, offering a cost-effective and durable solution for long-lasting road infrastructure.

II. MATERIALS AND METHODS

A. Materials

The Local Asphalt (LA) used in this research was obtained from the Kawashi area in Duhok, in the Kurdistan Region of Iraq. A 40/50 penetration grade asphalt was selected for the study, with its key characteristics presented in Table I. To improve its performance and change properties to suit the Iraqi conditions, the asphalt was modified using two types of polymers: Europrene (SBS), imported from Italy, and Naboli Pluse (EVA). The polymers, imported from Iran, were added to the asphalt at concentrations ranging from 0.5% to 6% by weight. The modification was carried out at 180°C and maintained for a period of 2 h [13]. Figures 1 and 2 present the chemical structures and shapes of SBS, EVA, and DBP, respectively.

SBS, EVA, and DBP were chosen for their proven roles in enhancing the asphalt performance: SBS improves elasticity and rutting resistance, EVA enhances stiffness and stability, and DBP acts as a plasticizer to reduce brittleness. Concentration levels (3–6% by asphalt weight) were chosen based on prior studies showing effective performance improvements without phase separation or excessive cost.

TABLE I. RHEOLOGICAL AND PHYSICAL CHARACTERISTICS OF 40/50 ASPHALT (LA)

Original asphalt	**Rheological and physical properties**	
	Specification value	**Specification range***
Viscosity at 135 °C (cP)	637.5	-
Ductility (cm, 25 °C)	+150	100
Softening point (°C)	49.2	49-60
Penetration (100g, 5s, 25 °C)	47.1	40-60

*Iraqi Standard Specifications for Roads and Bridges (SORP/R9)

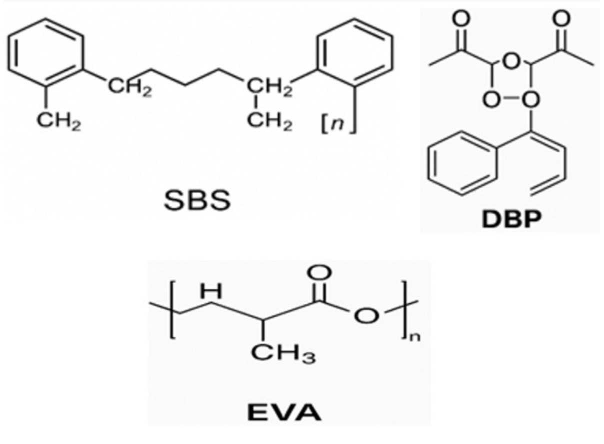


Fig. 1. Chemical structure of SBS, EVA, and DBP.

Sulfur was added at a concentration of 1% by weight to generate free radicals, which help initiate the chemical reaction and enhance the plasticity of the asphalt and work as a crosslinker [14]. Additionally, DBP $(C_6H_5-C(=O)\ O-)_2$ was used at a 0.3% weight ratio as an initiator and as a crosslinker to promote the interaction between the polymer and bitumen molecules [15]. The entire mixture was mechanically stirred at a speed of 1000 rpm.

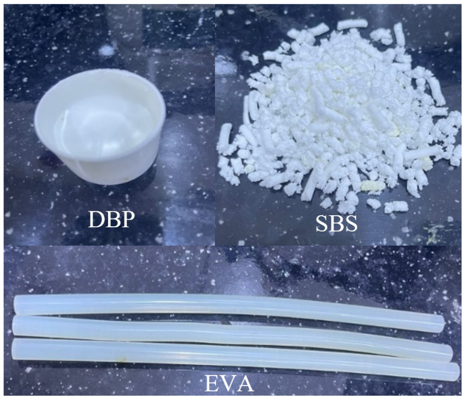


Fig. 2. Shapes of SBS, EVA, and DBP.

B. Test Methods

1) Conventional Bitumen Tests

The physical and rheological properties of both the original and modified asphalt samples were evaluated through internationally recognized standardized tests. These included penetrations, ductility, softening point, elasticity, and phase separation assessments, all conducted in accordance with ASTM standards: ASTM D5 for penetration [16], ASTM D113 for ductility [17], and ASTM D36 for softening point [18]. The Penetration Index (*PI*) [19]. Phase separation ASTM D7173 was also conducted to determine the asphalt binders' sensitivity to temperature variations because each test has their conditions as temperature and time of test, and size of templates [20]. Furthermore, FTIR was conducted to analyze the materials in greater detail, enabling the identification of functional groups and any chemical alterations [21]. SEM and EDX were utilized to examine the surface structure and makeup of materials, particularly polymer-modified asphalt used in road construction [22].

III. RESULTS AND DISCUSSION

A. Rheological Properties

In this study, two distinct polymers were employed to modify asphalt and improve its rheological properties. By comparing the *PI* of a modified sample with that of a control, engineers can assess material quality and identify potential inconsistencies. The *PI* also serves as a tool for predicting the asphalt performance, selecting appropriate binders for specific applications, evaluating long-term durability, and supporting further research in asphalt technology. The *PI* can be determined using [22]:

$$\frac{20-PI}{10+PI}=50\left(\frac{\log(800)-\log(pent)}{T_{RB}-T}\right) \quad (1)$$

where *Pent* is the penetration grade of the asphalt sample, T_{RB} is the softening point of the sample, and T is the temperature at which penetration is measured (25°C). This function measures the sensitivity of the asphalt material to the temperature variations [23].

1) Modification of Original Asphalt With SBA And EVA

LA can be enhanced by incorporating polymer additives, such as SBS and EVA [24]. SBS is a thermoplastic elastomer that improves the elasticity, temperature susceptibility, and overall mechanical performance of asphalt. It increases the binder's resistance to deformation at high temperatures and improves flexibility at low temperatures, making it more durable against cracking and rutting. SBS and EVA, added as powder or pellets and mixed at high temperatures with asphalt, produce polymer-modified asphalt with improved rheology, durability, and performance in diverse climates [25]. Table II presents the rheological performance of asphalt modified with combined SBS and EVA polymers in concentrations from 0.5% to 6%, showing a clear trend of improved properties as the polymer content increases. SBS enhances elasticity and high-temperature deformation resistance, while EVA contributes polar functional groups that improve adhesion, thermal stability, and aging resistance [26]. Together, they form a synergistic blend that increases stiffness (lower penetration), elasticity (higher elastic recovery), and heat resistance (higher softening point), while also improving temperature susceptibility (*PI*). Among all samples, SBE_5 (containing 2.5 wt.% total polymer) was selected as the optimal formulation, achieving a penetration of 42.2, elastic recovery of 43 cm, softening point of 53.7°C, and a *PI* of –0.701. It offers an ideal balance between the mechanical performance and economic efficiency, avoiding phase separation and excessive cost while delivering durable and flexible asphalt suitable for practical road construction.

B. Modification of Original Asphalt with SBS And EVA with 0.3 Wt% (DBP)

The original asphalt was modified using a combination of SBS and EVA polymers along with a fixed 0.3 wt.% of DBP as a chemical initiator. DBP facilitated the cross-linking reaction between the polymers and the asphalt matrix, enhancing the overall compatibility and stability of the modified binder [27]. As the combined SBS and EVA content increased from 0.5 to 6 wt.%, with DBP as a crosslinker, the asphalt showed performance improvements. The elastic recovery increased, indicating better elasticity, while the softening point rose, reflecting higher heat resistance. At the same time, the penetration decreased, showing greater stiffness and reduced flow under load. Overall, this modification significantly enhanced the rheological and mechanical properties, making the asphalt more suitable for heavy-duty road applications. Table III examines the modification of asphalt using SBS and EVA polymers. This is because the weight percentage of SBS and EVA in Table III, combined with 0.3 wt.% DBP, acts as a crosslinking agent, which enhances the chemical bonding between polymer chains and asphalt, improving compatibility, elasticity, and thermal stability. As the total polymer content increases from 0.5% to 6%, the penetration decreases, indicating increased stiffness, while the elastic recovery and softening point significantly rise, reflecting improved elasticity and heat resistance. The *PI* also improves, showing better temperature susceptibility. Among all samples, DES_5 (2.5 wt.% polymer) was selected as the optimal formulation due to its excellent performance—penetration of 41.8, elastic recovery of 39 cm, softening point of 54.2°C, and a *PI* of –0.610—while maintaining low material cost and avoiding instability or phase separation, making it the most balanced and economically efficient option for high-performance asphalt modification.

TABLE II. RHEOLOGICAL PROPERTIES OF ASPHALT MODIFIED WITH SBS AND EVA AT 180°C FOR 2 H

Sample no.	Rheological properties of asphalt modified with SBS and EVA				
	EVA and SBS (wt%, 50/50)	Penetration	Elastic recovery	Softening point (°C)	*PI*
SBE$_1$	0.5	45.9	8.0	49.9	-1.410
SBE$_2$	1.0	44.2	10.0	50.4	-1.369
SBE$_3$	1.5	43.3	17.0	51.7	-1.103
SBE$_4$	2.0	43.0	31.0	52.1	-1.025
SBE$_5$	2.5	42.2	43.0	53.7	-0.701
SBE$_6$	3.0	41.3	49.0	54.2	-0.637
SBE$_7$	3.5	38.9	58.0	55.1	-0.570
SBE$_8$	4.0	36.4	71.25	55.9	-0.541
SBE$_9$	4.5	34.7	73.6	56.8	-0.454
SBE1$_0$	5.0	33.2	74.7	58.9	-0.126
SBE$_{11}$	5.5	32.5	78.5	61.8	0.380
SBE$_{12}$	6.0	31.9	81.0	64.2	0.773

TABLE III. RHEOLOGICAL PROPERTIES OF ASPHALT MODIFIED WITH SBS AND EVA AT 180°C IN 0.3 WT.% DBP FOR 2 H

Sample No.	Rheological properties of asphalt treated with SBS, EVA, and 0.3 wt% DBP				
	EVA and SBS (wt%, 50/50)	Penetration	Elastic recovery	Softening point (°C)	*PI*
DES$_1$	0.5	45.7	9.0	49.4	-1.543
DES$_2$	1.0	43.6	10.5	50.6	-1.349
DES$_3$	1.5	43.1	15.0	51.7	-1.113
DES$_4$	2.0	42.7	29.0	52.4	-0.970
DES$_5$	2.5	41.8	39.0	54.2	-0.610
DES$_6$	3.0	41.0	44.0	54.8	-0.521
DES$_7$	3.5	40.8	58.0	55.3	-0.424
DES$_8$	4.0	38.2	70.0	55.5	-0.523
DES$_9$	4.5	36.0	72.7	57.1	-0.316
DES1$_0$	5.0	34.2	74.1	57.9	-0.262
DES$_{11}$	5.5	32.7	77.6	59.2	-0.099
DES$_{12}$	6.0	31.3	79.8	62.8	0.483

C. Phase Separation

In the phase separation test (also known as the softening point difference test using the tube test or cigar tube method), the acceptable range for the softening point difference is measured between the top (left ball) and bottom (right ball) of a polymer-modified asphalt sample. A softening point difference of 5 °C or less is generally considered acceptable, indicating good phase stability, uniform dispersion of SBS and EVA, and minimal risk of separation [28]. A difference between 5 and 10 °C is seen as borderline, suggesting minor separation, which might be manageable with additives or further optimization. Differences greater than 10 °C are considered unacceptable, pointing to significant phase separation, poor compatibility, or polymer migration during storage. This interpretation aligns with widely accepted standards, such as ASTM D5892 and AASHTO T53. Based on this, sample SBE$_5$, with a softening point difference of 2.6 °C, falls at the upper limit of acceptability and can be regarded as the most stable formulation among the tested SBS-modified asphalt blends [29].

Table IV evaluates the phase separation of asphalt modified with a 50/50 blend of EVA and SBS polymers at concentrations ranging from 0.5% to 6% as the weight percentage of SBS and EVA in Table III, based on the Iraqi standard, which considers a softening point difference of ≤5 °C between the top and bottom of the sample acceptable. As the polymer content increases, the elastic recovery and softening point improve, but phase separation becomes evident at higher concentrations, especially from SBE$_6$ onward, where the softening point difference exceeds the limit. Sample SBE$_5$, containing 2.5 wt% total polymer, was selected as the optimal formulation due to its excellent phase stability (softening point difference of 2.6 °C), desirable mechanical properties (penetration of 42.2, elastic recovery of 43 cm, softening point of 53.7 °C), and cost-effectiveness. This makes SBE$_5$ the most balanced and economically viable option for producing durable and thermally stable asphalt.

TABLE IV. PHASE SEPARATION OF ASPHALT TREATED WITH EVA AND SBS AT 163 °C FOR 48 H

Sample no.	Phase separation of asphalt treated with EVA and SBS				
	Penetration	Elastic recovery	Softening point (°C)	Right ball (°C)	Left ball (°C)
SBE$_1$	45.9	8.0	49.9	50.1	50.6
SBE$_2$	44.2	10	50.4	50.8	51.3
SBE$_3$	43.3	17	51.7	51.6	53.1
SBE$_4$	43	31	52.1	53.2	55.3
SBE$_5$	42.2	43	53.7	54.1	56.7
SBE$_6$	41.3	49	54.2	54.1	60.7
SBE$_7$	38.9	58	55.1	55.5	62.1
SBE$_8$	36.4	71.25	55.9	56.4	64.3
SBE$_9$	34.7	73.6	56.8	57.2	66.3
SBE1$_0$	33.2	74.7	58.9	58.8	68.1
SBE$_{11}$	32.5	78.5	61.8	61.0	69.0
SBE$_{12}$	31.9	81	64.2	64.9	75.3

Table V evaluates the phase separation of asphalt modified with a 50/50 blend of SBS and EVA polymers (0.5‑6 wt.%) with 0.3 wt.% DBP after storage at 163 °C for 2 days. According to Iraqi standards, a softening point difference of ≤5 °C indicates good dispersion and stability. The results show that as the polymer content increases, the elastic recovery and softening point improve, but samples from DES$_6$ onward exceed the 5 °C limit, indicating instability. The optimal sample, DES$_5$ (2.5 wt.% polymer + DBP), achieved a softening point difference of only 2.1 °C, confirming excellent stability. DES$_5$ also exhibited strong mechanical properties, including a penetration of 41.8, an elastic recovery of 39 cm, and a softening point of 54.2 °C. These results demonstrate balanced performance, moderate cost, and reliable resistance to thermal aging. Additionally, SS$_2$ (1 wt.% SBS + sulfur) and DES5 both satisfied Iraqi standards, with softening point differences of 0.6 °C and 2.1 °C, respectively. While SS$_2$ is more economical and offers stable performance, DES$_5$ provides superior elasticity and thermal resistance, making it the preferred choice for heavy-load and high-temperature conditions.

TABLE V. PHASE SEPARATION OF ASPHALT TREATED WITH EVA, SBS, AND DBP AS CROSSLINKER AT 163 °C FOR 48 H

Sample no.	**Phase separation of asphalt treated with EVA, SBS, and DBP**				
	Penetration	**Elastic recovery**	**Softening point (°C)**	**Right ball (°C)**	**Left ball (°C)**
SBE$_1$	45.7	9.0	49.4	49.3	49.3
SBE$_2$	43.6	10.5	50.6	50.7	51.0
SBE$_3$	43.1	15.0	51.7	51.7	53.7
SBE$_4$	42.7	29.0	52.4	52.8	54.2
SBE$_5$	41.8	39.0	54.2	55.1	57.2
SBE$_6$	41.0	44.0	54.8	53.8	62.6
SBE$_7$	40.8	58.0	55.3	55.7	64.2
SBE$_8$	38.2	70.0	55.5	56.0	65.9
SBE$_9$	36.0	72.7	57.1	57.8	67.7
SBE1$_0$	34.2	74.1	57.9	58.1	73.5
SBE$_{11}$	32.7	77.6	59.2	59.6	79.1
SBE$_{12}$	31.3	79.8	62.8	63.1	80.0

D. Fourier Transform Infrared Spectroscopy

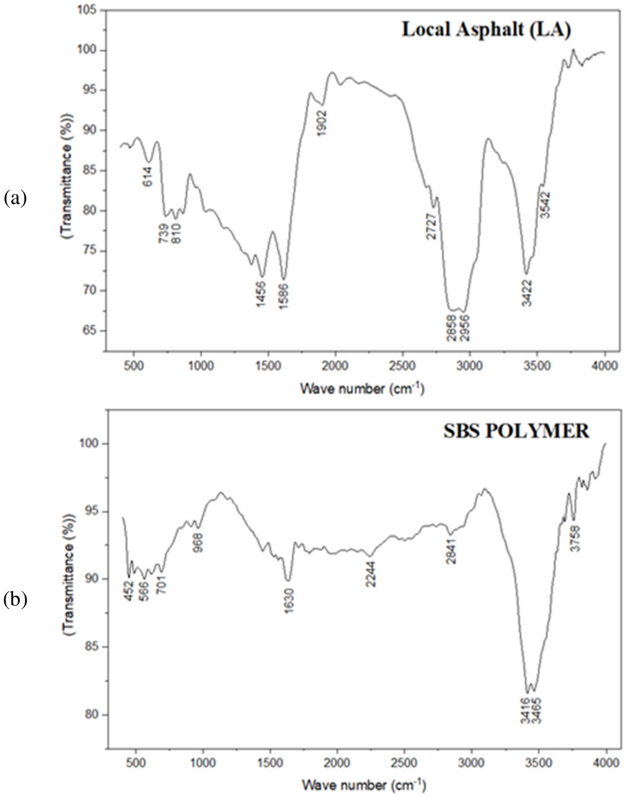
FTIR is commonly used to analyze the chemical structure and interactions of modified asphalt systems [30]. Key modifiers, such as SBS, EVA, and DBP, exhibit characteristic peaks corresponding to functional groups like C=O, C–H, C=C, O–H, and O–O. Asphalt itself shows complex spectra due to its aromatic, aliphatic, and sulfur-containing compounds. Comparing FTIR spectra before and after blending helps identify changes, such as the disappearance or formation of peaks, which indicate chemical interactions or compatibility between components, as displayed in Table VI [31].

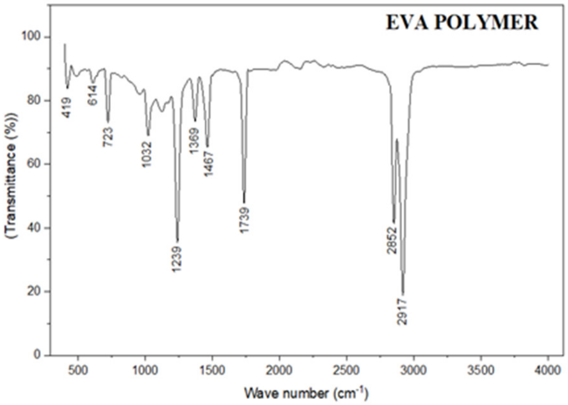
E. SBS and EVA Polymer (Spectrum) Key Bands Observed

The FTIR analysis of the SBE$_5$, as depicted in Figure 3, indicates complex interactions among the three components, resulting in both physical blending and chemical modification. The characteristic vinyl peak of SBS around 960–970 cm^{-1} disappears, suggesting that the double bonds in SBS have been consumed during the interaction with asphalt and possibly EVA. The carbonyl peak from EVA (1735 cm^{-1}) and the asphalt carbonyl region (1700 cm^{-1}) show shifts or reduced intensity, indicating interaction or partial overlap of the functional groups. Similarly, the broad O–H stretching band around 3400 cm^{-1} is reduced, likely due to hydrogen bonding or polarity balancing between the polymers and asphalt matrix. The appearance or intensification of peaks in the 1450–1370 cm^{-1} region (C–H bending) and 1030 cm^{-1} (C–O stretching) suggests increased aliphatic and ether-like structures, reflecting improved compatibility and possible co-network formation.

TABLE VI. FTIR CHARACTERISTIC PEAKS OF COMPONENTS AND THEIR ASSOCIATED FUNCTIONAL GROUPS

Component	**Functional group**	**FTIR peak region (cm^{-1})**
SBS	Aromatic C=C stretch (styrene)	~1600
	Aromatic C–H bending	~700–900
	Aliphatic C–H stretch (butadiene)	~2850–2950
	C=C (butadiene unsaturation)	~1640–1660
Asphalt	O–H stretch (phenols, alcohols)	~3200–3600
	C=O stretch (carbonyl compounds)	~1690–1740
	Aliphatic C–H stretch	~2850–2950
	Aromatic C=C stretch	~1600
	S=O stretch (sulfoxides)	~1030–1070
EVA	Aliphatic C–H stretch	~2850–2950
	C=O stretch (vinyl acetate group)	~1735
	C–O stretch	~1240–1260
DBP	C=O stretch (aromatic ester)	~1735–1750
	Aromatic C–H out-of-plane bending	~700–900
	O–O stretch (peroxide group)	~850–880 (weak)

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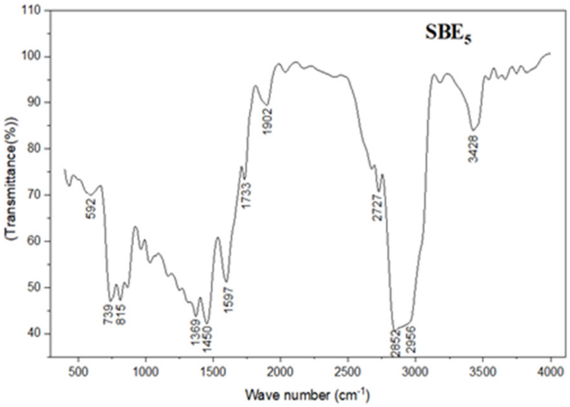
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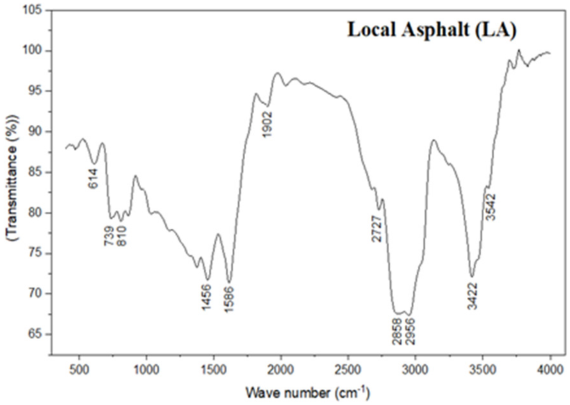
Fig. 3. FTIR Analysis of: (a) LA, (b) SBS polymer, (c) EVA Polymers, and (d) other blends (SBE$_5$).

These changes confirm that the asphalt–EVA–SBS system forms a more homogeneous and structurally integrated material with enhanced stability and performance.

F. Group Contributions in the Asphalt, SBS, EVA, and DBP Blend

The FTIR analysis of DES$_5$ shows clear chemical interactions and structural changes. The SBS vinyl peak (960–970 cm^{-1}) disappears, confirming crosslinking via DBP. The carbonyl peaks of EVA (1735 cm^{-1}) and asphalt (1700 cm^{-1}) shift or decrease in intensity, indicating bond formation and polarity changes.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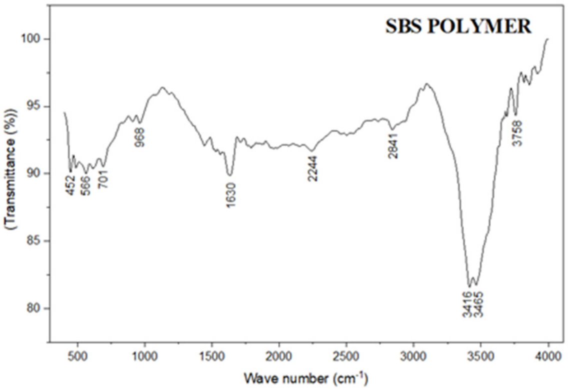
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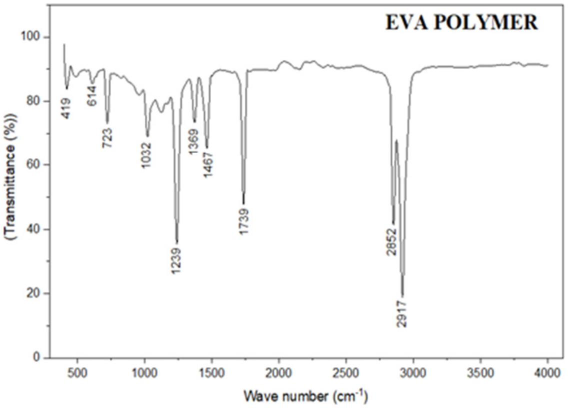
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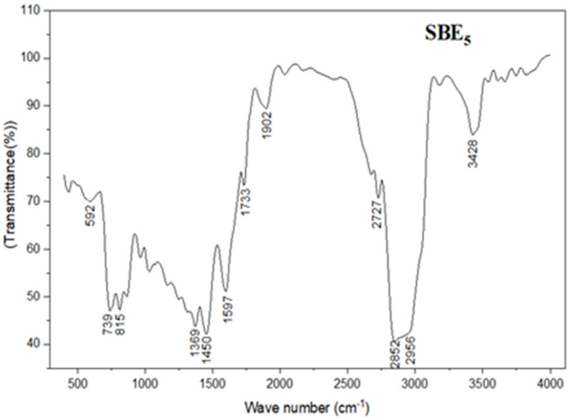
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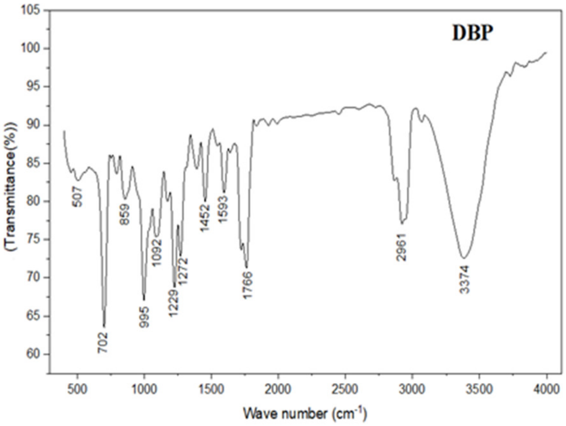
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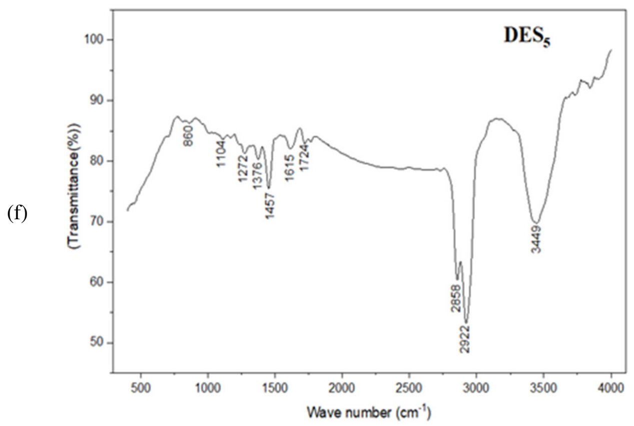


Fig. 4. FTIR Analysis of: (a) LA, (b) SBS polymer, (c) EVA polymers, (d) SBE$_5$, (e) DBP, (f) other blends (DES$_5$).

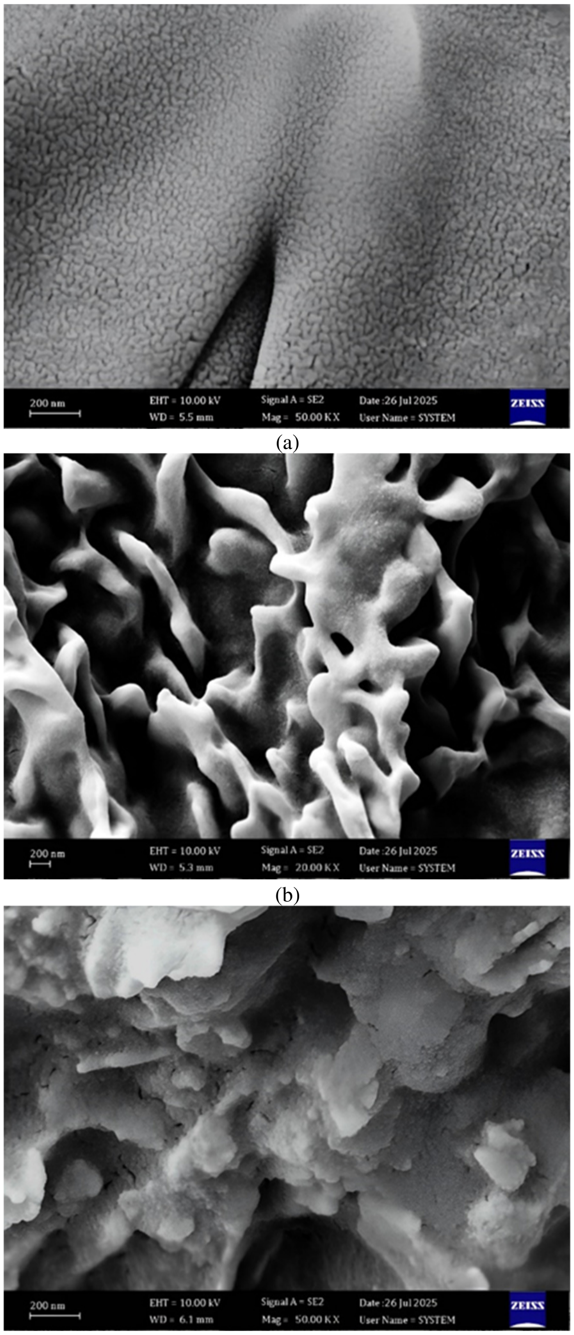
The O–H stretch at 3400 cm^{-1} decreases, suggesting less hydrogen bonding. Additionally, stronger peaks at 1030 cm^{-1} (C–O) and 1450–1370 cm^{-1} (C–H) reflect new aliphatic structures, while DBP peaks vanish, confirming complete reaction. These changes demonstrate that DBP crosslinks SBS and EVA, improving the asphalt's stability, elasticity, and performance.

G. Scanning Electron Microscopy and Energy-Dispersive X-Ray Spectroscopy

The SEM and EDX analyses show that both SBE$_5$ and DES$_5$ additives significantly modify the structure and composition of LA. The SEM images in Figure 5 reveal that LA has a smooth and compact surface, the addition of SBE$_5$ introduces roughness and heterogeneity, and DES$_5$ produces even more irregular and porous structures, indicating stronger modification effects. The EDX results, as presented in Table VII, confirm these changes as the carbon content decreases from 90.2% in LA to 62.4% in SBE$_5$ and 78.5% in DES$_5$, showing the incorporation of new chemical groups. The sulfur content decreases in SBE$_5$ (4.0%) but rises significantly in DES$_5$ (14.6%), suggesting that SBE$_5$ reduces the sulfuric compounds while DES$_5$ enhances crosslinking through sulfur interactions. Oxygen increases sharply in SBE$_5$ (16.6%) and moderately in DES$_5$ (6.9%), reflecting the introduction of oxygenated functional groups that improve adhesion and polarity. Overall, SBE$_5$ primarily enhances bonding and aggregate adhesion due to its oxygen-rich composition, while DES$_5$ improves elasticity and durability through sulfur-based crosslinking, making both additives effective in enhancing the mechanical performance and long-term resistance of asphalt compared to unmodified LA.

TABLE VII. EDX ANALYSIS COMPARING THE ELEMENTAL COMPOSITION OF ORIGINAL AND MODIFIED ASPHALT

Element	Wt.% LA	Wt.% SBE$_5$	Wt.% DES$_5$
C	90.2	62.4	78.5
S	8.9	4.0	14.6
O	0.9	16.6	6.9



(a)

(b)

(c)

Fig. 5. SEM Images for: (a) LA, (b) SBE5, (c) DES$_5$.

IV. CONCLUSION

This study presents a novel triple-component modification technique for improving the performance of 40/50 penetration grade asphalt by incorporating Styrene-Butadiene-Styrene (SBS), Ethylene-Vinyl Acetate (EVA), and Dibenzoyl Peroxide (DBP). The combined use of these additives produced a significant enhancement in elasticity, stiffness, thermal resistance, and phase stability, effectively overcoming the common issue of polymer phase separation. Among the tested formulations, DES$_5$ (2.5 wt.% SBS+EVA with 0.3 wt.% DBP) proved optimal, delivering excellent elastic recovery (39 cm), a higher softening point (54.2 °C), and stable dispersion with only a 2.1 °C softening point difference. The Fourier Transform Infrared Spectroscopy (FTIR) analysis confirmed strong chemical interactions and crosslinking between the additives and the asphalt matrix, while the Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) revealed improved microstructural uniformity and bonding. These results confirm that the synergistic interaction of SBS, EVA, and DBP offers a cost-effective and durable solution to the long-standing problem of instability in polymer-modified asphalt. Consequently, this research provides valuable insights for producing high-performance, climate-resilient, and sustainable asphalt binders suitable for the demanding road conditions in Iraq and similar environments.

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