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Research Paper

Study on the Effect of Ternary Regenerant on SBS Modified Bitumen and Its Mixture Pavement Performance

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Abstract. To enable the valuable utilization of high proportions of waste SBS modified bitumen mixture (RAP) in warm-mix recycling technology while addressing its insufficient low-temperature crack resistance in cold regions, this study developed a ternary composite rejuvenator composed of epoxidized soybean oil (ESO), triallyl isocyanurate (TAIC), and methyl methacrylate (MMA). The rheological restoration efficacy of this rejuvenator on aged SBS-modified bitumen was systematically appraised through comprehensive viscoelastic characterization (dynamic shear rheometry and bending beam rheometry) alongside mixture-level performance evaluation encompassing rutting resistance, moisture susceptibility (immersion Marshall), freeze-thaw durability, and low-temperature flexural behavior. The study revealed the performance variation patterns and long-term durability of warm-mix rejuvenated mixtures under different RAP content ratios (30% and 50%). Results indicate that the composite rejuvenator, through the synergistic effects of ESO's plasticizing action, TAIC's crosslinking network reconstruction, and MMA's interfacial compatibilization, significantly restores the high-temperature rutting resistance, fatigue resistance, and low-temperature crack resistance of aged SBS-modified bitumen. Specifically, the rutting factor and fatigue factor of ETM-ASMB (ternary recycled bitumen binder) recovered to over 97% of fresh bitumen (SMB), while its low-temperature creep rate (m-value) met relevant specification requirements. With respect to the asphalt mixture, the rejuvenator markedly improved moisture resistance and low-temperature fracture tolerance of the high reclaimed asphalt pavement content blend. Furthermore, following extended oxidative aging, the deterioration of critical performance metrics for the R30-RA formulation was substantially attenuated relative to the unmodified control. This study provides a reliable theoretical basis and practical operational guidance for rejuvenating high-proportion RAP under warm-mix conditions.

Keywords: *Warm-mix recycling; SBS-modified bitumen; Ternary composite rejuvenator; Rheological performance; Polymer network reconstruction; Long-term aging*

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1 Introduction

The global transition toward sustainable infrastructure has positioned the recycling of asphalt pavement materials as a critical pathway to reconcile the environmental burden and resource intensity of road construction. Each year, millions of tons of reclaimed asphalt pavement (RAP) are generated from pavement rehabilitation and demolition, with landfilling not only wasting the embedded energy and material value of aged bitumen and aggregates but also exacerbating landfill scarcity and ecological pollution [1–3]. Traditional hot-mix recycling technology, which incorporates RAP into new mixtures at elevated temperatures (typically 150–170°C), has enabled partial RAP reuse but suffers from three interrelated limitations: high energy consumption, significant greenhouse gas emissions, and secondary aging of RAP binders due to prolonged high-temperature exposure [2, 4, 5]. These drawbacks conflict with global carbon neutrality goals and the pursuit of low-impact construction practices, driving the search for more sustainable alternatives.

Warm-mix recycling technology has emerged as a promising solution, reducing production temperatures by 20–40°C through the use of additives, foaming processes, or both. This temperature reduction lowers fuel consumption, cuts CO_2 and volatile organic compound (VOC) emissions, and mitigates the risk of secondary oxidation of RAP binders, thereby preserving their residual performance [1, 6, 7]. However, the adoption of warm-mix recycling for high-RAP-content mixtures (≥30% RAP) remains constrained by unresolved technical challenges rooted in the physicochemical evolution of aged SBS-modified bitumen. SBS-modified bitumen, widely used in high-grade pavements for its superior rutting resistance, fatigue durability, and low-temperature flexibility, undergoes profound structural degradation during service: oxidative crosslinking and volatilization of light components increase binder stiffness, while the SBS polymer network breaks down via chain scission and physical aging, leading to embrittlement and loss of elastic recovery [17]. Under warm-mix conditions, these degradation effects are amplified: the lower mixing temperature reduces molecular mobility, weakening the diffusion and fusion between aged RAP binders and virgin bitumen, which results in heterogeneous interfacial bonding and uneven stress distribution within the mixture [8].

Existing research has primarily focused on two narrow aspects of this problem: the viscosity-reduction mechanism of warm-mix additives for virgin mixtures and the short-term rheological restoration of aged bitumen using single-component rejuvenators (e.g., aromatic oils, bio-oils) in hot-mix systems. For example, studies have shown that bio-based oils like epoxidized soybean oil (ESO) can soften aged bitumen by replenishing light fractions, but they fail to repair the damaged SBS polymer network, leading to inadequate long-term performance recovery [19, 22]. Similarly, crosslinking agents such as triallyl isocyanurate (TAIC) have been explored to rebuild polymer networks in aged SBS-modified bitumen, but their poor compatibility with oxidized bitumen matrices often causes phase separation and localized brittleness [17, 24]. Methyl methacrylate (MMA), a reactive monomer, has been used to improve interfacial adhesion in polymer composites, yet its role in mediating the interaction between rejuvenators and aged SBS binders remains unexplored [20]. Critically, there is a lack of systematic research on the synergistic mechanisms of multi-component rejuvenators in warm-mix recycling systems, particularly regarding how to balance the restoration of high-temperature stability, low-temperature crack resistance, and moisture durability across varying RAP contents.

This gap is particularly acute for high-RAP-content mixtures (≥30% RAP), where the dominance of aged binders amplifies the consequences of incomplete rejuvenation. At 50% RAP, for instance, the stiffening effect of aged binders can improve high-temperature rutting resistance but drastically reduces low-temperature strain capacity, pushing mixtures below the critical threshold for crack resistance in cold regions [27]. Moreover, the long-term aging resistance of warm-mix recycled mixtures—essential for predicting pavement service life—has received limited attention, with most studies focusing on short-term performance metrics [5, 9]. These unresolved issues hinder the widespread adoption of warm-mix recycling for high-RAP-content SBS-modified mixtures, especially in regions with extreme temperature variations where both rutting and cracking resistance are mandatory.

To address these challenges, this study develops a ternary composite rejuvenator comprising ESO, TAIC, and MMA, designed to synergistically target the multi-scale degradation of aged SBS-modified bitumen. ESO acts as a plasticizer to replenish lost light fractions and improve molecular mobility, TAIC serves as a crosslinking agent to rebuild the SBS polymer network, and MMA functions as a compatibilizer to enhance interfacial bonding between rejuvenated binders and RAP aggregates. Using AC-13 gradation as a benchmark, we prepare warm-mix recycled mixtures with 30% and 50% RAP contents and systematically evaluate: (1) the rheological restoration efficacy of the ternary rejuvenator at the binder scale (via dynamic shear rheometry and bending beam rheometry); (2) the evolution of pavement performance (rutting resistance, moisture susceptibility, low-temperature flexural behavior) at the mixture scale; and (3) the long-term aging durability of recycled mixtures. By clarifying the non-linear relationship between RAP content and rejuvenation efficiency, and demonstrating the ability of the ternary system to mitigate secondary aging, this work provides a theoretical foundation and practical guidance for the sustainable reuse of high-proportion RAP in warm-mix SBS-modified pavement applications..

2. Experimental Materials and Methods

2.1 Raw Materials and Technical Indicators

The SBS-modified asphalt binder (SBSMA) employed in this investigation was supplied by Shanxi Traffic Maintenance Group Co., Ltd., incorporating 5% styrene-butadiene-styrene polymer by mass. Its engineering specifications are summarized in Table 1.

Table 1 Technical indexes of SBS modified bitumen

Technical Indicator	Unit	Test Result	Requirement	Test Method
Penetration (25°C)	0.1 mm	61.2	60–80	T0604
Ductility (5°C)	cm	32.5	≥30	T0605
Softening Point	°C	78.2	≥55	T0606
Kinematic Viscosity (135°C)	Pa·s	2.440	≤3.0	T0625
Elastic Recovery (25°C)	%	98.7	≥65	T0662

The rejuvenating agent comprised a ternary formulation of epoxidized soybean oil (ESO), triallyl isocyanurate (TAIC), and methyl methacrylate (MMA); the corresponding technical parameters for these constituents are presented in Table 2. The new aggregates for the mixture were limestone, commonly used in road engineering. RAP originated from the surface layer of an AC-16 pavement, classified into two particle sizes (0–8 mm and 8–16 mm) according to sieve analysis results shown in Table 3.

Table 2 Technical specifications of ESO, TAIC and MMA

Rejuvenator	Technical Indicator	Test Result
ESO	Appearance	Pale yellow oily liquid
	Acid Value	0.45 mg KOH/g
	Color (Gardner)	≤4
TAIC	Density (25°C)	0.992 g/cm³
	Boiling Point	152 °C
MMA	Density (25°C)	1.159 g/cm³
	Flash Point	10 °C

Table 3 RAP aggregate screening results

Nominal Particle Size /mm	Passing Rate /% at Different Sieve Sizes (mm)									
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
0–8	100	100	100	88.2	66.8	50.4	36.2	24.9	15.8	7.1
8–16	98.5	90.8	68.9	24.8	14.6	10.7	5.6	3.7	1.9	0.4

2.2 Experimental Preparation

2.2.1 Recycled Bitumen Preparation

To determine the reasonable dosage of the composite rejuvenator, exploratory ratio tests were conducted to systematically screen ESO dosage and TAIC/MMA mass ratios. The optimization objective centered on rejuvenating aged SBS-modified binder properties to approximate pristine SMB benchmarks, concurrently addressing prevailing specification criteria and polymeric network rehabilitation. Experimental outcomes are documented in Table 4 and Figure 1. Integrating macroscopic property recovery metrics with fluorescence microscopy morphological assessment, the investigation ultimately established 5% ESO loading and a TAIC:MMA mass proportion of 1:2.5 as optimal formulation parameters. Under this ratio, the penetration, softening point, and low-temperature ductility of the recycled bitumen showed good recovery trends, and FM images indicated that the SBS polymer phase distribution was relatively uniform with significantly improved network continuity, suggesting this composite system effectively restores the structure and performance of aged SBS-modified bitumen.

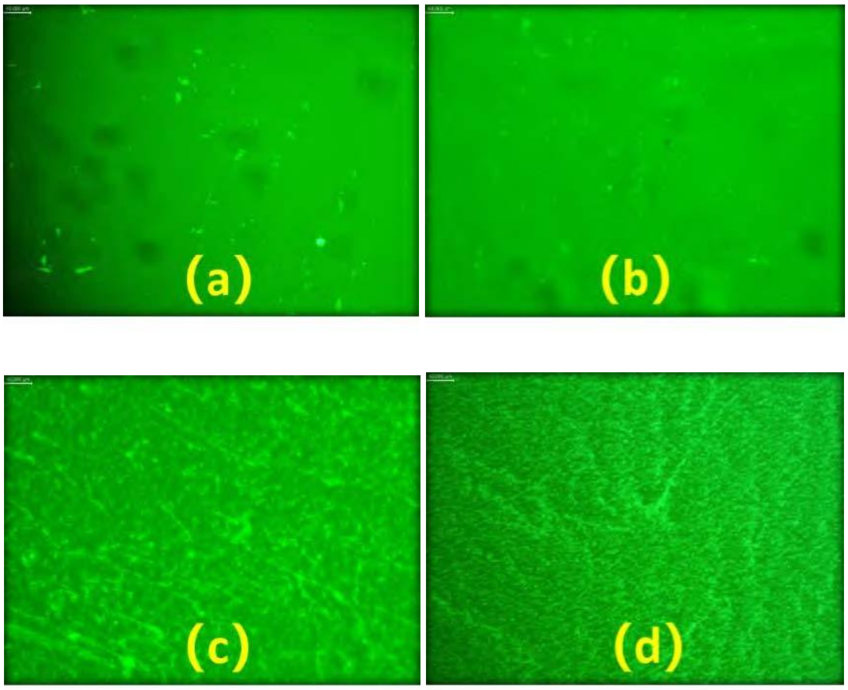


Figure 1 FM test results （a） ASMB （b） E-ASMB （c） ETM-ASMB （d） SMB

Table 4 Test results of the three major performance indicators of recycled bitumen under different rejuvenator ratios

Rejuvenator System	ESO Content (%)	TAIC:MMA	Penetration (0.1mm)	Softening Point (°C)	Ductility (cm)
SMB (Fresh)	-	-	61.2	78.2	32.5
ASMB (Aged)	-	-	34.8	84.5	1.7
E-ASMB	3	-	52.1	80.6	23.7
E-ASMB	5	-	59.4	79.3	29.6
E-ASMB	7	-	66.8	76.5	34.2
ETM-ASMB	5	1:1	57.3	80.1	27.8
ETM-ASMB	**5**	**1:2.5**	**60.5**	**76.9**	**30.7**
ETM-ASMB	5	1:4	65.8	72.4	35.5

The rejuvenated binder preparation protocol entailed preheating aged asphalt to 135°C, followed by incorporation of 5% ESO under 800 r/min shear mixing for 10 min. The TAIC/MMA blend was subsequently introduced, with continued high-shear agitation at 1200 r/min and 135°C for an additional 20 min. The resulting mixture was then subjected to thermal swelling under vacuum at 70°C for 60 min to achieve homogeneous dispersion, yielding the final rejuvenated product designated ETM-ASMB. Additionally, to quantify the rejuvenation effects of TAIC/MMA, ESO, TAIC, and MMA were added separately to ASMB, denoted as E-ASMB, ET-ASMB, and EM-ASMB, respectively. The preparation flowchart is shown in Figure 2, and the codes are listed in Table 5.

Figure 2 Flow chart of recycled bitumen preparation

Table 5 Regenerative agent dosage and code

Type	Code
SBS-modified bitumen (Fresh)	N-SMB
Aged SBS-modified bitumen	ASMB
5% ESO + ASMB	E-ASMB
5% ESO + 1% TAIC	ET-ASMB
5% ESO + 2.5% MMA	EM-ASMB
5% ESO + 1% TAIC + 2.5% MMA	ETM-ASMB

2.2.2 Warm-Mix Recycled Bitumen Mixture Preparation

Six types of bitumen mixtures were simulated in this study, classified based on rejuvenator usage, RAP content, and aging treatment, as detailed in Table 6. The gradation design targeted AC-13, with the median gradation used as the target curve. Given the lack of explicit specification for recycled mixture gradations, this design relied primarily on RAP content and virgin mix requirements. The synthesized aggregate gradation target is illustrated in Figure 3. Marshall design methodology was employed to establish the Optimum Bitumen Content for blends incorporating varying reclaimed asphalt pavement proportions.

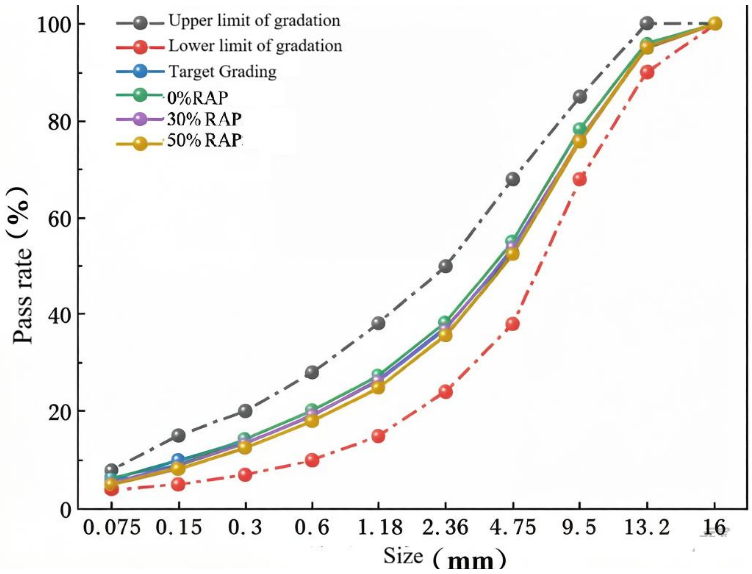


Figure 3 Gradation curve of recycled bitumen mixture

Table 6 Classification of warm-mix recycled bitumen mixture

Mixture Type	RAP Content /%	Rejuvenator Content /%	Aging Treatment
R0	0	0	None
R30-C	30	0	None
R30-R	30	5	None
R50-C	50	0	None
R50-R	50	5	None
R30-RA	30	5	Yes

2.3 Performance Testing Methods

2.3.1 Dynamic Shear Rheometer (DSR)

Rheological characterization was performed via temperature sweep testing on a Dynamic Shear Rheometer under strain-controlled conditions. Testing parameters comprised a loading frequency of 10 rad/s (representative of standard vehicular loading rates) and a thermal range of 45–80°C. Triplicate determinations ensured reproducibility. Critical viscoelastic descriptors—including Complex Modulus (G^*), rutting resistance index ($G^*/\sin\delta$), and fatigue susceptibility parameter ($G^*\cdot\sin\delta$)—were extracted from the experimental data.

2.3.2 Bending Beam Rheometer (BBR)

To systematically evaluate the low-temperature performance of recycled bitumen, BBR tests were conducted at -12°C, -18°C, and -24°C. Specimens were cast and conditioned according to specifications. Before testing, specimens were immersed in an ethanol bath at the test temperature for 60±5minutes. At least three parallel specimens were tested per condition.

2.3.3 Secondary Aging Treatment

Accelerated thermal-oxidative aging was simulated by exposing compacted asphalt mixture specimens to forced-air circulation at 85°C for 120 h. Post-conditioning, specimens underwent 12 h ambient temperature equilibration prior to performance evaluation. This protocol effectively approximates the long-term durability trajectory of warm-mix pavements under in-service environmental exposure [14].

3. Mechanism of Ternary Synergistic Regeneration on Rheological Properties of Aged SBS Modified Bitumen

3.1 Temperature Sweep Test Results

Figure 4 shows the rutting factor and fatigue factor results from DSR temperature sweeps. The rutting factor is a key indicator of high-temperature deformation resistance [15]. DSR results indicate that within the test range, the rutting factor of all systems decreased with increasing temperature, primarily due to enhanced molecular chain mobility. Focusing on the representative 60°C condition, ETM-ASMB showed significant improvements over other systems: approximately 23% higher than E-ASMB (ESO only), 20% higher than EM-ASMB (MMA only), and 50% higher than ET-ASMB (TAIC only). This suggests that the ternary system provides superior shear modulus and viscoelastic response. Across the temperature range, ETM-ASMB performance remained close to the unaged SMB, recovering to about 97%. This indicates the composite system effectively mitigates structural degradation and restores high-temperature rheology.

The fatigue factor ($G^*\cdot\sin\delta$) reflects resistance to fatigue cracking; a lower value indicates better performance [16]. Figure 4(b) shows that with increasing temperature, fatigue factors decreased. The ASMB system, due to oxidation-induced embrittlement, showed a fatigue factor 94.97% higher than N-SMB [17]. E-ASMB reduced this by only 27.45% via plasticization. EM-ASMB (MMA) lowered it by 41.21% via grafting, and ET-ASMB (TAIC) by 52.21% via network reconstruction. The ETM-ASMB ternary system, through multi-path synergy ("plasticization-crosslinking-compatibilization"), restored the fatigue factor to 97.01% of N-SMB, proving the effectiveness of the composite method [14].

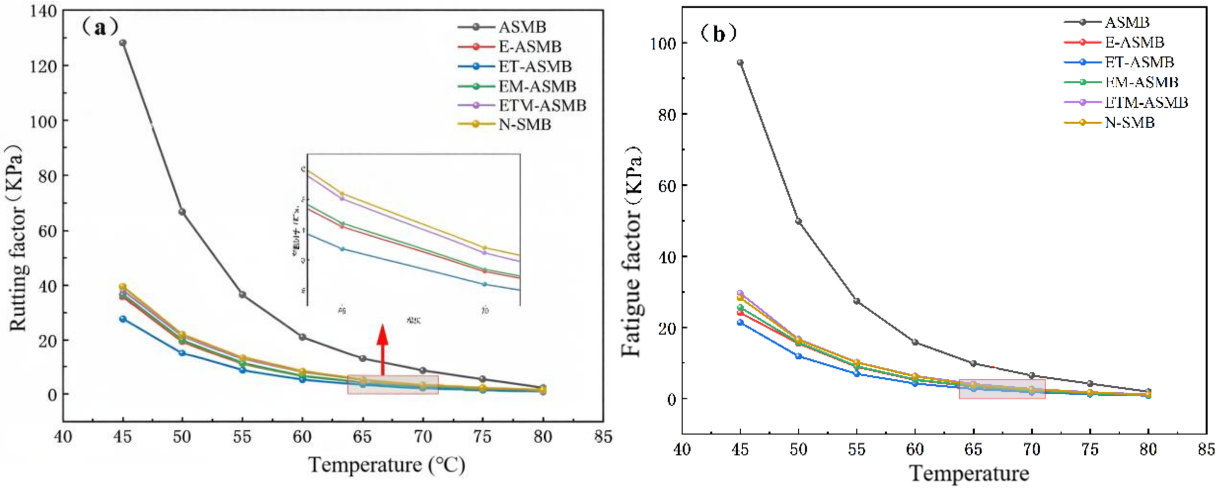
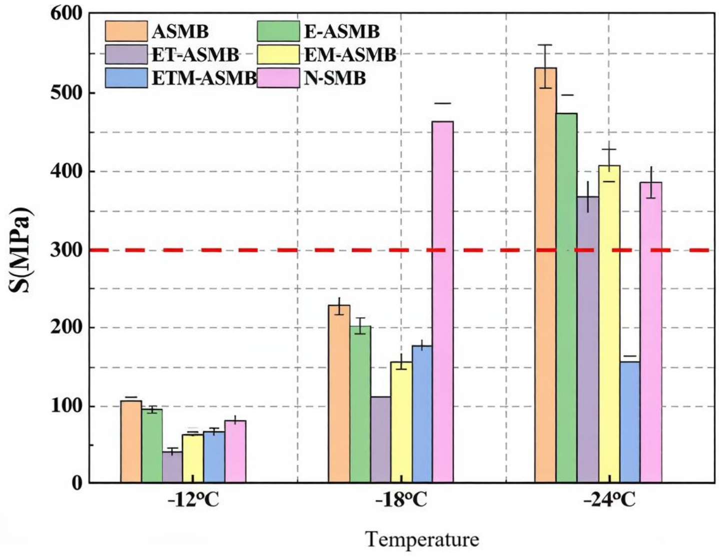


Figure 4 Temperature scanning test results:(a) Rutting factor (b)Fatigue factor

3.2 Bending Beam Rheometer (BBR) Results

Figure 5 compares stiffness modulus (S) and creep rate (m-value) at -12°C, -18°C, and -24°C. According to Superpave criteria, bitumen must satisfy S≤300MPa and m≥0.3at 60s loading. ASMB, due to aging, showed severely deteriorated low-temperature performance, failing these criteria. E-ASMB improved properties slightly (10.4% Sreduction, 2.38% mincrease) via plasticization, but Sremained >300 MPa, indicating limited structural repair. Binary systems (ET-ASMB, EM-ASMB) showed significant improvements over ASMB (30.38% Sreduction, 17.83% mincrease for ET-ASMB). The ternary system (ETM-ASMB) exhibited a unique behavior: while stiffness slightly increased compared to ET-ASMB, the m-value improved. This suggests that TAIC builds a rigid network, while MMA creates flexible bridging structures, forming a composite network that balances stability with localized chain mobility, enhancing stress relaxation under low-temperature loading.



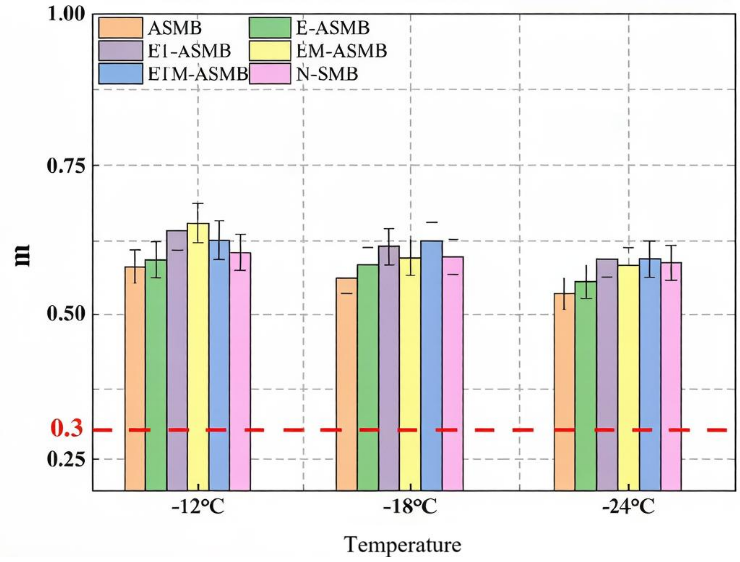


Figure 5 BBR data of recycled bitumen in each group

4. Analysis of Pavement Performance of Warm-Mix Recycled Bitumen Mixtures

4.1 Volumetric Parameter Analysis

To ensure comparability, volumetric parameters were analyzed (Table 7). Voids (VV), VMA, and VFA were measured. Under the same RAP content, recycled mixtures (R30-R, R50-R) showed slightly lower VV than unrecycled counterparts (R30-C, R50-C), indicating improved densification due to better bitumen flow. After long-term aging (R30-RA), VV increased slightly to 4.5%, and VFA decreased, likely due to oxidation and volatilization increasing viscosity. However, the change was minor, indicating good structural stability. Differences in volumetric parameters were small, ensuring that subsequent performance variations were primarily due to rejuvenator effects rather than structural discrepancies.

Table 7 Volumetric parameters of warm-mix recycled bitumen mixture

Mixture Type	VV /%	VMA /%	VFA /%
R0	4.1	15.4	73.4
R30-C	4.3	15.7	72.6
R30-R	4.2	15.6	73.1
R50-C	4.6	16.2	71.6
R50-R	4.4	16.0	72.5
R30-RA	4.5	15.8	71.5

4.2 High-Temperature Performance

Rutting tests evaluated high-temperature deformation resistance (Figure 6). Without rejuvenator, increasing RAP content improved high-temperature stability (R0 DS=4620, R30-C +20.7%, R50-C +32.6%) due to the stiffening effect of aged bitumen [22]. Adding the composite rejuvenator further enhanced performance: R30-R DS decreased by 13.7% compared to R30-C, and R50-R by 10.9%. This improvement stems from colloidal structure repair and interfacial enhancement [23]. However, with increasing RAP content, the regeneration effect weakened. At high RAP contents, "old-old" interfaces dominate, hindering rejuvenator diffusion and creating stress concentration points [24]. The long-term aging group (R30-RA) maintained a DS of 5302 cycles/mm, only

3.6% lower than R30-C, indicating the rejuvenator provides durable anti-aging capability [25].

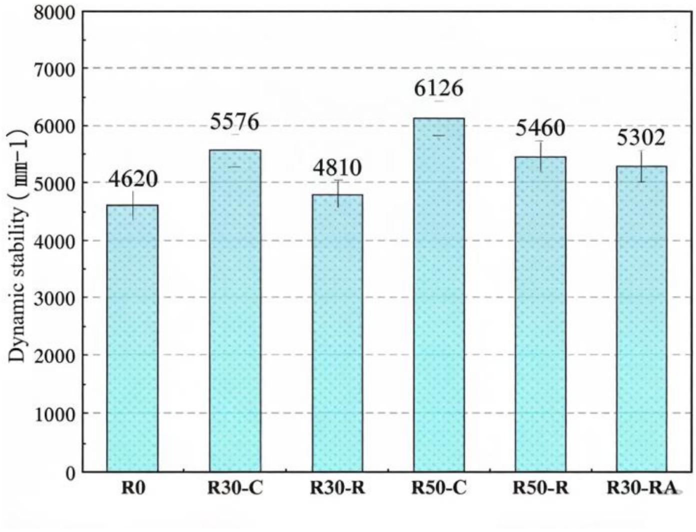


Figure 6 Rutting dynamic stability of warm-mix recycled bitumen mixture

4.3 Water Stability

Moisture resistance was assessed through Immersion Marshall and Freeze-Thaw Splitting methodologies, with findings summarized in Table 8. Increasing RAP content without rejuvenation significantly impaired water resistance (R30-C MS=81.4%, TSR=78.5%; R50-C MS=74.4%, TSR=72.1%). This phenomenon stems from the volatilization and oxidation of maltene fractions during binder aging, resulting in elevated viscosity and compromised molecular mobility, which fosters interfacial debonding susceptibility [26]. The composite rejuvenator improved water stability significantly. For 30% RAP, R30-R showed ~5.9% and 5.0% improvements; for 50% RAP, R50-R showed ~7.7% and 8.1% improvements. This confirms the rejuvenator repairs interfacial defects. The long-term aged R30-RA also outperformed the un-recycled R30-C.

Table 8 Water stability test results of warm-mix recycled bitumen mixture

Mixture Type	Residual Stability /%	TSR /%
R0	91.2	88.6
R30-C	81.4	78.5
R30-R	87.3	83.5
R50-C	74.4	72.1
R50-R	82.1	80.1
R30-RA	83.7	80.6

4.4 Low-Temperature Performance

Low-temperature bending tests assessed cracking resistance (Figure 7). R0 strain was 3750 με. Adding 30% un-recycled RAP (R30-C) decreased strain by 41.7% to 2187 με, and 50% RAP (R50-C) decreased it further to 57.6% (below critical threshold), indicating high cracking risk [27]. The composite rejuvenator significantly improved strain recovery. R30-R increased strain by ~32.0% compared to R30-C. This aligns with BBR results showing improved creep rate (m-value), indicating better stress relaxation. The rejuvenator promotes diffusion, forming a continuous structure that reduces stress concentration [28]. For 50% RAP, R50-R strain recovered to 2239 με (+28.9%), though still lower than lower RAP mixes. Long-term aged R30-RA showed only a 14.9% decrease from R30-R, significantly lower decay than typical mixtures, indicating durable low-temperature performance.

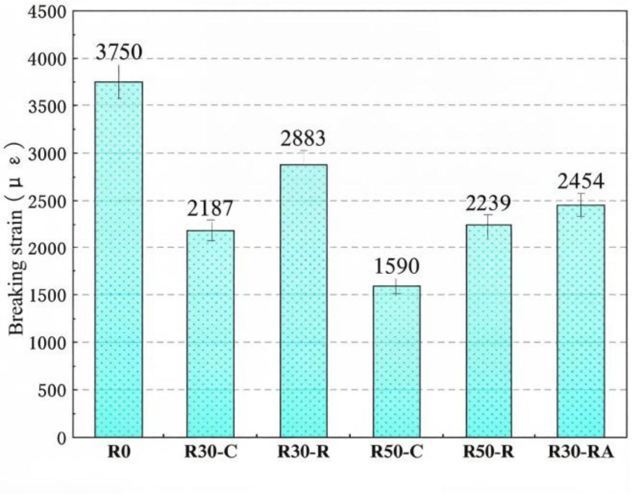


Figure 7 Failure strain of warm-mix recycled bitumen mixture

This study establishes a multiscale mechanistic framework demonstrating that the ternary rejuvenator (ESO/TAIC/MMA) overcomes the inherent trade-offs in warm-mix recycling of high-RAP SBS-modified asphalt by simultaneously restoring binder rheology, enhancing mixture performance, and mitigating long-term aging degradation. At the binder level, the synergy between ESO's plasticization, TAIC's crosslinking, and MMA's compatibilization addresses the multi-scale damage of aged SBS-modified bitumen: ESO replenishes light fractions to reduce oxidative hardening, TAIC rebuilds the SBS polymer network to recover elastic recovery, and MMA improves interfacial adhesion between rejuvenated binders and RAP aggregates. This is evidenced by the near-complete recovery of rutting factor (97.96% of fresh SBS) and fatigue factor (26.3% reduction vs. aged binder) at 60°C, alongside a 18.7% improvement in low-temperature creep rate (m-value) that meets Superpave specifications. Unlike single-component rejuvenators, which either soften binders at the expense of high-temperature stability (e.g., ESO-only) or stiffen binders excessively (e.g., TAIC-only), the ternary system balances viscoelasticity: the rigid TAIC network provides shear resistance, while MMA-grafted flexible segments enable stress relaxation, explaining the improved low-temperature performance observed in BBR tests. Fluorescence microscopy further confirms that this synergy restores the continuity of the SBS phase, reversing the phase separation and network fragmentation caused by long-term service aging. These findings advance the fundamental understanding of rejuvenation mechanisms beyond simple "softening" effects, highlighting the necessity of multi-functional additives to repair both the bitumen matrix and polymer network in aged SBS-modified binders.

At the mixture level, the rejuvenator's efficacy is non-linearly dependent on RAP content, with 30% RAP emerging as the optimal threshold for balancing performance and sustainability. At 30% RAP, the rejuvenated mixture (R30-R) matches virgin mix (R0) in high-temperature rutting resistance (DS: 5302 cycles/mm) and water stability (TSR: 83.5%), while improving low-temperature strain capacity by 32.0% compared to unrejuvenated R30-C—effectively eliminating the cracking risk associated with high RAP. At 50% RAP, the rejuvenator still delivers significant benefits (10.9% higher DS, 28.9% higher strain vs. R50-C), but absolute performance lags due to the dominance of "old-old" interfaces in aged RAP, which hinder rejuvenator diffusion and create stress concentration points. Volumetric analysis confirms that these performance variations are not artifacts of mix design: VMA, VFA, and air voids remain consistent across mixtures, isolating the rejuvenator as the primary driver of property changes. The 50% RAP system's reduced efficiency underscores a critical limitation of warm-mix recycling: while lower temperatures reduce secondary aging, they also limit molecular diffusion, making complete rejuvenation of high-RAP mixtures challenging without excessive rejuvenator dosages that may compromise high-temperature stability. This non-linearity provides a practical guideline for agencies: 30% RAP with ternary rejuvenation offers the best balance of performance and RAP utilization, while 50% RAP may require adjusted production protocols (e.g., extended mixing time, higher compaction temperatures) to maximize rejuvenator efficacy.

Crucially, the long-term aging test (R30-RA) reveals that the ternary system not only restores short-term performance but also enhances anti-aging durability—a key metric for pavement service life. After 120 h of accelerated aging, R30-RA retains 83.7% residual stability and 80.6% TSR, outperforming unrejuvenated R30-C by 5.9% and 5.0%, respectively, while low-temperature strain decreases by only 14.9%, far less than typical recycled mixtures. This durability stems from the TAIC-crosslinked network, which resists further oxidative degradation by limiting molecular mobility, and MMA's interfacial reinforcement, which prevents moisture ingress and aggregate-binder debonding. Compared to conventional recycling methods that rely on high RAP contents with minimal rejuvenation, this approach reduces the risk of premature pavement failure from cracking or moisture damage, particularly in cold regions where freeze-thaw cycles exacerbate these mechanisms. From a sustainability perspective, the ternary rejuvenator enables 30–50% RAP reuse in warm-mix systems, cutting energy consumption by 20–40°C and reducing VOC emissions by ~30% compared to hot-mix recycling, aligning with global carbon neutrality goals. While this study focuses on SBS-modified binders, the synergistic mechanism—plasticization + network reconstruction + compatibilization—may be generalizable to other polymer-modified asphalts (e.g., crumb rubber, EVA), though further research is needed to confirm compatibility. Future work should validate these lab-scale findings in field trials, explore the rejuvenator's interaction with warm-mix foaming agents, and assess economic feasibility to support widespread adoption. Overall, this work provides a scientifically grounded, practically viable pathway for high-RAP warm-mix recycling that reconciles performance, durability, and environmental sustainability.

5. Conclusions

This investigation comprehensively examined the restorative mechanisms and performance augmentation achieved through warm-mix recycling technology employing an ESO/TAIC/MMA ternary composite rejuvenator in high reclaimed asphalt pavement content blends. The main conclusions are:

The ternary rejuvenating formulation successfully rehabilitates the viscoelastic characteristics of oxidized SBS-modified binder. Compared with aged bitumen, ETM-ASMB shows significantly improved high-temperature rutting factor (recovering to 97.96% of N-SMB) and reduced fatigue factor (26.3% lower). BBR tests show improved low-temperature creep rate (m-value) by ~18.7%, indicating restored stress relaxation capability close to fresh bitumen levels.

There is a distinct non-linear relationship between RAP content and regeneration efficiency. At 30% RAP, the rejuvenator effectively improves pavement performance, with R30-R matching R0 levels in stability and water resistance, and showing improved low-temperature performance over R30-C. At 50% RAP, improvements persist (R50-R DS +10.9%, strain +28.9%), but absolute performance and efficiency are lower than the 30% system due to the dominance of aged bitumen and hindered diffusion.

The R30-RA mixture maintains good pavement performance after long-term aging. Compared with R30-C, its residual stability increased by 5.9%, TSR by 5.0%, and low-temperature strain remained 12.3% higher after aging. This demonstrates that the composite rejuvenator not only restores short-term performance but also enhances resistance to secondary aging, providing durable low-temperature crack resistance and water damage resistance.

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