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# Predicting the rheological response of Uzbekistan's polymer-modified binders: a comparative analysis of conventional empirical tests and the complex shear modulus

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**Abstract:** The transition towards performance-based pavement specifications in Central Asia is often hindered by the limited availability of advanced rheological instrumentation. This study bridges this gap by characterizing the viscoelastic performance of asphalt binders currently utilized in Uzbekistan through theoretical modeling based on routine quality control data. A comprehensive laboratory program was conducted on conventional unmodified bitumen (BND 50/70) and three complex modified binders: locally produced polymer-modified bitumen (PMB), crumb rubber modified ('Rezina') bitumen, and sulfur-extended ('Sero') bitumen. Using experimental results from Penetration, Softening Point, and Elastic Recovery tests, the Complex Shear Modulus ( $G^*$ ) and Phase Angle were estimated using the Ullidtz and Van der Poel predictive models, calibrated for the non-Newtonian behavior of modified binders. The study provides a cost-effective framework for predicting high-temperature rutting resistance, demonstrating how traditional empirical data can be transformed into fundamental rheological parameters for mechanistic-empirical pavement design in Uzbekistan's specific climatic conditions.

**Keywords:** Rheology of bitumen, complex shear modulus, phase angle, Ullidtz model, Van der Poel predictive model

## 1. Introduction

The Republic of Uzbekistan is currently undergoing a significant transformation in its transport infrastructure, driven by the "New Uzbekistan" development strategy and the need to integrate into the Central Asia Regional Economic Cooperation (CAREC) corridors. However, the country's continental climate presents a severe challenge to pavement durability. With summer ambient temperatures frequently exceeding 40°C and pavement surface temperatures reaching up to 60–70°C, asphalt concrete layers are subjected to extreme thermal loading. Under these conditions, the primary mode of pavement failure is permanent deformation (rutting).[10-13]

Recent reports from the Asian Development Bank (ADB) and local road authorities highlight that conventional unmodified bitumen (BND grades) often lacks the viscoelastic stiffness required to resist these heavy traffic loads at high temperatures. Consequently, there is an urgent industry shift towards modified binders, including Polymer-Modified Bitumen (PMB), Crumb Rubber Modified Bitumen ("Rezina"), and Sulfur-Extended Bitumen ("Sero"). While the adoption of modified binders is accelerating, the quality control (QC) infrastructure in Central Asia remains largely based on empirical standards (GOST). Conventional tests such as Penetration (at 25°C) and Ring & Ball Softening Point are effective for classifying unmodified bitumen but are increasingly criticized for their inability to predict the fundamental rheological performance of complex modified systems. Research has shown that polymers create a non-Newtonian network within the bitumen that "decouples" the relationship between empirical hardness and actual rutting resistance. For instance, a polymer-modified binder may share the same penetration value as a neat binder but exhibit vastly superior elastic recovery and stiffness at high temperatures—a distinction that simple penetration tests fail to capture. To fully characterize these materials, the global asphalt community has transitioned to performance-based specifications using the Dynamic Shear Rheometer

(DSR), which measures the Complex Shear Modulus ( $G^*$ ) and Phase Angle. Despite the clear benefits of DSR testing, the high capital cost and technical complexity of this equipment limit its availability in many routine quality control laboratories in Uzbekistan. This creates a disconnect: engineers are using advanced modified materials but assessing them with outdated empirical tools. There is a critical need for a reliable method to "bridge" this gap, allowing practitioners to estimate fundamental performance parameters ( $G^*$ ) from the routine data they already collect (Penetration, Softening Point, and Elastic Recovery). Historical research by Van der Poel (1954) and later mathematical refinements by Ullidtz (1987) established that the stiffness of bitumen could be predicted with reasonable accuracy from empirical data, provided the loading time and temperature susceptibility (Penetration Index) were known. [9-13]

While originally developed for neat bitumen, recent studies suggest that these predictive models can be calibrated for modified binders if the Elastic Recovery is incorporated to account for the phase angle deviation. This approach offers a practical, cost-effective tool for Uzbekistan's road sector, enabling the estimation of mechanistic performance without the immediate need for expensive DSR instrumentation. The primary objective of this research is to evaluate the applicability of the Ullidtz and Van der Poel predictive models for characterizing locally produced modified binders in Uzbekistan. This study analyzes the physical properties of four distinct binder types: standard BND 50/70, local Polymer-Modified Bitumen (PMB), Crumb Rubber Modified ("Rezina") Bitumen, and Sulfur-Extended ("Sero") Bitumen. Estimates the Complex Shear Modulus ( $G^*$ ) and Phase Angle using mathematical derivation from routine test results. Proposes a calibrated framework for predicting high-temperature rutting resistance in the absence of DSR testing, tailored to the specific climatic conditions of Central Asia.



## 2. Research methodology

GOSTR 52056 [1] specifies the technical conditions for road polymer-bitumen binders (PBV) based on viscous road petroleum bitumens and styrene-butadiene-styrene (SBS) block copolymers. These binders are designed for the construction, reconstruction, and repair of roads, bridges, and airfields. The classification of PBV is strictly based on the depth of needle penetration at 25°C. The standard defines specific grades: PBV 300, PBV 200, PBV 130, PBV 90, PBV 60, and PBV 40.

**Elasticity Calculation and Method.** The standard provides a specific method for determining elasticity, which measures the proportion of elastic (fully reversible) deformation. **Testing Method:** Elasticity is determined immediately after testing the sample for ductility. The molds with the ruptured samples are removed from the ductilometer and placed in a water bath at 35°C to accelerate the contraction of the samples. After 15 minutes (or once the length change is no more than 0.1 cm), the length of both parts of the sample is measured from the free end to the mold clip. The elasticity is calculated using the following formula:

$$E = \frac{(D+l)-L}{D} \cdot 100\% \quad (1)$$

Where, D-Ductility in sm, l-Length of the sample before stretching, equal to 3 cm. L-The sum of the lengths of the two parts of the sample after recovery (based on the final measurement) in sm.

The standard establishes the physical-mechanical requirements for each grade. The key indicators required for acceptance include:

- Needle Penetration (at 25°C and 0°C).
- Softening Point (Ring and Ball method), which ranges from not lower than 45°C (PBV 300) to 56°C (PBV 40).
- Fraass Breaking Point, which must be as low as -40°C for PBV 300 and -15°C for PBV 40.
- Elasticity at 25°C, which generally must be at least 85% for most grades (80% for PBV 60 and 40).
- Flash Point, which must be not lower than 220°C for softer grades and 230°C for harder grades.

Materials to evaluate the applicability of the rheological predictive models, four distinct types of asphalt binders currently used or proposed for use in Uzbekistan's road network were selected for this study.

**Neat Bitumen (BND 60/90):** A conventional unmodified binder complying with GOST 33133-2014. This serves as the control sample.

**Polymer-Modified Bitumen (PBV):** Produced by modifying the base bitumen with a Styrene-Butadiene-Styrene (SBS) copolymer. This binder is designed to meet the requirements of GOST R 52056-2003.

**Crumb Rubber Modified Bitumen ("Rezina"):** A composite binder produced by incorporating finely ground crumb rubber from recycled tires (wet process) into the base bitumen at 180°C.

**Sulfur-Extended Bitumen ("Sero"):** An experimental binder prepared by introducing technical-grade sulfur into the bitumen matrix to improve stiffness and reduce high-temperature susceptibility.

**2.2 Laboratory Testing Methods** The physical and mechanical properties of the binders were determined in accordance with the relevant Interstate Standards (GOST). To ensure international comparability, the corresponding

European (EN) and American (ASTM) standards are referenced where applicable.

The following routine empirical tests were conducted:

**Needle Penetration at 25°C:** This test measures the hardness of the bitumen. Performed in accordance with GOST 33136-2014 (Bitumens: Method for determination of needle penetration depth).

**Softening Point (Ring and Ball):** This test determines the temperature at which the bitumen reaches a specific consistency, serving as an indicator of high-temperature stability. Performed in accordance with GOST 33142-2014, harmonized with EN 1427 [3] and ASTM D36 [4] shown in Figure 1.

**Ductility at 25°C:** This measures the tensile properties and cohesion of the binder. Performed in accordance with GOST 11505-75.

**Elastic Recovery at 25°C:** For the polymer-modified samples, elastic recovery was measured to quantify the presence of the polymer network. Performed in accordance with GOST R 52056 [1] (Bitumens: Determination of elastic recovery), equivalent to EN 13398. [2]

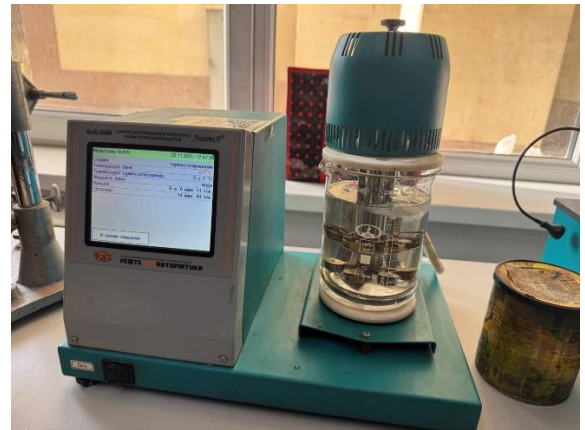


Fig. 1. Ring and Ball. Softening point test

Table 1

Results table				
Bitumen types	Softening point, °C	Penetration at 25 °C (0.1 mm).	Ductility(sm)	Elastic recovery (%)
BND 60/90	49.9	69	96	0
Polymer Bitumen	67.6	48	25	70
Rubber bitumen	57.4	63	14.24	58.9
sulfur-extended ('Sero') bitumen	54.2	87	16	0

### 3. Predictive Models.

The transition from empirical quality control to mechanistic-empirical pavement design requires the characterization of bituminous binders in terms of

fundamental rheological properties: the Complex Shear Modulus ( $G^*$ ) and Phase Angle. While the Dynamic Shear Rheometer (DSR) is the standard apparatus for obtaining these parameters, historical research has demonstrated that the rheological behavior of bitumen is intrinsically linked to its conventional consistency and temperature susceptibility. The foundational work by Van der Poel (1954) [9-12] established that the stiffness of pure bitumen behaves as a function of loading time and temperature, summarized in the widely used "Van der Poel Nomograph". However, manual interpretation of the nomograph is prone to reading errors. To integrate this relationship into computational models, Ullidtz (1987) [12-13] derived a mathematical approximation of the nomograph. This study adopts the Ullidtz analytical approach to estimate the linear viscoelastic properties of local Uzbekistan binders from routine empirical data.

### 3.2 Determination of Temperature Susceptibility (PI)

The first step in the predictive framework is to quantify the temperature sensitivity of the binder. The **Penetration Index (PI)** provides a measure of the deviation of the binder from a purely Newtonian fluid. It is calculated using the classical equation proposed by Pfeiffer and Van Doormaal (1936), which assumes a linear relationship between the logarithm of penetration and temperature:

$$PI = \frac{1952 - 500 \log(Pen_{25}) - 20T_{R\&B}}{50 \log(Pen_{25}) - T_{R\&B} - 120} \quad (2)$$

Where  $Pen_{25}$  is the needle penetration at 25°C (0.1mm).  $T_{R\&B}$  is the Ring and Ball Softening Point (°C).

### 3.3 Transformation of Loading Frequency to Time

The stiffness of viscoelastic materials is time-dependent. In DSR testing, the load is applied cyclically at a specific frequency. The Van der Poel and Ullidtz models, however, are based on loading time. To correlate the two, the angular frequency is converted to an equivalent loading time using the standard relation:

$$t = \frac{1}{\omega} = \frac{1}{2\pi f} \quad (3)$$

Where:  $t$  is the loading time (seconds),  $f$  is the frequency (Hz). Note: For standard traffic speed simulation,  $f = 1.59$  Hz (10 rad/s) is typically used.

**3.4 Prediction of Bitumen Stiffness Modulus.** Based on the computed PI and loading time  $t$ , the Bitumen Stiffness Modulus is estimated using the Ullidtz model. This empirical equation predicts the stiffness at any temperature ( $T$ ) below the softening point:

$$S_{bit} = 1.157 \times 10^7 t^{-0.368} e^{-PI(T_{R\&B} - T)^5} \quad (4)$$

Where:  $S_{bit}$  is the predicted Bitumen Stiffness Modulus (Pa).  $T$  is the pavement design temperature (°C). Constraint: The model is valid only when  $T < T_{R\&B}$ .

### 3.5 Derivation of Complex Shear Modulus ( $G^*$ )

The stiffness modulus  $S_{bit}$  obtained from Equation (3) represents the extensional stiffness (analogous to Young's Modulus,  $E$ ). For pavement design, the shear stiffness ( $G^*$ ) is the primary input. Assuming that bitumen behaves as an incompressible material (Poisson's ratio, 0.5) under the test conditions, the relationship is defined by classical mechanics:

$$G^* = \frac{S_{bit}}{3} \quad (5)$$

**3.6 Estimation of Phase Angle ( $\delta$ ) for Modified Binders.** While  $G^*$  represents the total resistance to deformation, the

Phase Angle ( $\delta$ ) indicates the viscoelastic balance between the elastic ( $G'$ ) and viscous ( $G''$ ) components. For neat bitumen,  $\delta$  is strongly correlated with stiffness. However, for the Polymer-Modified Bitumen (PMB) and Crumb Rubber Modified ("Rezina") binders used in this study, the polymer network provides enhanced elastic recovery that decouples  $\delta$  from stiffness. To account for this non-Newtonian behavior, this study estimates  $\delta$  using the empirical correlation with Elastic Recovery (ER) proposed by Airey et al. (2002) and validated for SBS-modified systems:

$$\delta = 90 - (0.52ER_{25}) \quad (6)$$

where,  $\delta$  is the Phase Angle (degrees),  $ER_{25}$  is the Elastic Recovery at 25°C (%).

## 3. Results and Discussions

This section presents the rheological properties of the local Uzbekistan bituminous binders—specifically Polymer-Modified Bitumen (PMB) and Crumb Rubber Modified (Crumber) binders—derived from routine empirical tests using the Ullidtz and Van der Poel analytical frameworks. The predicted parameters, specifically the Complex Shear Modulus ( $G^*$ ) and Phase Angle ( $\delta$ ), are evaluated against the performance criteria set forth by the Superpave system (AASHTO M320) [3] and its analog in the CIS region, GOST R 58400.1 [5]. Predicted linear viscoelastic properties The primary limitation of traditional empirical testing (Penetration and Softening Point) is its inability to describe the binder's behavior under specific traffic loading rates. By utilizing the Ullidtz mathematical approximation (Eq. 4) and converting the standard traffic loading frequency ( $f = 1.59$  Hz) to loading time ( $t$ ), The Stiffness Modulus for all binder samples. Subsequently, the Complex Shear Modulus ( $G^*$ ) was derived assuming a Poisson's ratio of 0.5. As anticipated, the modified binders exhibited significantly higher  $G^*$  values at high temperatures compared to conventional penetration-grade bitumen. This increase in stiffness is attributed to the polymer network and the swollen rubber particles (in Rezina), which reinforce the bituminous matrix and restrict flow under load. However, stiffness alone does not fully capture the benefit of modification. The Phase Angle ( $\delta$ ), estimated via the Airey et al. correlation with Elastic Recovery (Eq. 6), revealed the distinct viscoelastic nature of the modified binders. While neat bitumen typically exhibits a phase angle approaching  $90^\circ$  (purely viscous flow) at high temperatures, the PMB and Rezina samples demonstrated significantly lower  $\delta$  values. This reduction indicates a shift towards elastic behavior, where a larger portion of the deformation energy is stored and recovered rather than dissipated as heat. Performance Grading and Superpave (GOST R 58400) Compliance To contextualize the predicted properties within modern pavement design standards, the results were compared against the Rutting Parameter requirements of AASHTO M320 and GOST R 58400.1-2019. The Superpave specification requires that the rutting parameter, defined as  $\frac{G^*}{\sin(\delta)}$  must exceed 1.00 kPa for unaged binder at the maximum pavement design temperature. Rutting Resistance: The analysis shows that both the polymer-modified bitumen binder achieves the threshold of 1.0 kPa at significantly higher temperatures than unmodified bitumen. This suggests that the local Uzbekistan modified binders are capable of meeting higher Performance



Grades (PG), such as PG 64, PG 70, or potentially PG 76, depending on the specific modifier dosage.

Climate suitability: Given the continental climate of Uzbekistan, characterized by extreme summer heat, the ability to maintain a high  $\frac{G^*}{\sin(\delta)}$  at temperatures above 60 °C is critical. The empirical-mechanistic prediction confirms that the modification effectively extends the upper temperature limit of the binder, reducing the risk of permanent deformation (rutting) on heavy-traffic highways.

**Table 2**  
**Predicted Rheological Properties ( $G^*$ ,  $\delta$ ) of Binders**  
**Estimated using the Ullidtz Model**

Bitumen types	Temperature, °C	$G^*$ , kPa	$\delta$ (°)	Rutting parameter, $\frac{G^*}{\sin(\delta)}$	Superpave Criterion (min 1.0 kPa)
BND 60/90	49.9	0.33	90	0.33	Fail
Polymer Bitumen	67.6	0.51	64.7	0.57	Pass
Rubber bitumen	57.4	0.33	59.37	0.39	Fail
sulfur-extended ('Sero') bitumen	54.2	0.33	90	0.33	Fail

## 4. Conclusion

The mechanistic-empirical analysis of the local binder samples reveals a distinct hierarchy in performance suitable for Uzbekistan's continental climate.

-Polymer-Modified Bitumen (PMB): The Superior Choice The PMB sample demonstrates the most robust modification, achieving the highest Softening Point (67.6°C) and a significantly reduced Phase Angle (64.7°). This confirms the formation of a strong elastomeric network (SBS), which allows the binder to behave viscoelastically—resisting rutting at high temperatures while maintaining the ability to recover from deformation. It is the primary candidate for meeting high-demand Superpave grades (e.g., PG 70 or PG 76).

-Rubber Bitumen ("Rezina"): High Elasticity The Rubber bitumen exhibits the lowest Phase Angle (59.37°), indicating exceptional elastic behavior driven by the "spring-like" rubber particles. However, its thermal resistance (Softening Point 57.4°C) is lower than that of the PMB. While highly effective for stress absorption and fatigue resistance, it may require higher dosages or stabilization to

match the high-temperature rutting resistance of PMB.

-Sulfur-Extended vs. Neat Bitumen: Stiffness without Elasticity The Sulfur-extended ('Sero') bitumen shows a slight increase in Softening Point (54.2°C) compared to the baseline BND 60/90 (49.9°C), indicating a stiffening effect. However, crucially, its Phase Angle remains at 90° (identical to the neat BND), revealing that it remains a purely viscous fluid with zero elastic recovery. Unlike Polymer or Rubber modification, Sulfur hardens the bitumen but does not improve its resilience to dynamic traffic loads, limiting its utility for heavy-duty highways where elastic recovery is required to prevent permanent deformation.

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