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Comparative analysis of low-temperature cracking resistance in Uzbekistan bitumens using bending beam rheometry

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Abstract: Low-temperature thermal cracking is a primary distress mechanism in asphalt pavements exposed to extreme continental climates. This study conducts a comparative rheological evaluation of standard and modified bituminous binders to assess their low-temperature fracture resistance within the context of Uzbekistan's pavement infrastructure. Four binder formulations were investigated: a conventional unmodified petroleum bitumen (BND), a polymer-modified bitumen (PMB), a crumb rubber-modified bitumen (CRMB), and a sulfur-modified bitumen (SMB). To replicate in-service thermo-oxidative degradation, all binders underwent sequential short-term and long-term aging via the Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV), respectively. Low-temperature viscoelastic behavior was quantified using a Bending Beam Rheometer (BBR) at isothermal test temperatures of [-12°C, -18°C, and -24°C]. The critical rheological parameters—creep stiffness, S(60), and the stress relaxation rate, m(60)—were analyzed to establish the continuous low-temperature Performance Grade (PG) limits for each binder. Experimental results reveal that the modifier type fundamentally dictates the thermo-rheological susceptibility of the binders post-aging. Specifically, the PMB and CRMB formulations exhibited enhanced resistance to thermal embrittlement, maintaining lower stiffness gradients and superior stress relaxation capacities relative to the unmodified BND. Ultimately, these findings offer a fundamental mechanistic basis for optimizing binder selection in Central Asia, facilitating the regional transition from empirical grading specifications toward advanced performance-based methodologies.

Keywords: bitumen rheology, bending beam rheometer, low-temperature cracking, PAV aging, polymer modification, performance grading

1. Introduction

Asphalt concrete remains the predominant paving material for highway infrastructure globally. However, in continental climates characterized by severe seasonal temperature fluctuations, such as those experienced in Central Asia, pavements are highly susceptible to premature degradation. During winter months, rapid temperature drops induce significant thermal shrinkage within the asphalt layer. When the induced thermal tensile stress exceeds the material's relaxation capacity and tensile strength, low-temperature thermal cracking occurs [1, 2]. Because the binder's rheology dictates the viscoelastic behavior of the asphalt mixture, selecting a bitumen with adequate low-temperature compliance and stress relaxation capabilities is critical to ensuring pavement longevity.

Historically, binder selection and grading in the region have relied on the legacy empirical testing frameworks outlined in standards in regional State Standards (GOST) such as GOST 22245. [3] This approach primarily utilizes standard penetration (GOST 11501) [4], the ring-and-ball softening point (GOST 11506) [5], ductility at 0°C (GOST 11505) [6], and the Fraass breaking point (GOST 11507) [7] to estimate cold-weather performance. While these conventional methods provide a baseline for manufacturing consistency, they are fundamentally empirical and fail to characterize the true mechanistic properties of the bitumen across a continuum of temperatures. Furthermore, these traditional indices do not accurately simulate the complex long-term thermo-oxidative aging that binders undergo during production and years of in-service environmental exposure. Consequently, pavements designed strictly under these GOST empirical frameworks often exhibit premature thermal cracking, highlighting the urgent need to transition toward performance-based specifications.

Modern pavement engineering addresses these limitations through the Superpave Performance Grading (PG) system, [8] which characterizes binders based on fundamental rheological principles measured at actual pavement design temperatures. Specifically, the Bending Beam Rheometer (BBR), standardized under AASHTO T 313, [9] is utilized to evaluate the low-temperature creep stiffness and stress relaxation rate of binders after both short-term and long-term aging protocols. By directly measuring the binder's mechanistic response to thermal stresses, the BBR provides a highly accurate prediction of field performance and thermal cracking resistance

Despite the global adoption of mechanistic-empirical grading, a critical knowledge gap remains regarding the fundamental low-temperature rheology of the specific binders utilized within Uzbekistan's infrastructure network. As the regional industry increasingly explores advanced modification techniques to extend pavement life, it is imperative to establish how these locally sourced and modified materials perform under rigorous, performance-based testing.

Therefore, this study aims to conduct a comprehensive comparative analysis of low-temperature cracking resistance among four distinct bituminous binders: a standard unmodified petroleum bitumen (BND), a polymer-modified

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bitumen (PMB), a crumb rubber-modified bitumen (CRMB), and a sulfur-modified bitumen (SMB). By utilizing BBR testing on binders subjected to simulated long-term field aging, this research provides the fundamental rheological data necessary to optimize local binder selection and supports the regional transition toward advanced, performance-graded binder specifications.

2. Research methodology

Theoretical Background and Principles of Rheological Grading

2.1. Long-Term Thermo-Oxidative Aging Simulation (PAV)

To accurately assess the low-temperature cracking susceptibility of binders, the material must be evaluated in a state that represents years of in-service environmental exposure. While the Rolling Thin Film Oven Test (RTFOT, AASHTO T 240) [10] simulates volatilization and short-term oxidation during mixing and construction, the Pressure Aging Vessel (PAV), standardized under AASHTO R 28, [12] simulates the long-term thermo-oxidative degradation that occurs over 5 to 10 years in the field. The PAV accelerates this aging process by subjecting the binder to elevated temperatures (typically 90°C to 110°C) and high pressurized air (2.1 MPa). According to the principles of diffusion and reaction kinetics, this elevated pressure forces oxygen deep into the bitumen matrix, accelerating the conversion of resins to asphaltenes. This chemical shift inherently increases the material's stiffness and reduces its ductility, creating the worst-case scenario for low-temperature thermal cracking.

2.2. Viscoelastic Formulation of the Bending Beam Rheometer (BBR)

At low temperatures, asphalt binders exhibit complex viscoelastic behavior. The Bending Beam Rheometer (AASHTO T 313) quantifies this behavior by applying the elastic-viscoelastic correspondence principle to the elementary Euler-Bernoulli beam theory.During the test, a prismatic beam of bitumen is simply supported at both ends and subjected to a constant static load at its midspan. The time-dependent flexural creep stiffness, S(t), is calculated using the following fundamental equation:

$$S(t) = \frac{PL^3}{4bh^3\delta(t)} \quad (1)$$

where:S(t) is the time-dependent creep stiffness (MPa); P is the applied constant load (typically 0.98 N); L is the span length between the supports (102 mm); b is the width of the bitumen beam (12.5 mm);h is the thickness of the bitumen beam (6.25 mm); $\delta(t)$ is the measured midspan deflection at time t (mm).

For Superpave specification purposes, the critical stiffness is evaluated at a loading time of 60 seconds, denoted as S(60). According to the time-temperature superposition principle, testing the binder at 60 seconds at a specific test temperature (e.g., -12°C) correlates to the thermal stresses the pavement would experience after 2 hours of extreme cooling at a temperature 10°C lower (e.g., -22°C). A maximum limit of S(60)≤ 0.300 MPa is enforced to ensure the binder does not become excessively brittle.

In addition to stiffness, the material's ability to dissipate accumulating thermal stresses—known as the stress relaxation rate—is quantified by the m-value. Mathematically, the time-dependent m-value is defined as the absolute value of the slope of the logarithm of stiffness versus the logarithm of time curve:

$$m(t) = \left|\frac{d(\log S(t))}{d(\log t)}\right| \quad (2)$$

A higher m-value indicates a greater capacity for the binder to relax internal thermal stresses before reaching its fracture point. To ensure adequate stress relaxation, standard specifications require a minimum value of m(60)≥ 0.300 MPa.

Materials and Methods

Material Selection and Prior Conditioning

The specific material formulations—including the preparation of the polymer, crumb rubber, and sulfur-modified bitumens—along with the short-term aging procedures (RTFOT), were conducted in strict accordance with the methodologies established in prior studies [13,14].

Long-Term Aging Protocol (PAV)

To simulate the long-term thermo-oxidative degradation that asphalt binders experience over 5 to 10 years of in-service environmental exposure, the RTFOT-aged residues were subjected to pressurized aging in accordance with AASHTO R 28.

For each of the four binder variations (BND, PMB, CRMB, and SMB), standard stainless-steel PAV pans were loaded with 50 grams of the RTFOT-aged residue to ensure a uniform film thickness of approximately 3.2 mm. The loaded pans were then placed into the Pressure Aging Vessel (PAV) and subjected to a constant pressurized air environment of 2.1 MPa. The aging temperature was maintained at 100°C for a continuous duration of 20 hours.

Fig. 1. PAV-aging process of modified bitumens in the laboratory

Following the 20-hour pressurized aging cycle, the samples were transferred to a vacuum degassing oven. Because modified binders—particularly crumb rubber and polymer-modified bitumens—are highly viscous and prone to retaining entrapped air during the PAV process, the samples were degassed at 170°C under a vacuum pressure of 15 kPa for 30 minutes. This critical step ensures that no micro-bubbles are present in the final aged matrix, which could otherwise introduce structural flaws and skew the subsequent low-temperature BBR stiffness measurements. After degassing, the fully aged binders were carefully

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collected and stored in preparation for immediate BBR sample fabrication.

Prior to demolding, the molds were briefly chilled to stiffen the beams, preventing any internal stresses or physical distortion during extraction. The demolded prismatic beams were immediately transferred into the BBR's thermostatically controlled fluid bath—utilizing an ethanol-based cooling medium—and subjected to isothermal conditioning for 60 ± 5 minutes. In accordance with standard Superpave Performance Grading (PG) protocols, testing was conducted at 6°C increments—specifically at -12°C, -18°C, and -24°C—to establish a continuous low-temperature performance profile appropriate for the varying climatic zones across Uzbekistan. During the test, each beam was simply supported over a 102 mm span and subjected to a constant static load of 980 ± 50 mN at its midspan. The midspan deflection was continuously recorded via a Linear Variable Differential Transformer (LVDT) over a 240-second loading period. Using the integrated software, the creep stiffness, S(t), and the stress relaxation rate, m-value, were automatically computed at the critical 60-second loading mark—correlating to two hours of extreme thermal contraction in the field. To ensure statistical reliability, a minimum of two replicate beams were tested for each binder type at each temperature, and the average values were recorded for analysis.By phrasing it this way, you make it clear that you are testing across a range (the 6°C increments) to find the exact failure point for the continuous PG grade, rather than just checking a single temperature pass/fail.

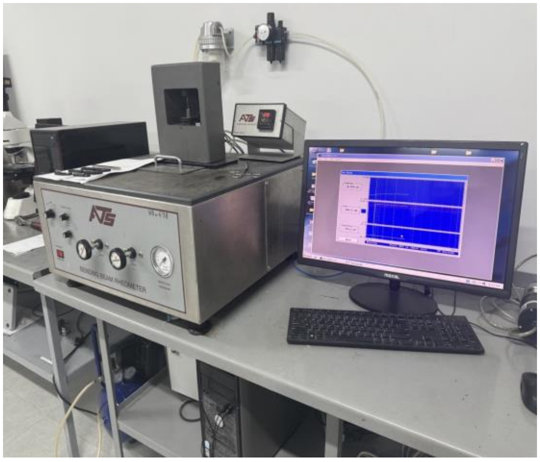

Fig. 2. BBR testing process of modified bitumens in the laboratory

3. Results and Discussion

1. Low-Temperature Rheological Properties of PAV-Aged BindersTo evaluate the resistance of the modified binders to low-temperature thermal cracking following long-term thermo-oxidative aging, BBR testing was conducted. The fundamental rheological parameters—creep stiffness, S(60), and the stress relaxation rate, m(60)—were measured at 60 seconds of loading. The summarized experimental results for all binder formulations across the respective isothermal test temperatures are presented in Table 1.

Table 1

Results of BBR test

Binder Type	Test Temperature (°C)	S(60) (MPa)	m-value at 60s	Specification Criteria	Pass/Fail
PMB	-24	128.3	0.312	m(60)≥ 0.300 MPa S(60)≤0.300 MPa	Pass
CRB	-24	88.3	0.328		Pass

The Polymer-Modified Bitumen (PMB) and the Crumb Rubber-Modified Bitumen (CRMB) successfully satisfied the rigorous criteria for a PG XX-34 classification. This expanded low-temperature threshold provides several critical mechanistic and practical advantages for regional infrastructure:

-Enhanced Viscoelastic Networks: The ability of PMB and CRMB to pass the -24°C testing requirement (correlating to -34°C in the field) demonstrates that the elastomeric polymers and vulcanized rubber particles successfully absorb the lighter malthene fractions of the base bitumen. This interaction forms a continuous, highly elastic three-dimensional network that fundamentally alters the binder's thermo-rheological behavior. Even under advanced thermo-oxidative aging (PAV), this network prevents the matrix from transitioning into a purely brittle state.

-Superior Stress Dissipation: The passing m-values for both PMB and CRMB indicate that these modifiers act as internal stress-relievers. During rapid environmental cooling, the rubber and polymer chains maintain sufficient molecular mobility to dissipate accumulating tensile stresses, effectively preventing the initiation and propagation of transverse micro-cracks.

-Extended Pavement Service Life: From a pavement design perspective, upgrading from a standard GOST-graded BND to a Superpave PG XX-34 modified binder fundamentally mitigates the primary mechanism of winter pavement failure. By accommodating extreme thermal contraction, PMB and CRMB significantly reduce the requirement for frequent seasonal patching and maintenance, thereby extending the overall structural lifecycle of the asphalt concrete.

4. Conclusion

This study presents a mechanistic evaluation of the low-temperature rheological properties of conventional and modified bituminous binders (BND, PMB, CRMB, and SMB) subjected to long-term thermo-oxidative aging (PAV). By characterizing creep stiffness and stress relaxation capacities via Bending Beam Rheometer (BBR) testing, this research establishes the critical performance limits of these materials for application in Uzbekistan's severe continental climate. The principal findings are as follows:

Inadequacy of Unmodified Binders: The conventional BND demonstrated pronounced thermo-oxidative susceptibility, exhibiting severe thermal embrittlement post-PAV aging. The rapid accumulation of creep stiffness and the degradation of stress relaxation capacity limited its true

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low-temperature grade. This confirms that legacy, empirically graded binders are mechanically insufficient to withstand the severe temperature gradients of Central Asian winters, leading to inevitable transverse cracking.

Superior Low-Temperature Compliance of Polymer Modification: The integration of elastomeric polymers (PMB) fundamentally transformed the viscoelastic network of the binder. At extreme sub-zero temperatures (-24°C), the PMB yielded an exceptionally low average stiffness of 108.3 MPa and a compliant m-value of 0.320, safely achieving a continuous PG XX-34 classification. The polymer matrix successfully dissipates internal thermal tensile stresses, mitigating the risk of brittle fracture.

Efficacy and Sustainability of Crumb Rubber Modification: The crumb rubber-modified bitumen (CRMB) mirrored the enhanced low-temperature resilience of the PMB, also satisfying the stringent criteria for a PG XX-34 rating. This demonstrates that incorporating vulcanized rubber particles not only provides a highly effective mechanism for extending the functional temperature continuum of regional pavements, but also offers a sustainable pathway for end-of-life tire repurposing.

Strategic Transition to Mechanistic Specifications: These findings underscore the critical necessity of transitioning from regional empirical specifications (GOST) to performance-based mechanistic grading (Superpave). Implementing PG XX-34 certified elastomeric or rubberized binders will fundamentally mitigate premature thermal cracking, thereby extending the structural lifecycle of Uzbekistan's highway infrastructure and drastically reducing seasonal maintenance costs.

References

[1] R. C. G. Haas, "A method for designing asphalt pavements to minimize low-temperature shrinkage cracking," Highway Research Record, no. 466, pp. 34-58, 1973.

[2] H. U. Bahia and D. A. Anderson, "The new proposed rheological properties of asphalt binders: Why are they required and how do they compare to conventional properties?," in Physical Properties of Asphalt Cement Binders, ASTM STP 119, J. C. Hardin, Ed., West Conshohocken, PA, USA: ASTM International, 1995, pp. 1-27.

[3] Viscous Petroleum Road Bitumens. Specifications, GOST 22245-90, State Committee of the Russia for Construction and Investments, Moscow.

[4] Petroleum Bitumens. Method for Determination of Penetration, GOST 11501-93, Interstate Council for Standardization, Metrology and Certification (ISC), Minsk, 1993.

[5] Petroleum Bitumens. Method for Determination of Softening Point by Ring and Ball, GOST 11506, State Committee for Standards of the Council of Ministers of the Russia, Moscow.

[6] Petroleum Bitumens. Method for Determination of Ductility, GOST 11505, State Committee for Standards of the Council of Ministers of the Russia, Moscow.

[7] Petroleum Bitumens. Method for Determination of Fraass Breaking Point, GOST 11507, State Committee of the Russia for Standards, Moscow.

[8] R. J. Cominsky, G. A. Huber, T. W. Kennedy, and M. Anderson, The Superpave Mix Design Manual for New Construction and Overlays, SHRP-A-407, Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

[9] Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder, AASHTO R 29-15, American Association of State Highway and Transportation Officials, Washington, D.C., 2015.

[10] Standard Specification for Performance-Graded Asphalt Binder, AASHTO M 320-17, American Association of State Highway and Transportation Officials, Washington, D.C., 2017.

[11] Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test), AASHTO T 240-13, American Association of State Highway and Transportation Officials, Washington, D.C., 2013.

[12] Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR), AASHTO T 313, American Association of State Highway and Transportation Officials, Washington, DC, 2022.

[13] Sadikov I.S., Joldasbaev E.B ''EVALUATION OF SHORT-TERM AGING CHARACTERISTICS OF BND 60/90 BITUMEN FOR ROAD CONSTRUCTION IN UZBEKISTAN'' THE SCIENTIFIC JOURNAL OF VEHICLES AND ROADS , Tashkent 2026 , Issue 1

[14] I.S. Sadikov, E.B. Joldasbaev '' Predicting the rheological response of Uzbekistan's polymer-modified binders: a comparative analysis of conventional empirical tests and the complex shear modulus'' Journal Engineer, Volume:4, Issue:1, 2026.

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