Comparative Study on the Low-Temperature Performance of Recycled Asphalt Treated with WR and WR/SBS Blends

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Abstract: The widespread adoption of reclaimed asphalt pavement (RAP) presents a sustainable solution to material scarcity in modern road construction; however, the degradation of low-temperature performance in aged binders remains a critical obstacle. Warm-mix rejuvenators (WRs) have emerged as viable modifiers for restoring binder ductility, yet their standalone efficacy under extreme cold conditions is often limited. This study investigates the potential of a direct-addition SBS modifier (DASBS), used in conjunction with WR, to enhance the low-temperature crack resistance of recycled asphalt systems. Three formulations—aged asphalt (A), WR-rejuvenated asphalt (WR+A), and WR/SBS-modified asphalt (WR/SBS+A)—were evaluated using Bending Beam Rheometer (BBR) testing at −12 °C, −18 °C, and −24 °C. The analysis focused on creep stiffness (S) and creep rate (m) as performance indicators. Results revealed that although WR+A showed moderate improvements, it failed to meet SHRP performance thresholds at −24 °C. In contrast, the WR/SBS+A formulation exhibited substantial reductions in S and corresponding increases in m across all temperatures, achieving full compliance with SHRP criteria. These enhancements were attributed to the synergistic mechanism between WR and DASBS: WR replenished light fractions and improved molecular mobility, while DASBS enabled in-situ polymer network formation that strengthened elastic recovery and reduced thermal brittleness. The findings confirm the effectiveness of DASBS as a direct-addition modifier and demonstrate its strategic relevance for cold-region pavement engineering requiring robust low-temperature durability.

Keywords: Recycled Asphalt Pavement; Warm-Mix Rejuvenator; Direct-Addition SBS; Low-Temperature Performance; Bending Beam Rheometer

1.Introduction

The transition of China's road construction sector from an expansion-driven phase to one centered on preservation and maintenance has amplified the strategic importance of recycling reclaimed asphalt pavement (RAP). As a resource-efficient and cost-effective solution, asphalt recycling has garnered increasing attention in both research and engineering practice. Extensive studies have demonstrated that aged asphalt undergoes severe volatility loss and oxidation, leading to densification of its internal structure and heightened brittleness, which substantially increases its susceptibility to crack propagation under low-temperature conditions [1-3].

Enhancing the ductility and flexibility of aged asphalt binders has long relied on the application of rejuvenators as restorative additives. Among these, warm-mix rejuvenators (WRs)—recognized for their low construction temperatures, reduced volatility, and superior diffusion capacity—have emerged as a promising class of modifiers in recent years [4,5]. Despite such advantages, recent investigations suggest that WRs alone often fail to restore the low-temperature performance of severely aged asphalt to a satisfactory level—particularly under extreme cold conditions (e.g., below −18 °C), where premature cracking risks remain significant [6-8].

In light of the performance limitations of WRs under extreme thermal conditions, researchers have explored the incorporation of styrene–butadiene–styrene (SBS) modifiers into recycled asphalt systems [9,10]. This strategy aims to leverage the elastic recovery and crack resistance provided by SBS while preserving the construction and energy-saving advantages of WR-based formulations. Among emerging techniques, the dry-process direct-injection of SBS (DISBS) has attracted growing attention due to its simplified handling, improved field compatibility, and reduced blending requirements. Although the operational benefits of DISBS are well-recognized, its functional contribution to the low-temperature performance of WR-treated binders has not yet been systematically verified. These gaps in current knowledge underscore the need for systematic evaluation of the mechanical performance of WR/SBS-modified binders under low-temperature conditions.

This study centers on evaluating the low-temperature crack resistance of recycled asphalt binders through a structured comparison among three formulations: untreated aged asphalt, WR-regenerated asphalt, and a composite system incorporating WR with a dry-injected SBS modifier. The experimental framework involved Bending Beam Rheometer (BBR) testing at −12 °C, −18 °C, and −24 °C, with a particular focus on two rheological indices—creep stiffness (S) and creep rate (m)—which, taken together, provide a quantitative basis for assessing thermal flexibility and stress relaxation behavior. By systematically benchmarking these formulations under severe thermal loading, the study seeks to establish an informed technical reference for the design and implementation of modified recycled asphalt in cold-region pavements.

2.Experiment

2.1 Materials

The base binder utilized in this study was a 70# penetration-grade asphalt, procured from Qilu Petrochemical Corporation, which served as the foundational material for subsequent modification and aging treatments. Aged asphalt was prepared through a two-stage laboratory simulation that replicated both short-term and long-term oxidative processes: the first involved exposure to 163 ± 0.5 °C in a Rolling Thin Film Oven (RTFOT) for 85 minutes, simulating thermal conditions during mixing and compaction; the second subjected the binder to 100 °C and 2.1 MPa in a Pressure Aging Vessel (PAV) for 20 hours to mimic in-service oxidative aging.

The warm-mix rejuvenator (WR), synthesized in-house for this research, comprised a low-viscosity mineral oil base, a surface-active warm-mix additive, and a targeted penetrant, collectively formulated to optimize flow characteristics, enhance thermal resistance, and facilitate molecular diffusion at reduced temperatures. Performance evaluations—summarized in Table 1—demonstrated that the WR satisfies the criteria specified for Type RA-I rejuvenators, characterized in particular by its elevated light-fraction content and thermal stability under high-temperature conditions.

Table 1. Performance Evaluations of WR

Test		Results	Standard
Density / (g/cm^3)		1.007	Measured value
Viscosity (60 °C) / Pa·s		62	50 ~ 175
Flashpoint /°C		243	≥220
Saturate content / %		18	≤30
Aromatic content / %		63	Measured value
after TFOT	Viscosity ratio	1.22	≤3
	Quality change/ %	-0.698	-4 ~ 4

The direct-addition SBS modifier (DASBS), synthesized in-house for this study, was specifically designed for in-line incorporation during asphalt mixing, without the need for pre-swelling or prior wet blending. Compared to conventional linear SBS, the DASBS exhibits a shorter molecular backbone and reduced molecular weight, along with a high melt index—features that collectively promote rapid dispersion, accelerated swelling, and the in-situ formation of a polymeric network within the asphalt matrix under warm-mix conditions.

Enhanced miscibility with the asphalt binder, partly attributed to synergistic interactions with the penetrant components of WR, enables DASBS to integrate efficiently into the mixing process. This streamlined compatibility not only reduces the time and energy required for shear development but also obviates the need for auxiliary compatibilizers or stabilizers. A summary of the characterization parameters is provided in Table 2.

Table 2. Performance Evaluations of DASBS

Index	Single particle mass/g	SBS content/%	Ash content/%	Melting index/(g/min)
DISBS	0.1	70	2	10
Indicators	≤0.3	≥50	≤5.0	≥5.0

2.2 Sample Preparation

A comparative experimental framework was developed to evaluate the influence of warm-mix rejuvenator (WR), both independently and in conjunction with the direct-addition SBS modifier (DASBS), on the low-temperature performance of recycled asphalt binders. The study design comprised three groups, as detailed in Table 3.

Table 3. Experiment Design Scheme

Group	Material	Label
Reference group	Aged asphalt	A
Experimental groups	8% WR + Aged asphalt	WR+A
	8% WR + 7% DISBS + Aged asphalt	WR/SBS+A

All three formulations were based on aged asphalt as the control matrix, with WR or WR+DASBS added for rejuvenation and modification, respectively. The preparation process for each sample is detailed below:

- Rejuvenation phase (WR+A): The aged asphalt was first heated to 135 °C to achieve fluidity. Subsequently, 8% WR (by weight) was incorporated and mixed at 350 rpm for 5 minutes, followed by continuous low-speed stirring for an additional 30 minutes to ensure uniform dispersion.
- Modification phase (WR/SBS+A only): Building upon the WR-rejuvenated binder, the mixture was heated to 145–150 °C. DASBS was then added at 7% by weight, subjected to low-speed pre-mixing for 5 minutes, and subsequently processed through high-shear mixing at 4000 rpm for 30 minutes. A final development stage was performed at 155 °C and 750 rpm for 60 minutes to complete network formation.
- Specimen casting: All binders were cast into standard beams (127 mm × 12.7 mm × 6.35 mm) in accordance with AASHTO T313 specifications, for subsequent BBR testing.

The only distinction between the WR+A and WR/SBS+A groups lies in the incorporation of DASBS and its associated development procedure, with all other variables—including WR dosage and processing temperature—held constant. This controlled setup ensures that performance differences can be confidently attributed to the presence of DASBS, thereby enabling a focused assessment of its role within warm-recycled asphalt systems.

2.3.Performance Testing

The low-temperature properties of the prepared binders were evaluated using a Bending Beam Rheometer (BBR) system, following the procedures outlined in AASHTO T313-12. Testing was conducted at three temperature levels—−12 °C, −18 °C, and −24 °C—to simulate progressively colder environmental conditions. Two rheological parameters were recorded:

- Creep stiffness (S, MPa): reflecting the binder's resistance to initial deformation; lower values indicate greater flexibility.
- Creep rate (m-value): quantifying the binder's stress relaxation capability; higher values suggest improved crack resistance under sustained loading.

As defined by SHRP specifications, binders are considered suitable for cold-climate service when they simultaneously satisfy $S \le 300$ MPa and $m \ge 0.300$ at the given test temperature. In this study, the temperature-dependent evolution of these two indices was used to characterize the thermal flexibility of the WR- and DASBS-modified systems. Particular attention was given to identifying the performance limits of WR alone under extreme cold and assessing the extent to which DASBS improves low-temperature ductility within a direct-addition framework. These results provide a mechanistic foundation for the performance comparisons presented in the following section.

3.Results and Discussion

Creep stiffness (S) and creep rate (m), as measured by the Bending Beam Rheometer (BBR), serve as critical indicators for evaluating the low-temperature cracking resistance of asphalt binders. While a lower S value signifies enhanced flexibility, a higher m-value reflects improved stress relaxation capacity under sustained thermal loading. Figure 1 presents the comparative performance of five asphalt formulations, where aged asphalt exhibits the highest S and lowest m values across all temperature conditions. This decline in performance is widely recognized as a consequence of thermo-oxidative aging, during which the volatilization of light components and the polymerization of smaller molecular fractions lead to the accumulation of asphaltenes and increased macromolecular content. These structural changes reduce segmental mobility and severely hinder thermal relaxation behavior, rendering the binder more susceptible to cracking under low-temperature shrinkage stress [11].

The incorporation of 8% WR into aged asphalt results in measurable improvements in both rheological indices. Specifically, S values decrease while m-values increase across all test temperatures, indicating a partial restoration of the binder's flexibility and stress accommodation capacity. This effect is largely attributed to the presence of light, low-molecular-weight constituents in the WR formulation, which act as molecular diluents. These components replenish the lost volatiles, reduce the glass transition range, and enhance intermolecular spacing—thereby facilitating improved molecular mobility and mitigating the embrittlement effects of aging. Nevertheless, at −24 °C, the WR+A binder fails to satisfy SHRP criteria ($S \leq 300$ MPa, $m \geq 0.300$), suggesting a critical limitation in its applicability under extreme cold conditions.

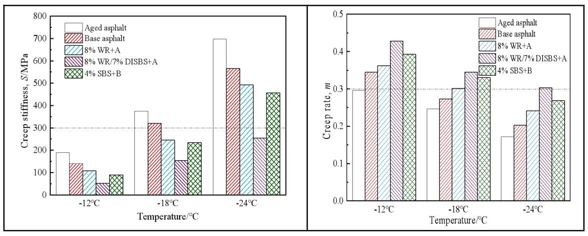

Figure 1. BBR Test Results of Different Asphalt Types: (A) Test Results for *S* Value; (B) Test Results for *M* Value.

This performance deficit can be primarily ascribed to two factors. First, the diffusion kinetics of WR slow markedly at sub-zero temperatures, which compromises its ability to uniformly permeate the aged asphalt matrix. Second, in the absence of an elastic reinforcement phase, the WR+A system lacks the internal microstructural framework necessary to redistribute localized stress. As a result, stress concentrations accumulate in the brittle matrix, promoting microcrack initiation and propagation. These findings suggest that WR alone, although effective in moderately cold climates, may not ensure long-term performance in regions exposed to extreme freeze–thaw cycling.

In contrast, the WR/SBS+A formulation exhibits significantly improved low-temperature behavior across all temperature levels tested. Relative to WR+A, the S values of WR/SBS+A decrease by 52.2%, 37.4%, and 48.4% at −12 °C, −18 °C, and −24 °C, respectively, while the corresponding m-values increase by 18.2%, 14.6%, and 25.7%. Notably, WR/SBS+A is the only formulation in this study that simultaneously meets both SHRP performance thresholds at all three temperature points, highlighting its robust adaptability to severe thermal stress environments.

The superior performance of WR/SBS+A can be attributed to the synergistic interaction between WR and the direct-addition SBS modifier (DASBS). While WR contributes to restoring flowability and molecular mobility through light-fraction replenishment, DASBS engages in rapid swelling and interfacial absorption, followed by the in-situ formation of a three-dimensional polymer network within the asphalt matrix. This network enhances network entanglement and introduces elastic domains capable of dissipating thermal stress and delaying crack nucleation. The resulting microstructure demonstrates greater cohesion, elasticity, and resistance to segmental decoupling under low temperatures.

Importantly, given that the only difference between WR+A and WR/SBS+A lies in the inclusion of DASBS—while all other parameters were held constant—the enhanced performance can be confidently attributed to the presence of the modifier. These findings not only validate the efficacy of DASBS as a direct-addition modifier under warm-mix conditions, but also underscore its practical value in cold-region pavement applications where reliable crack resistance is critical for extending service life.

4. Conclusion

This study examined the low-temperature performance of recycled asphalt binders incorporating a warm-mix rejuvenator (WR), both independently and in conjunction with a direct-addition SBS modifier (DASBS), using BBR-derived creep stiffness (S) and creep rate (m) as diagnostic indicators. While WR alone provided moderate improvements in flexibility and thermal stress accommodation, its effectiveness proved insufficient under extreme low-temperature conditions (−24 °C), where the binder failed to satisfy established performance thresholds.

In contrast, the DASBS-modified formulation consistently exhibited enhanced rheological behavior across all temperatures evaluated. Substantial reductions in S and concurrent increases in m underscored the system's improved capacity to resist thermal cracking, particularly under severe environmental loading. These enhancements can be mechanistically linked to the dual contribution of WR-facilitated molecular replenishment and DASBS-induced in-situ network formation, which together elevate both molecular mobility and elastic recovery.

Given the controlled nature of the experimental design—wherein all parameters aside from the inclusion of DASBS were held constant—the observed performance differentials can be unequivocally attributed to the presence of the modifier. The outcomes of this investigation reinforce the functional validity of direct-addition SBS modification in warm-recycled systems and further articulate its strategic value in cold-region pavement engineering, where preserving low-temperature integrity poses an ongoing challenge.

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