ISSN: 2181-3337 | SCIENTISTS.UZ VOLUME 5 ISSUE 8 AUGUST 2026

DEVELOPMENT OF AN OPTIMIZED PERFORMANCE-GRADED (PG) ASPHALT BINDER FOR UZBEKISTAN'S ROAD-CLIMATIC CONDITIONS AND TRAFFIC LOADS: RHEOLOGICAL CHARACTERIZATION AND HYBRID POLYMER MODIFICATION

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DOI: 10.67620/sai.58a0001

ABSTRACT

This study characterized a BND 50/70 paving-grade asphalt binder used in Uzbekistan and evaluated four polymer-modification strategies designed to achieve a PG 76-28 performance grade. The testing program included rotational viscosity, flash point, dynamic shear rheometer testing of unaged and rolling thin-film oven-aged binders, multiple stress creep recovery (MSCR), pressure aging vessel aging, and bending beam rheometer (BBR) testing. The modifiers were TITAN 7686 plastomer, LG501S styrene-butadiene-styrene elastomer, their hybrid combination, and a hybrid formulation containing 1.0% Reclamite® plasticizer. For base-binder measurements with available duplicates, means, sample standard deviations, and coefficients of variation were calculated. The base binder had a mean viscosity of 0.625 ± 0.038 Pa·s at 135 °C and a mean flash point of 270.0 ± 8.49 °C. Polymer modification increased the reported critical high temperature to 77.62 °C with TITAN 7686, 83.30 °C with 3.0% LG501S, 83.10 °C with the LG501S/TITAN hybrid, and 79.30 °C with the LG501S/TITAN/Reclamite® hybrid. The optimized formulation had an S(60) value of 170 MPa and an m-value of 0.305 at −18 °C, with a reported critical low temperature of approximately −29.1 °C. It was therefore classified as PG 76-28. Because replicate-level observations were unavailable for every modified formulation, inferential statistics were not applied. The results support hybrid elastomeric-plastomeric modification with controlled plasticization, while additional replicate MSCR and mixture-level validation remain necessary before field implementation.

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25.08.26

Keywords: *asphalt binder, performance grade, polymer modification, MSCR, BBR, Uzbekistan.*

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Introduction

Asphalt pavement performance is governed by interactions among binder properties, aggregate structure, environmental conditions, traffic loading, and aging. Pavement temperature and repeated traffic loading are particularly important because asphalt binders exhibit strongly temperature- and time-dependent viscoelastic behavior. At elevated temperatures, reduced binder stiffness and viscosity can promote permanent deformation and rutting, whereas excessive stiffness and inadequate stress relaxation at low temperatures can increase susceptibility to thermal cracking.

The Performance Grade (PG) system developed through the Strategic Highway Research Program provides a performance-related framework for selecting asphalt binders according to expected pavement temperatures. Unlike conventional penetration- or viscosity-based classifications, PG grading relates binder properties to maximum and minimum pavement design temperatures and applies rheological criteria to high-, intermediate-, and low-temperature performance (American Association of State Highway and Transportation Officials [AASHTO], 2023; ASTM International, 2023a).

The Superpave approach is particularly relevant where high pavement temperatures coincide with substantial traffic loading. Binder selection should therefore consider both environmental conditions and traffic characteristics. NCHRP research has emphasized the importance of incorporating traffic loading into performance-based asphalt-binder and mixture evaluation, particularly for heavily trafficked pavements (Bahia et al., 2001; West et al., 2018).

Uzbekistan has a predominantly continental climate characterized by hot, dry summers, substantial seasonal temperature variation, and marked spatial variability. Previous investigations applying Superpave principles to long-term meteorological observations have demonstrated the feasibility of estimating pavement-temperature extremes and corresponding PG classes for different regions of Uzbekistan (Sadikov et al., 2021). Road-climatic zoning research has likewise identified substantial regional differences in environmental conditions that affect pavement performance (Urakov et al., 2022).

Selection of BND 50/70 binder on the basis of penetration and other conventional physical properties does not explicitly account for the combined effects of high pavement temperatures and heavy or slow-moving traffic. Polymer modification is therefore a potentially effective strategy for increasing high-temperature stiffness, elastic recovery, resistance to permanent deformation, and rheological stability.

Among polymer modifiers, SBS elastomers are widely used because they can form an elastomeric network within the asphalt phase, increasing elastic response and resistance to repeated deformation. Plastomeric modifiers can increase stiffness and deformation resistance at elevated temperatures, but excessive stiffening may impair low-temperature relaxation. Compatibility, dosage, morphology, aging behavior, and interactions among modifiers must therefore be considered (Behnood & Gharehveran, 2019; Yang et al., 2024).

The dynamic shear rheometer (DSR) is a principal instrument for characterizing the temperature-dependent viscoelastic behavior of asphalt binders. The complex shear modulus, $|G^*|$, and phase angle, δ, describe binder stiffness and viscoelastic response. The parameter $|G^*|/\sin\delta$ is used in conventional high-temperature PG criteria (ASTM International, 2025b).

The multiple stress creep recovery (MSCR) test provides additional information on nonrecoverable creep compliance (Jnr) and elastic recovery under repeated loading. It is particularly relevant for polymer-modified binders subjected to heavy or slow-moving traffic because it captures response characteristics that are not fully represented by the conventional $|G^*|/\sin\delta$ parameter (ASTM International, 2024; Liu et al., 2021).

At low temperatures, the bending beam rheometer (BBR) is used to determine creep stiffness, S, and the m-value. These parameters characterize the binder's ability to relax thermally induced stresses and are therefore associated with low-temperature cracking susceptibility (ASTM International, 2025a).

Although polymer modification of asphalt binders has been widely studied, comparatively little research has examined the combined use of SBS, plastomeric, and plasticizing modifiers for BND 50/70 binders under Uzbekistan's hot continental climate and traffic conditions. This study therefore characterized a BND 50/70 asphalt binder used in Uzbekistan and evaluated four polymer-modification strategies aimed at achieving PG 76-28 performance. Particular attention was given to the balance between high-temperature rutting resistance and low-temperature flexibility. The study's principal contribution is the experimental evaluation of an SBS-plastomer-plasticizer hybrid system for a BND 50/70 binder used

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in Uzbekistan, with the final formulation selected on the basis of high- and low-temperature rheological performance.

Materials and Methods

Base Asphalt Binder

The base binder was BND 50/70 paving-grade petroleum asphalt supplied from the Russian Federation by JSC Gazpromneft-Moscow Oil Refinery (Gazpromneft-MNPZ) for road-construction applications in Uzbekistan. It was characterized using rotational viscosity, flash point, DSR, RTFO, PAV, BBR, and MSCR procedures, and the measured properties were compared with applicable PG requirements.

Polymer Modifiers and Formulations

Four modification strategies were investigated:

1. Modification I: BND 50/70 + 2.0% TITAN 7686
2. Modification II: BND 50/70 + 3.0% LG501S
3. Modification III: BND 50/70 + 2.5% LG501S + 0.7% TITAN 7686
4. Modification IV: BND 50/70 + 2.5% LG501S + 0.7% TITAN 7686 + 1.0% Reclamite®

LG501S was used as the SBS elastomeric modifier, TITAN 7686 as the plastomeric modifier, and Reclamite® as the plasticizing component.

Table 1

Composition of the Optimized Binder Formulation

Component	Content, % of base binder	Approximate content, % of total formulation
BND 50/70	100.0	95.97
LG501S (SBS elastomer)	2.5	2.40
TITAN 7686 (plastomer)	0.7	0.67
Reclamite® plasticizer	1.0	0.96

Binder Modification Procedure

The BND 50/70 binder was heated to a temperature suitable for polymer incorporation and homogenization. The selected modifiers were gradually introduced under mechanical mixing. For the hybrid formulation, LG501S and TITAN 7686 were incorporated together, followed by Reclamite®. The resulting polymer-bitumen systems were conditioned before rheological testing. Preparation and conditioning procedures were kept as consistent as possible across formulations, and mixtures were visually checked for homogeneity and phase separation.

Experimental Testing Program

The experimental program consisted of:

1. Rotational viscosity measurement at 135 °C
2. Flash-point determination
3. DSR testing of the unaged binder
4. RTFO aging
5. DSR testing after RTFO aging
6. MSCR testing
7. PAV aging
8. DSR testing after PAV aging
9. BBR testing at low temperatures
10. Determination of the final PG classification

The testing program was based on applicable ASTM, AASHTO, and GOST procedures.

Rotational viscosity testing followed ASTM D4402/D4402M-23 and GOST 33137-2014 (ASTM International, 2023b; GOST 33137-2014, 2014). Short-term aging used the rolling thin-film oven test in

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accordance with ASTM D2872-22 and GOST 33140-2014 (ASTM International, 2022; GOST 33140-2014, 2014). DSR testing followed ASTM D7175-25 and GOST R 58400.10-2019 (ASTM International, 2025b; GOST R 58400.10-2019, 2019), MSCR testing followed ASTM D7405-24 and GOST R 58400.6-2019 (ASTM International, 2024; GOST R 58400.6-2019, 2019), PAV aging followed GOST R 58400.5-2019 (GOST R 58400.5-2019, 2019), and BBR testing followed ASTM D6648-25a and GOST R 58400.8-2019 (ASTM International, 2025a; GOST R 58400.8-2019, 2019). PG classification was interpreted using ASTM D6373-23, AASHTO M 320-23, and GOST R 58400.1-2019 (AASHTO, 2023; ASTM International, 2023a; GOST R 58400.1-2019, 2019). Flash-point testing followed GOST 33141-2014 (GOST 33141-2014, 2014).

Replicate Measurements and Statistical Analysis

To improve transparency and reliability, individual replicate measurements were evaluated statistically wherever raw replicate data were available.

The arithmetic mean was calculated as:

$$\bar{x} = (1/n) \sum_{i=1}^{n} x_i$$

The sample standard deviation was calculated as:

$$SD = \sqrt{[\sum_{i=1}^{n} (x_i - \bar{x})^2 / (n - 1)]}$$

The coefficient of variation was calculated as:

$$CV = (SD / \bar{x}) \times 100$$

For the original BND 50/70 binder, duplicate measurements were available for dynamic viscosity, flash point, RTFOT mass change, BBR creep stiffness, and BBR m-value. These measurements are reported as mean ± SD together with CV. For the polymer-modified binders, the available dataset consisted primarily of final measured values for each formulation and test condition; replicate-level observations were not available for every parameter. Consequently, SD and CV were not assigned to those values, and inferential tests such as ANOVA and post hoc comparisons were not performed. Comparisons among modified binders are therefore based on measured rheological response and compliance with relevant PG criteria rather than statistical ranking of treatment means.

Performance Grade Determination

The high-temperature PG was determined from the critical temperature at which the binder satisfied the specified $|G^*|/\sin\delta$ criteria for unaged and RTFO-aged conditions. The low-temperature PG was determined from BBR creep stiffness and m-value criteria. Final grades were assigned in standard 6 °C increments. Accordingly, a reported critical high temperature of 79.3 °C and a reported critical low temperature of approximately −29.1 °C correspond to the discrete PG 76-28 classification.

Results

Statistical Characterization of the Unmodified BND 50/70 Binder

The individual replicate results and calculated descriptive statistics are presented in Table 2.

Table 2

Replicate Measurements and Statistical Characteristics of the BND 50/70 Binder

Parameter	Individual measurements	n	Mean	SD	CV, %
Dynamic viscosity at 135 °C, Pa·s	0.652; 0.598	2	0.625	0.038	6.11
Flash point, °C	276; 264	2	270.0	8.49	3.14
RTFOT mass change, %	0.42; 0.58	2	0.500	0.113	22.63
Reported BBR S(60), MPa	170; 208	2	189.0	26.87	14.22
Reported BBR m-value	0.302; 0.318	2	0.310	0.011	3.65

The dynamic viscosity measurements were 0.652 and 0.598 Pa·s, yielding a mean of 0.625 ± 0.038 Pa·s and a CV of 6.11%. This value was well below the specified maximum of 3 Pa·s.

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Flash-point measurements were 276 and 264 °C, yielding a mean of 270.0 ± 8.49 °C and a CV of 3.14%. The mean flash point exceeded the specified minimum of 230 °C.

RTFOT mass changes were 0.42% and 0.58%, yielding a mean of 0.50 ± 0.11%. Although the CV was relatively high (22.63%), the mean mass change remained within the specified limit.

The available BBR duplicate measurements yielded a mean creep stiffness of 189 ± 26.87 MPa and a mean m-value of 0.310 ± 0.011. Because the comparative low-temperature table uses a different set of reported test temperatures and values, the original BBR grading worksheet should be consulted before publication to confirm the test-temperature labels.

The relatively low CV for the m-value (3.65%) indicates good repeatability for this parameter, whereas the higher CV for RTFOT mass change reflects the small absolute magnitude of the measured changes.

High-Temperature Performance of the Investigated Binders

The high-temperature performance of the five investigated binder systems is summarized in Table 3.

Table 3

High-Temperature Rheological Performance of the Investigated Binders

Binder formulation	Reported critical high temperature, °C	Discrete high PG
BND 50/70	69.90	PG 64
BND 50/70 + 2.0% TITAN 7686	77.62	PG 76
BND 50/70 + 3.0% LG501S	83.30	PG 82
BND 50/70 + 2.5% LG501S + 0.7% TITAN 7686	83.10	PG 82
BND 50/70 + 2.5% LG501S + 0.7% TITAN 7686 + 1.0% Reclamite®	79.30	PG 76

The unmodified BND 50/70 binder had a reported critical high temperature of approximately 69.9 °C. Addition of 2.0% TITAN 7686 increased the reported critical temperature to 77.62 °C, an increase of 7.72 °C. The 3.0% LG501S formulation reached 83.30 °C, while the SBS/plastomer hybrid reached 83.10 °C. Addition of 1.0% Reclamite® reduced the reported critical temperature from 83.10 to 79.30 °C, but the value remained above the 76 °C threshold for the PG 76 high-temperature class. Because replicate observations were unavailable for all modified formulations, these values are presented as measured critical temperatures rather than statistically tested treatment means.

RTFO-Aged Binder Performance

RTFO aging increased the rheological stiffness of the investigated binders.

For the original BND 50/70 binder, the reported |G*|/sin δ values after RTFO aging were:

- 2.30 kPa at 64 °C
- 1.23 kPa at 70 °C

A critical high-temperature value of approximately 69.9 °C was reported for the RTFO-aged base binder. For the modified binders, reported RTFO-aged critical temperatures ranged from approximately 77.97 to 83.30 °C, while the final SBS/TITAN/Reclamite® formulation retained a reported critical temperature of approximately 79.3 °C. These results indicate that the polymer-modified binders maintained improved high-temperature deformation resistance after simulated short-term aging. The critical-temperature interpolation should be checked against the original DSR worksheet before publication.

PAV-Aged Binder Performance

For the unmodified BND 50/70 binder, the reported PAV-aged |G*|/sin δ values were:

- 1,700 kPa at 25 °C
- 6,160 kPa at 13 °C

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The intermediate critical temperature was reported as approximately 16 °C. The value at 25 °C remained below the 5,000 kPa criterion, whereas the value at 13 °C exceeded it. These results were used to characterize intermediate-temperature performance. For the optimized formulation, PAV-aged response should be interpreted together with the low-temperature BBR results to ensure that increased high-temperature stiffness does not create unacceptable thermal-cracking susceptibility.

Low-Temperature Performance

The low-temperature properties of the investigated binders are summarized in Table 4.

Table 4

Low-Temperature Performance of the Investigated Binders

Binder	S(60), −12 °C, MPa	S(60), −18 °C, MPa	m-value, −18 °C	Reported critical low temperature, °C	Discrete low PG
BND 50/70	94.5	208	0.310	−26.62*	−28
+2.0% TITAN 7686	136	241	0.257	−22.94	−22
+3.0% LG501S	158	264	0.255	−24.10	−24
+2.5% LG501S + 0.7% TITAN 7686	179	217	0.257	−23.10	−22
+2.5% LG501S + 0.7% TITAN 7686 + 1.0% Reclamite®	119	170	0.305	−29.10	−28

Note. The base-binder discrete low PG is reported as −28 in the source dataset. Because the tabulated critical value (−26.62 °C) and the separate duplicate BBR results are not fully aligned, the original BBR grading worksheet should be checked before publication. The remaining values are presented as reported.

MSCR Performance and Traffic Considerations

The available MSCR results are presented in Table 5.

Table 5

MSCR Parameters of the Investigated Binder Formulations

Binder	Jnr,0.1, kPa^{-1}	Jnr,3.2, kPa^{-1}	Recovery, %
BND 50/70	1.157	1.553	34.23
+2.0% TITAN 7686	0.3703	1.173	216.8*
+3.0% LG501S	1.121	2.208	67.05
SBS/TITAN hybrid	0.401	1.250	211.8*
SBS/TITAN/Reclamite® hybrid	0.626	1.015	62.1

Note. Recovery values marked with an asterisk exceed 100%, which is physically unusual for conventional percent recovery. These values should be verified against the original MSCR calculation sheet and unit convention before publication. The optimized hybrid formulation had a reported Jnr,3.2 of 1.015 kPa^{-1} and recovery of 62.1%, indicating lower nonrecoverable compliance than the unmodified BND 50/70 binder. Final traffic classification should be assigned using the applicable MSCR specification and traffic category.

Discussion

Effect of Polymer Modification

Polymer modification substantially altered the high-temperature rheological behavior of BND 50/70. TITAN 7686 increased the reported critical high temperature from 69.90 to 77.62 °C. The 3.0% LG501S formulation produced a reported critical temperature of 83.30 °C, and the hybrid LG501S/TITAN system produced 83.10 °C. The similarity of these values suggests that the SBS component was a major contributor to the high-temperature improvement, while the hybrid system may provide a useful balance of elastomeric and plastomeric behavior.

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Role of Reclamite® in the Optimized Formulation

Addition of Reclamite® reduced the reported critical high temperature from 83.10 to 79.30 °C. Although this reduction may appear adverse, the BBR results indicate improved low-temperature response. The S(60) value of the final formulation was 119 MPa at −12 °C, compared with 179 MPa for the binary SBS/TITAN formulation. At −18 °C, the final formulation had an m-value of 0.305, compared with 0.257 for the binary SBS/TITAN system. Reclamite® therefore appears to have moderated polymer-network stiffness and improved low-temperature stress relaxation. The optimized formulation represents a compromise between high-temperature rutting resistance and low-temperature flexibility.

Balance Between High- and Low-Temperature Performance

Maximizing high-temperature stiffness did not produce the best overall rheological balance. The SBS/TITAN formulation had a reported critical high temperature of approximately 83.1 °C but less favorable low-temperature behavior. By contrast, the SBS/TITAN/Reclamite® formulation had a lower reported critical high temperature of 79.3 °C but improved low-temperature characteristics. This finding underscores the need to select binders on the basis of the full rheological response rather than a single high-temperature parameter. The optimized formulation achieved:

- Critical high temperature: 79.3 °C
- Discrete high PG: 76
- BBR stiffness at −18 °C: 170 MPa
- m-value at −18 °C: 0.305
- Critical low temperature: approximately −29.1 °C
- Discrete low PG: −28

Accordingly, the final binder was classified as PG 76-28.

Relevance to Uzbekistan Climate Conditions

Selection of a PG 76-28 binder is relevant for road sections exposed to high pavement temperatures and sufficiently low winter pavement temperatures. The PG 76 high-temperature grade indicates compliance with the rheological requirements associated with the 76 °C class, while the −28 low-temperature grade indicates compliance with the corresponding low-temperature class. PG classification, however, should not be interpreted as a direct guarantee of pavement performance under every traffic condition. Pavement structure, aggregate gradation, air voids, layer thickness, axle loading, traffic speed, and environmental exposure can substantially affect rutting and cracking performance.

Effect of Traffic Loading and MSCR

The conventional $|G^*|/\sin\delta$ parameter is useful for high-temperature PG grading but does not fully characterize recoverable and nonrecoverable response under repeated loading. MSCR testing provides additional information through Jnr and percent recovery. Lower Jnr generally indicates lower susceptibility to permanent deformation, whereas higher recovery indicates a larger elastic contribution. The optimized formulation had a reported Jnr,3.2 of 1.015 kPa^{-1}, compared with 1.553 kPa^{-1} for the base BND 50/70 binder. This reduction indicates improved resistance to nonrecoverable creep at the higher stress level. Nevertheless, the MSCR dataset should be expanded through replicate testing and verification of the recovery calculations before a traffic category is assigned.

Comparison of the Investigated Formulations

The investigated formulations can be grouped by their rheological balance. The unmodified BND 50/70 had a reported critical high temperature of approximately 69.9 °C and was reported as PG 64-28. TITAN 7686 increased the high-temperature grade to PG 76, while LG501S and the SBS/TITAN hybrid produced reported critical temperatures above 82 °C. The SBS/TITAN/Reclamite® hybrid had a lower high-temperature critical value than the binary SBS/TITAN system but substantially improved low-temperature behavior. It was therefore selected as the most balanced formulation for the target PG 76-28 classification. Because replicate measurements were unavailable for all modified formulations, this

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comparison should be interpreted as a performance-based evaluation rather than a statistical ranking of treatment means.

Optimized PG 76-28 Binder Formulation

Based on the laboratory results, the recommended PG 76-28 composition is summarized in Table 1.

The proposed binder can therefore be designated PG 76-28 for road applications in which calculated pavement temperatures and traffic conditions justify this performance level.

Conclusions

The experimental investigation supports the following conclusions:

1. The original BND 50/70 binder had a mean dynamic viscosity of 0.625 ± 0.038 Pa·s at 135 °C (CV = 6.11%, n = 2), satisfying the applicable viscosity requirement.
2. The mean flash point was 270.0 ± 8.49 °C (CV = 3.14%, n = 2), exceeding the specified minimum.
3. The mean RTFOT mass change was 0.50 ± 0.11%, remaining within the specified limit.
4. The unmodified binder had a reported critical high temperature of approximately 69.9 °C, corresponding to the discrete high-temperature class PG 64.
5. The available duplicate BBR measurements yielded a mean creep stiffness of 189 ± 26.87 MPa and a mean m-value of 0.310 ± 0.011. The original BBR grading worksheet should be checked to reconcile the test-temperature labels used across the manuscript.
6. TITAN 7686 increased the reported critical high temperature from 69.90 to 77.62 °C.
7. The 3.0% LG501S formulation and the 2.5% LG501S + 0.7% TITAN 7686 hybrid had reported critical high temperatures of 83.30 and 83.10 °C, respectively.
8. Addition of 1.0% Reclamite® reduced the reported critical high temperature to 79.30 °C while improving low-temperature rheological performance.
9. The optimized formulation had an S(60) value of 170 MPa and an m-value of 0.305 at −18 °C, satisfying the stated low-temperature criteria.
10. The reported critical low temperature of approximately −29.1 °C corresponds to the discrete −28 PG class.
11. The combination of 2.5% LG501S, 0.7% TITAN 7686, and 1.0% Reclamite® produced the most balanced high- and low-temperature rheological response among the investigated formulations.
12. The optimized binder was classified as PG 76-28.
13. The available MSCR results indicate lower nonrecoverable creep compliance for the optimized hybrid formulation than for the unmodified BND 50/70 binder, although the dataset requires replicate verification.
14. PG classification alone is insufficient for final pavement design under severe traffic conditions. MSCR traffic classification and asphalt-mixture testing for rutting, fatigue, moisture susceptibility, and low-temperature cracking should also be considered.
15. The statistical analysis underscores the importance of replicate measurements. Mean, SD, and CV were calculated only where duplicate observations were available; statistical significance was not inferred for modified-binder parameters lacking replicate-level data.

Limitations and Recommendations for Further Research

Several limitations should be acknowledged. First, the investigation used one source of BND 50/70 binder. Binder chemistry and rheological response can vary among refineries, crude-oil sources, production batches, and storage conditions; additional source binders should therefore be evaluated.

Second, replicate-level observations were available only for selected measurements of the original BND 50/70 binder. Although descriptive statistics were calculated for those measurements, complete replicate datasets were not available for all polymer-modified formulations, so inferential statistical tests were not performed.

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Future studies should use at least three independent replicate specimens for each formulation and test condition where technically appropriate. Reporting means, SDs, CVs, confidence intervals, and inferential comparisons would permit more rigorous evaluation of modification strategies.

Third, the MSCR results should be expanded through repeated testing at 0.1 and 3.2 kPa, with verified Jnr and percent-recovery calculations. The original DSR and BBR worksheets should also be checked to reconcile the critical-temperature interpolation and test-temperature labels reported across the manuscript.

Further research should include:

- Replicate MSCR testing
- Jnr,0.1 and Jnr,3.2 determination
- Percent recovery
- Frequency-sweep testing
- Temperature-sweep testing
- Fluorescence microscopy for polymer morphology
- FTIR spectroscopy for chemical-interaction analysis
- Storage-stability testing
- Extended PAV aging
- Intermediate-temperature fatigue testing
- Thermal stress restrained specimen testing
- Wheel-tracking and rutting tests
- Repeated-load permanent-deformation tests
- Moisture-susceptibility testing
- Low-temperature cracking tests
- Asphalt-mixture performance testing
- Field validation using measured pavement-temperature and traffic data from different regions of Uzbekistan

Future research should establish direct relationships between binder-level rheological indicators, including Jnr, $|G^*|/\sin\delta$, BBR stiffness, and m-value, and asphalt-mixture performance. Such a program would allow the proposed PG 76-28 binder to be validated at the binder, mixture, and pavement-performance levels.

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