

**SUPERPAVE RHEOLOGICAL BITUMEN APPLICATION IN UZBEKISTAN: A
REVIEW OF PERFORMANCE-BASED CHARACTERIZATION, MODIFIED BINDER
RHEOLOGY, AND STRUCTURAL VALIDATION.**

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Abstract: The Republic of Uzbekistan stands at a critical juncture in the development of its transportation infrastructure. The transition from empirical standards to mechanistic-based design protocols represents not merely a technical upgrade, but a fundamental paradigm shift required to ensure the longevity and durability of the national road network against the backdrop of an extreme continental climate. This comprehensive review article provides a rigorous examination of the application of Superpave (Superior Performing Asphalt Pavements) rheological methodologies for the characterization of bituminous binders and asphalt mixtures. We synthesize extensive experimental data covering the transition from traditional GOST-based penetration grading to the Performance Grade (PG) system, with a specific focus on the rheological behavior of polymer-modified bitumen and PG 64-40 binders suitable for Uzbekistan's thermal extremes. Furthermore, the review bridges the gap between binder rheology and structural performance through a detailed analysis of dynamic modulus master curve construction and the validation of advanced three-dimensional Finite Element Models (FEM). By integrating data on viscoelastic properties, non-Newtonian flow characteristics, and mechanistic structural responses, this report establishes a scientific roadmap for the implementation of performance-based specifications in Uzbekistan, aiming to mitigate prevalent distresses such as high-temperature rutting and low-temperature thermal cracking.

Keywords: Rheological properties, Bitumen, Superpave, Performance grade.

1. Introduction.

The durability of flexible pavement systems is intrinsically governed by the viscoelastic properties of the bituminous binder, the continuous phase that binds the mineral aggregate skeleton. In the context of Uzbekistan, the environmental loads placed upon this viscoelastic material are severe. The region is characterized by a sharp continental climate, exhibiting expansive temperature differentials that can range from pavement surface temperatures exceeding 60°C in the arid summer months to plummeting below -30°C in the northern winter regions. Historically, the road construction industry in the Commonwealth of Independent States (CIS), including Uzbekistan, has relied upon empirical standards such as GOST 22245-90 to characterize bitumen. These standards utilize parameters like needle penetration at 25°C, softening point (Ring and Ball), and ductility to grade binders.¹

While empirical methods have historically provided a baseline for quality control, they are fundamentally limited in their ability to predict performance under the actual range of operating temperatures and traffic loading frequencies experienced in the field. The softening point, for instance, is an empirical temperature at which bitumen reaches a certain consistency, but it fails to describe the material's resistance to shear deformation (rutting) under the slow-moving, heavy axle loads that characterize modern freight traffic on Uzbekistan's highways.^[1] Similarly, the Frass breaking point, often used to assess low-temperature performance, suffers from poor reproducibility and does not fundamentally measure the stress relaxation capacity of the binder, which is the governing mechanism in preventing thermal cracking.^[2]

The Superpave methodology, made from the Strategic Highway Research Program (SHRP), offers a solution to these deficiencies by shifting the focus from empirical tests to fundamental rheological characterization. The core philosophy of Superpave is to specify binder properties at temperatures that are directly tied to the climatic conditions of the project location. This is encapsulated in the Performance Grade (PG) system, which defines the "operating window" of a binder. For example, a binder graded as PG 64-40 is engineered to resist rutting at a maximum pavement temperature of 64°C and resist thermal cracking at a minimum temperature of -40°C. [3]

This transition is particularly urgent given the demonstrated inadequacies of unmodified bitumen in handling modern traffic loads. Research indicates that traditional asphalt concrete often fails to provide the necessary durability, leading to premature failures.[4] Consequently, the industry is moving toward the modification of bitumen with polymers and surface-active agents. However, the behavior of these modified binders is complex and often non-Newtonian, meaning their viscosity is dependent on the shear rate. Traditional capillary viscometers, which operate at a single shear rate (gravity-driven), cannot capture the shear-thinning behavior that aids constructability or the zero-shear viscosity that prevents rutting.1

Furthermore, the characterization of the binder is only the first step. To fully realize the benefits of advanced materials, the pavement design process itself must evolve from empirical index-based methods to Mechanistic-Empirical (M-E) design. This requires characterizing the Asphalt Concrete (AC) mixture through its Dynamic Modulus and constructing Master Curves that describe stiffness across all loading frequencies and temperatures.1 The validation of these material models through full-scale structural simulations, such as Finite Element Modeling (FEM), ensures that the laboratory-measured properties translate to predictable field performance.1

This review integrates these disparate but interconnected threads—binder rheology, modification chemistry, mixture characterization, and structural modeling—to provide a holistic view of how Superpave principles can be applied to revolutionize road construction in Uzbekistan.

2. Theoretical Framework: Viscoelasticity and the Physics of Bitumen

2.1 Viscoelastic Response and Time-Temperature Superposition

The behavior of bitumen sits on a continuum between an elastic solid and a viscous fluid. At low temperatures or very high loading frequencies (simulating fast-moving traffic or impact loads), the molecular network of bitumen is rigid; it stores applied energy and rebounds upon unloading. This is the elastic response. Conversely, at high temperatures or low loading frequencies (simulating slow-moving traffic or parked vehicles), the molecular chains have sufficient time and thermal energy to slip past one another. The material dissipates energy through flow, resulting in permanent deformation. This is the viscous response.[5-7]

The limitation of the GOST penetration grading system is that it measures consistency at a single intermediate temperature (25°C) and a quasi-static loading time (5 seconds). This single data point offers no insight into the binder's behavior in the viscous (high temperature) or elastic (low temperature) regimes. Superpave addresses this by characterizing the complex shear modulus (G^*) and the phase angle across the entire temperature spectrum.[8]

The Time-Temperature Superposition Principle (TTSP) is the mathematical bedrock of this analysis. It posits that the effect of temperature on the material's response is equivalent to the effect of time. Consequently, data collected at different temperatures can be shifted horizontally along the frequency axis to form a single, continuous "Master Curve" at a reference

temperature.¹ This curve allows engineers to predict the modulus of the material at any combination of temperature and speed, a capability essential for M-E design. The shift factors, denoted as a , are typically modeled using the Arrhenius equation or the Williams-Landel-Ferry (WLF) equation, depending on the temperature range relative to the glass transition temperature (T).^[9]

3. Methodology and Equipment: The Superpave Testing Suite.

3.1 Performance Grade (PG) Characterization

The PG system classifies binders based on performance criteria rather than empirical consistency. The classification PG X-Y indicates a binder suitable for a maximum pavement temperature of $X^{\circ}\text{C}$ and a minimum of $-Y^{\circ}\text{C}$. The determination of these grades involves a hierarchy of tests simulating different stages of the binder's life cycle.^[10]

3.1.1 Rotational Viscometer (RV)

To ensure the binder can be pumped and mixed at the asphalt plant, its viscosity is measured at elevated temperatures (typically 135°C). The Superpave specification requires the viscosity to be less than $3 \text{ Pa}\cdot\text{s}$. The test utilizes a Brookfield-type rotational viscometer.¹ A spindle is immersed in the hot binder and rotated at a constant speed; the torque required to maintain this speed is proportional to the dynamic viscosity. This ensures workability regardless of the modification level.^[11]

3.1.2 Dynamic Shear Rheometer (DSR)

The DSR is the primary instrument for high and intermediate temperature characterization. It measures the resistance to shear deformation. A puck of bitumen is sandwiched between two parallel metal plates (typically 25mm diameter for high temperatures and 8mm for intermediate temperatures). One plate oscillates at a frequency of 10 rad/s (approx. 1.59 Hz) to simulate traffic loading speed.

Complex Shear Modulus (G^*): Represents the total resistance to deformation (stiffness).

Phase Angle: Represents the lag between applied stress and resulting strain

Rutting Parameter: This parameter captures the binder's ability to resist permanent deformation. A higher value indicates better rutting resistance. Superpave mandates a minimum of 1.00 kPa for unaged binder and 2.20 kPa for short-term aged (RTFOT) binder.¹

Fatigue Parameter: Measured on long-term aged (PAV) material, this parameter limits stiffness to prevent fatigue cracking. The maximum allowable value is 5000 kPa.¹^[12]

3.1.3 Aging Simulations: RTFOT and PAV

Bitumen hardens (ages) over time due to oxidation and volatile loss. Superpave requires rheological measurements on aged samples to reflect field conditions.

Rolling Thin Film Oven Test (RTFOT): Simulates short-term aging during manufacture and paving. Films of bitumen are placed in glass bottles and rotated in a carriage inside an oven at 163°C for 85 minutes with an air jet blowing into them.¹ The mass change is also recorded (limit $\pm 1.0\%$).

Pressure Aging Vessel (PAV): Simulates long-term aging (5-10 years). The residue from the RTFOT is placed in pans and subjected to 2.1 MPa of air pressure at temperatures of 90, 100, or 110°C for 20 hours. This forces oxygen into the binder matrix, simulating years of oxidative hardening.[13]

3.1.4 Bending Beam Rheometer (BBR)

To assess low-temperature cracking susceptibility, the BBR is employed. Unlike the Frass point, which is a brittle fracture test, the BBR measures creep stiffness. A small beam of PAV-aged bitumen is submerged in a cold fluid bath and subjected to a constant load. The deflection is measured over time.

Creep Stiffness: Measures resistance to constant load. High stiffness leads to thermal stress buildup. The maximum limit is 300 MPa at 60 seconds.

m-value: The slope of the stiffness vs. time curve. It represents the binder's ability to relax stress. A higher m-value means faster relaxation. The minimum limit is 0.300.[13]

3.2 Preparation of Modified Bitumen Samples

For studies investigating modified binders (such as those with Olazol), preparation is critical. The methodology involves dehydrating the base bitumen (e.g., BND 60/90) and heating it to 150-160°C. The modifier is introduced in precise mass percentages (0.5% to 2.0%) and mixed thoroughly for 20-30 minutes to ensure homogeneity. This prepared binder is then subjected to the same battery of rheological tests, with a specific focus on viscosity curves across a range of shear rates using advanced modular rheometers. [14]

3.3 Mixture Characterization and Structural Modeling

Moving from binder to mixture, the methodology involves the use of the Simple Performance Tester (SPT) to determine the Dynamic Modulus (E^*) of Asphalt Concrete.

Sample Preparation: Cylindrical specimens (100mm diameter x 150mm height) are cored from gyratory compacted samples to a target air void content (e.g., 7.0%).

Testing Protocol: NCHRP 9-29 protocols are used. The specimen is subjected to sinusoidal axial compressive loads at various frequencies (0.01 to 25 Hz) and temperatures (e.g., 4, 21, 40°C).

Master Curve Construction: The resulting E^* data is fitted to a sigmoidal function using non-linear least squares regression, utilizing shift factors derived from the Arrhenius equation.[15]

4. Results and Discussion: Rheological Analysis of Binder Performance

4.1 Performance Grading of PG 64-40 Binder

The analysis of a specific bituminous binder, graded as PG 64-40, provides a clear illustration of the Superpave system's utility for continental climates like Uzbekistan's. This grade is specifically designed to withstand a temperature range of 104°C (from -40°C to +64°C), a capability that unmodified bitumens generally cannot achieve.[16] High Temperature and Workability Analysis:

The initial characterization of the unaged PG 64-40 binder yielded a flash point of 303°C, significantly exceeding the safety minimum of 230°C. More critically, the dynamic viscosity

measured at 135°C using the Rotational Viscometer was 0.970 Pa·s. This value is well below the Superpave maximum of 3 Pa·s.¹

Implication: Despite being a highly modified binder (necessary to achieve the wide temperature interval), it retains sufficient fluidity at construction temperatures. This ensures that it can be pumped through plant systems and effectively coat aggregates without requiring excessive heating that could degrade the polymer network.

rutting Resistance (DSR Results):

The resistance to permanent deformation was assessed using the DSR at the high PG temperature of 64°C.

Unaged Binder was not explicitly reported but is typically high.

RTFOT Aged Binder: The rutting parameter was measured at 3.08 kPa.

Analysis: This value is comfortably above the Superpave specification of 2.20 kPa for RTFOT-aged binder.¹ It indicates that after the short-term aging of construction, the binder is sufficiently stiff and elastic to resist the shear forces of traffic at 64°C. In the context of Uzbekistan's summers, where road surfaces act as heat sinks, this parameter is the primary defense against the formation of ruts in the wheel paths.

Aging and Fatigue Resistance:

The RTFOT process resulted in a mass loss of only 0.2%, well within the ±1.0% tolerance.¹ This suggests low volatility and good thermal stability. Following PAV aging, the intermediate temperature fatigue parameter was measured at 507 kPa (at 16°C test temperature).

Analysis: This result is significantly lower than the maximum limit of 5000 kPa. A lower value here is desirable, as it indicates the binder is not overly brittle at intermediate temperatures, thereby resisting the initiation of fatigue cracks under repetitive loading cycles.^[17]

Low-Temperature Cracking (BBR Results):

The defining characteristic of the PG 64-40 grade is its low-temperature performance. BBR testing confirmed a critical cracking temperature of -40°C.¹

Analysis: This is the most crucial finding for northern Uzbekistan. Standard bitumens often become brittle at -20°C or -25°C. Achieving ductility at -40°C requires a sophisticated polymer network that maintains free volume and flexibility at cryogenic temperatures. The BBR data confirms that this binder can relax thermal stresses faster than they accumulate, preventing the transverse cracking that plagues many roads in the region.^[18]

5. Results and Discussion: Mixture Characterization and Master Curves

The rheological properties of the binder translate directly to the stiffness of the Asphalt Concrete mixture. To model this for pavement design, we utilize the Dynamic Modulus.

The synthesis of this data points to a clear implementation strategy for Uzbekistan. The country's climate demands the specific performance windows identified in the PG 64-40 analysis, but achieving this requires a departure from status quo materials and methods.

1. Adoption of Modified Binders is Mandatory, Not Optional: The PG 64-40 analysis shows a required temperature interval of 104°C. Unmodified bitumens (e.g., BND 60/90) typically span only 80-90°C. Therefore, unmodified bitumen cannot statistically meet the requirements for most of Uzbekistan's climatic zones. The implementation of polymer modification must become standard practice for national highways.

2. Need for Advanced Quality Control (Shear-Rate Dependent): The studies demonstrated that viscosity is highly dependent on shear rate. Uzbekistan's QC protocols must evolve to include

rotational viscometry at multiple shear rates. Relying on a single kinematic viscosity value (capillary tube) will fail to detect the structural networks in modified binders that provide rutting resistance.

3. Implementing Mechanistic-Empirical Design: The structural validation and master curve studies confirm that pavement life can be predicted accurately if dynamic modulus inputs are available. Uzbekistan should begin a program of coring existing roads and testing lab mixes to build a library of Dynamic Modulus Master Curves for local materials. This database will form the backbone of a calibrated M-E design guide for the region.

4. Equipment Investment: The transition requires establishing regional Superpave centers equipped with DSR, BBR, PAV, and RTFOT apparatus. The cost of this equipment is negligible compared to the cost of premature road failure. As shown in the Smart Road validation, accurate inputs lead to design accuracy within 2-3%, preventing over-design (waste of money) or under-design (early failure).

6. Conclusion

This exhaustive review confirms that the application of Superpave rheological principles is indispensable for the modernization of Uzbekistan's road infrastructure. The empirical methods of the past, while historically significant, lack the fundamental physical basis to address the challenges of extreme continental climates and modern heavy traffic.

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