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EVALUATION OF CREEP–RECOVERY BEHAVIOR OF TPS-MODIFIED ASPHALT BINDERS

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Abstract. Due to increasing traffic loads and high pavement temperatures, improving the rutting resistance and durability of asphalt pavements has become a critical issue in road engineering. Conventional asphalt binders often show inadequate resistance to permanent deformation under severe loading and temperature conditions. This study investigates the effect of TAFPACK-Super (TPS) modification on the high-temperature performance of asphalt binders using Multiple Stress Creep Recovery test. Tests were conducted at stress levels of 0.1 and 3.2 kPa over temperatures ranging from 52°C to 88°C. Asphalt binders containing different TPS contents (6%, 13.6%, and 18%) were compared with base asphalt and polymer-modified asphalt. Non-recoverable creep compliance (Jnr) and percent recovery were analyzed to evaluate rutting resistance and elastic response. The results show that TPS significantly enhances deformation resistance by reducing J_{nr} values and increasing recovery rates. Temperature mainly affects J_{nr}, while TPS dosage strongly influences elastic recovery behavior. Overall, TPS modification improves the rheological properties of asphalt binders by forming a stable polymer network, resulting in lower temperature sensitivity and better long-term pavement performance under heavy traffic conditions.

Keywords: Multiple Stress Creep Recovery (MSCR), non-recoverable creep compliance, percent recovery, additive, asphalt binder, modified asphalt binder.

1. INTRODUCTION

Rutting is recognized as one of primary distress modes in flexible asphalt pavements, characterized by the accumulation of longitudinal permanent deformations along wheel paths under cyclic traffic loading. This phenomenon is mainly attributed to the progressive development of permanent deformation within asphalt layers [1]. As the primary binding agent in asphalt mixtures, the asphalt binder plays a critical role in rutting resistance, particularly at high service temperatures [2-4]. To address the challenges of increasing traffic volumes, heavier loads, and changing climatic conditions, polymer-modified asphalt binders have been widely adopted in asphalt mixtures for pavement applications. These modifiers significantly enhance the rheological properties of asphalt binder, increasing stiffness at high temperatures [4,] and thereby improving rutting resistance under wheel loading [5 -6].

For many years, the Superpave Performance Grading (PG) system according to AASHTO M 320 [7] has employed $G^*/\sin\delta$ parameter (measured following AASHTO T 315 [8]) to evaluate high-temperature performance of asphalt binders. However, numerous studies have shown that this parameter does not accurately reflect the field performance of asphalt binders, particularly polymer-modified ones [4, 9–12]. This limitation arises because these tests are conducted at very low stress and strain levels within the linear viscoelastic (LVE) range, where polymer network is not sufficiently activated to develop its elastic properties and primarily functions as a stiffening filler.

To overcome these inherent limitations, Multiple Stress Creep Recovery (MSCR) test has been developed as a more performance-based characterization method, standardized in AASHTO M 332 [13] and T 350 [14]. The MSCR test utilizes a creep–recovery loading protocol to quantify two key parameters: non-recoverable creep compliance (J_{nr}), which reflects resistance to permanent deformation, and percent recovery (R), which assesses the elastic response and the effectiveness of polymer modification [14 - 22].

Field and laboratory studies [5, 15, 16, 18, 20 - 22], including Accelerated Loading Facility (ALF) and MnROAD tests [10], have demonstrated that J_{nr} exhibits a much stronger correlation with actual rut depth than $G^*/\sin\delta$. Consequently, MSCR test allows asphalt binders to be graded according to traffic levels (S, H, V, E) under AASHTO M 332 [13], providing a more reliable and performance-oriented approach compared to the traditional Performance Grade (PG) system. Moreover, MSCR test enables the identification of the nature and density of the polymer network through its elastic recovery characteristics, thereby providing meaningful insights into the underlying working mechanisms of modified binders. However, numerous studies have indicated that the reliability and discriminative capability of the MSCR test are strongly dependent on the type of modifier and the microstructural characteristics of the material system. Specifically, while MSCR provides clear and consistent results for SBS-modified asphalt binders [10], it exhibits notable limitations when applied to more complex systems such as crumb rubber modified (CRM) binders, where particle size effects and material heterogeneity can distort the measured parameters [15]. Similarly, for wax-based additives such as LEADCAP and Sasobit, although improvements in certain technological and mechanical properties have been reported, the MSCR parameters (Jnr and R) do not clearly capture differences in rutting resistance within the same base binder [15].

Among the various high-performance additives, TAFPACK-Super (TPS) is a specialized modifier developed to enhance the performance of asphalt binders, particularly for porous asphalt mixtures. Porous asphalt is widely employed due to its functional benefits, including effective water drainage and noise reduction; however, it necessitates high-quality binders to ensure long-term structural durability [23]. Although previous studies have extensively assessed modifiers using the MSCR protocol [5, 15, 17, 20, 22], a comprehensive understanding of the specific effects of TPS on the creep–recovery behavior of asphalt binders under varying stress levels remains lacking.

This study aims to investigate the effect of TAFPACK-Super (TPS) on the creep–recovery behavior of asphalt binders. By conducting MSCR tests at varying stress levels and temperatures, the research seeks to quantify the improvements in non-recoverable creep compliance (J_{nr}) and percent recovery (R) imparted by TPS modification. These results are expected to provide valuable insights into the stress sensitivity and elastic response of TPS-modified binders, thereby supporting their application in high-performance asphalt mixtures.

2. MATERIALS AND METHODS

2.1. Materials

This study used 60/70 penetration grade asphalt binder supplied by Petrolimex Asphalt Company Limited. This is a conventional base asphalt binder with stable properties, widely used in road construction projects in Vietnam. Its fundamental physical properties comply with technical requirements specified in TCVN 13567-1:2022 [24].

TAFPACK-Super (TPS) additive was supplied by Taiyu Vietnam Company Limited. This is a specialized additive used to improve the performance of asphalt binder. This additive, in yellow pellet form, exhibits excellent dispersibility in hot asphalt mixtures, contributing to improved homogeneity of the blend.

Modified asphalt binders were prepared by mixing TPS additive into 60/70 base asphalt binder at different contents.

Figure 1. TAFPACK-Super (TPS) additive.

2.2. Sample preparation

a) Blending of TPS additive into 60/70 base asphalt binder

Three types of modified asphalt binders were prepared by incorporating TAFPACK-Super (TPS) additive into 60/70 penetration grade base asphalt binder at different contents. The selected TPS contents were 6%, 13.6%, and 18% by weight of the base binder, in order to evaluate the effect of additive content on rheological properties of the binder.

Blending process was carried out using a high-shear mixing device. Base asphalt binder was heated to an appropriate temperature (145–150°C), after which TPS additive was gradually added and mixed at approximately 2000 rpm for 20 minutes. These mixing conditions ensured uniform dispersion of the additive within the base asphalt binder, resulting in a highly homogeneous modified binder system (Figure 2)

Figure 2. Equipment for mixing TPS additive into 60/70 asphalt binder.

b) Short-term aging

Short-term aging of asphalt binder was conducted using Rolling Thin Film Oven (RTFO) in accordance with AASHTO T 240, to simulate the oxidative aging and hardening of binder during mixing, transportation, and construction processes.

c) Sample preparation

After completion of RTFO aging process, hot binder was immediately poured into silicone molds to form standard test specimens. MSCR specimens were prepared with a diameter of 25 mm.

Figure 3. Modified asphalt binder samples prepared with TPS additive.

Table 1. Experimental plan for the MSCR test.

Sample ID	TPS content (%)	Condition	Shear stress (kPa)	Test temperature (°C)
60/70	0	RTFO	0.1 and 3.2	52, 58, 64, 70, 76
60/70_6%TPS	6	RTFO	0.1 and 3.2	58, 64, 70, 76
60/70_13,6%TPS	13.6	RTFO	0.1 and 3.2	58, 64, 70, 76, 82
60/70_18%TPS	18	RTFO	0.1 and 3.2	58, 64, 70, 76, 82, 88
PMB III	-	RTFO	0.1 and 3.2	64, 70, 76, 82, 88

2.3. **Experimental Methods**

Multiple Stress Creep Recovery (MSCR) test was performed using a Dynamic Shear Rheometer (DSR) (Anton Paar) (Figure 4) on asphalt binder samples after short-term aging using RTFO.

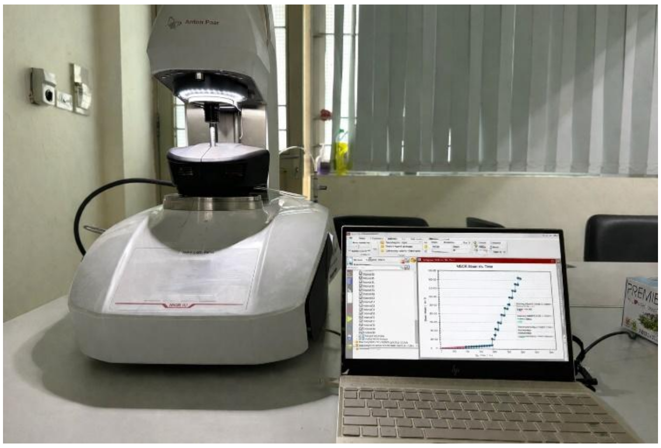

Figure 4. Dynamic Shear Rheometer (DSR) manufactured by Anton Paar.

This test consisted of 10 cycles at two stress levels (0.1 kPa and 3.2 kPa), with each cycle lasting 10 seconds, including 1 second of loading followed by 9 seconds of recovery. Figure 5 illustrates one loading–recovery cycle in the MSCR test.

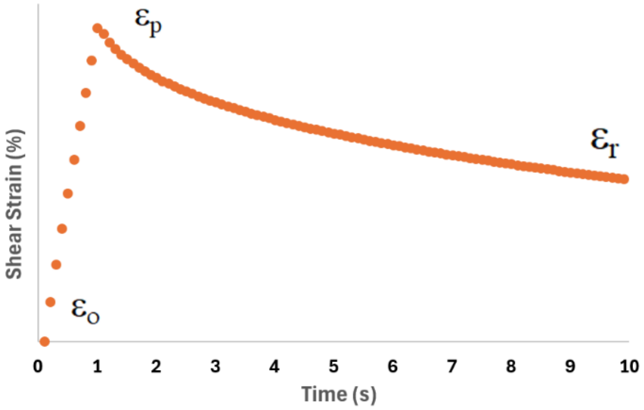

Figure 5. A typical loading–unloading cycle in the MSCR test.

Non-recoverable creep compliance (J_{nr}) and percent recovery (R) were adopted as primary performance indicators. Representative values of these parameters were calculated as the average of 10 consecutive loading–recovery cycles, in accordance with Equations (1) and (2).

$$J_{nr} = \frac{1}{10}\sum_{i=1}^{10}\frac{\varepsilon_{r,i} - \varepsilon_{0,i}}{\sigma} \quad (1)$$

$$R = \frac{1}{10}\sum_{i=1}^{10}\frac{\varepsilon_{p,i} - \varepsilon_{r,i}}{\varepsilon_{p,i}} \quad (2)$$

Where:

$\varepsilon_{o,i}$: initial strain of the specimen before the start of the i-th loading cycle.

$\varepsilon_{r,i}$: residual strain of the specimen at the end of the recovery phase in the i-th cycle.

$\varepsilon_{p,i}$: strain of the specimen at the end of the loading phase in the i-th cycle.

σ: applied shear stress level (0.1 kPa and 3.2 kPa).

3. RESULTS AND DISCUSSION

3.1. Non-recoverable creep compliance (J_{nr})

Non-recoverable creep compliance was measured at stress levels of 0.1 kPa and 3.2 kPa (denoted as $J_{nr,3.2}$ and $J_{nr,0.1}$, respectively) across temperatures from 52 °C to 88 °C. The results for five asphalt binders, including three TPS-modified binders at 6%, 13.6%, and 18% dosages and two control binders, 60/70 and PMB III, are presented in Figure 6 and Figure 7.

Figures 6 and 7 indicate that J_{nr} is strongly dependent on both temperature and applied stress level, exhibiting a pronounced increase as either parameter rises.

For the 60/70 base asphalt, a pronounced sensitivity to temperature is observed. At 52°C, the non-recoverable creep compliance values $J_{nr,\ 0.1}$ and $J_{nr,\ 3.2}$ are relatively low, at 0.353 kPa^{-1} and 0.389 kPa^{-1}, respectively. However, as the temperature increases to 76°C, these values rise sharply to 8.686 kPa^{-1} and 14.454 kPa^{-1}, indicating a significant reduction in non-recoverable deformation resistance.

In contrast, the temperature-dependent variation of J_{nr} for TPS-modified asphalt and PMB 3 exhibits considerably improved stability. For the binder containing 18% TPS, $J_{nr,0.1}$ remains within a narrow range of 0 to 0.27 kPa^{-1}, while $J_{nr,3.2}$ varies from 0 to 5.09 kPa^{-1} as the temperature increases from 58°C to 82°C. Similarly, PMB 3 shows $J_{nr,0.1}$ values between 0.01 and 0.65 kPa^{-1} and $J_{nr,3.2}$ values from 0.09 to 2.27 kPa^{-1} over the temperature range of 64°C to 82°C. These results demonstrate that TPS modification effectively reduces the temperature susceptibility of asphalt binders, which can be attributed to the formation of a stable polymer network that enhances binder stiffness at high temperatures.

J_{nr} at the higher stress level (3.2 kPa) is consistently greater than that at the lower stress level (0.1 kPa) at the same test temperature for all investigated binders. This indicates that asphalt binders undergo more severe non-recoverable deformation under higher loading conditions, particularly at high temperatures. At the low stress level (0.1 kPa), the material response is predominantly within the linear viscoelastic range. However, when the stress level increases to 3.2 kPa, the internal structure of the binder is more significantly disrupted, leading to a substantial increase in permanent deformation. This effect is especially pronounced for the 60/70 base asphalt at 76°C, where the J_{nr} value increases markedly from 8.686 kPa^{-1} (at 0.1 kPa) to 14.454 kPa^{-1} (at 3.2 kPa), highlighting its high sensitivity to applied stress and limited resistance to rutting under severe loading conditions.

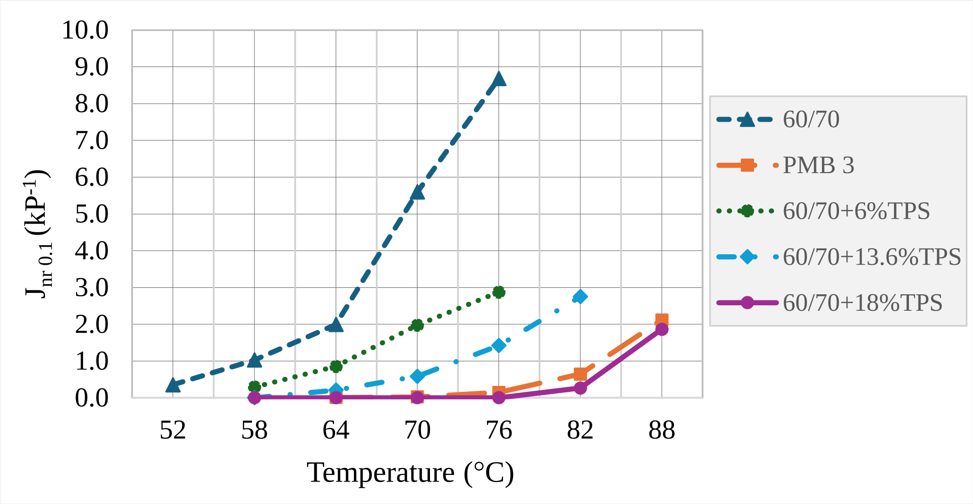

Figure 6. Non-recoverable creep compliance (J_{nr}) at a stress level of 0.1 kPa.

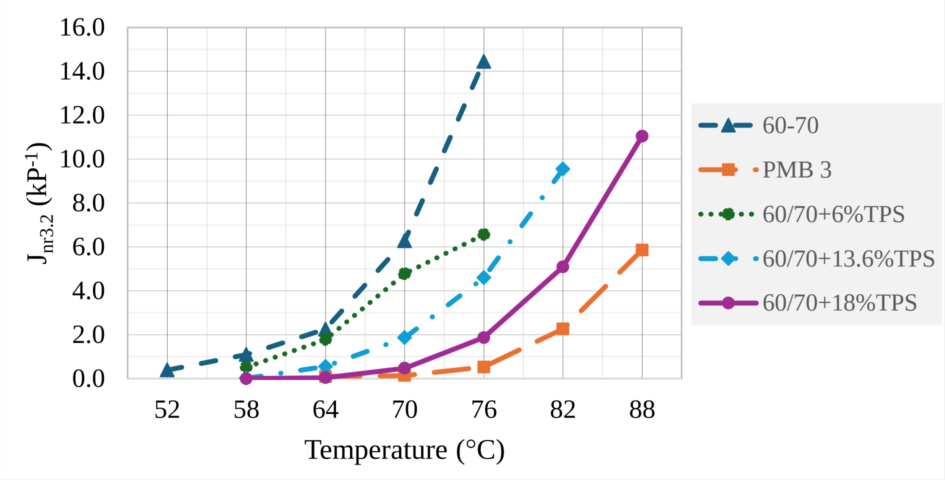

Figure 7. Non-recoverable creep compliance (J_{nr}) at a stress level of 3.2 kPa.

Furthermore, the dosage of TPS has a decisive influence on J_{nr}, with a clear decreasing trend observed as the additive content increases under all temperature and stress conditions:

- At the low stress level (0.1 kPa), the base asphalt exhibits significant thermal susceptibility, with $J_{nr,0.1}$ increasing from 1.026 kPa^{-1} at 58°C to 8.686 kPa^{-1} at 76°C. The incorporation of TPS markedly improves this behavior; at 76°C, the addition of 6% TPS reduces $J_{nr,0.1}$ to 2.88 kPa^{-1} (approximately a 67% reduction), while the 18% TPS binder achieves a near-zero value, indicating almost complete recovery under the tested conditions.

- At the high stress level (3.2 kPa), which simulates heavy traffic loading, the effectiveness of TPS becomes even more evident. $J_{nr,3.2}$ value of the base asphalt reaches 14.45 kPa^{-1} at 76°C, suggesting a high susceptibility to permanent deformation. In comparison, increasing TPS content to 13.6% and 18% reduces this value to 4.59 kPa^{-1} and 1.87 kPa^{-1}, respectively. Notably, the 18% TPS-modified binder achieves a reduction of up to 87% relative to the base asphalt, demonstrating a substantial enhancement in resistance to shear deformation and a significant limitation of non-recoverable strain.

− Compared to PMB III, TPS-modified asphalt binders exhibit consistently higher $J_{nr,3.2}$ values, particularly at high temperatures. Specifically, at 82°C, TPS binders (5.09–9.55 kPa^{-1}) are significantly higher than PMB III (2.27 kPa^{-1}), while at 88°C, the 18% TPS binder (11.04 kPa^{-1}) is nearly twice that of PMB III (5.86 kPa^{-1}). These results indicate that TPS-modified binders (6–18%) exhibit inferior resistance to non-recoverable deformation under high shear stress conditions.

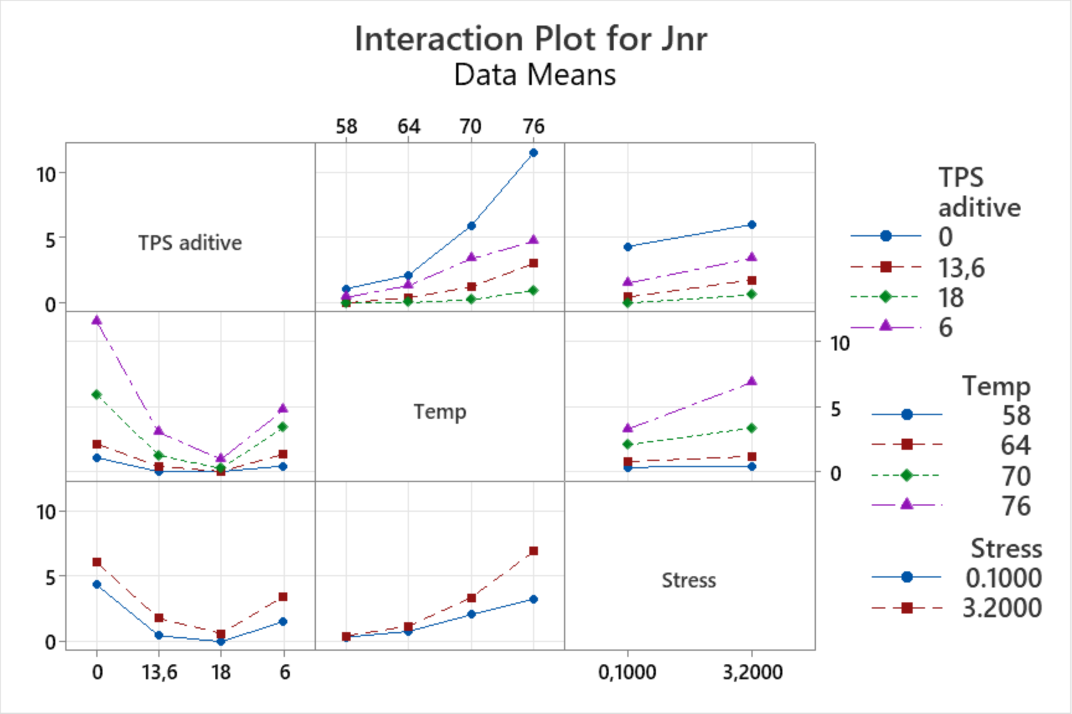

Figure 8. Interaction effects of temperature, stress level, and TPS additive content on non-recoverable creep compliance.

Figure 8 presents the interaction plots for J_{nr} as a function of temperature, stress level, and TPS additive content. These plots capture not only the individual effects of each factor but also their coupled interactions. A pronounced increase in J_{nr} with increasing temperature and stress level is observed, particularly for the base asphalt, indicating a high susceptibility to thermal and loading conditions

In contrast, the incorporation of TPS significantly reduces J_{nr} and results in a more stable response across the examined temperature range. The non-parallel trends among the curves reveal notable interaction effects, especially between temperature and additive content, as well as between temperature and stress level. This suggests that non-recoverable deformation resistance of asphalt binders is governed by the combined influence of these parameters rather than by any single factor independently.

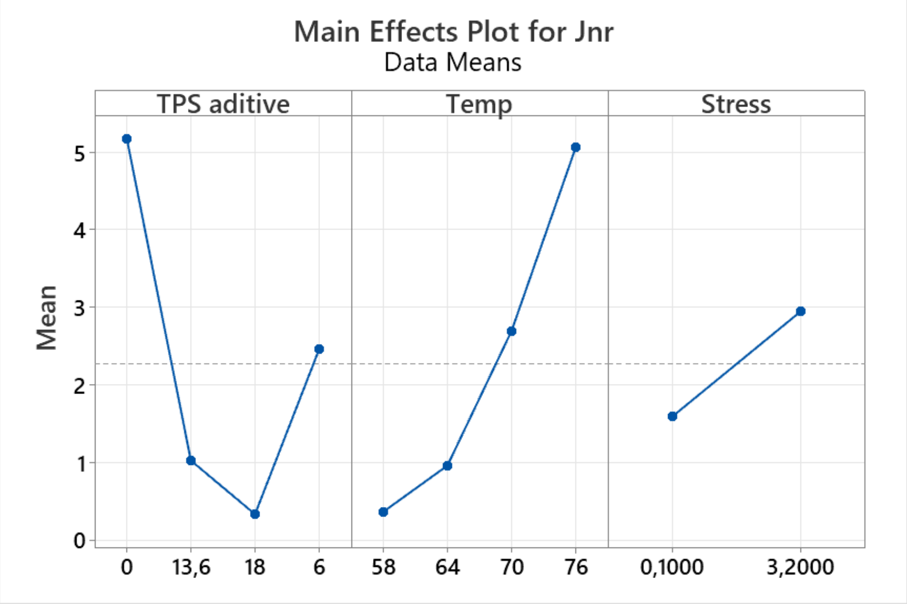

Figure 9. Main effects plot of non-recoverable creep compliance (J_{nr}) as a function of TPS additive content, temperature, and stress level.

Figure 9 presents the main effects plot of J_{nr} as a function of TPS additive content, temperature, and stress level. The results indicate that temperature is the most dominant factor, with J_{nr} increasing sharply as the temperature rises from 58°C to 76°C, clearly reflecting a reduction in deformation resistance at high temperatures. The stress level also has a significant effect, as J_{nr} increases at 3.2 kPa compared to 0.1 kPa.

3.2. Percent recovery (R)

A comprehensive assessment of the permanent deformation resistance of asphalt binders requires consideration of not only J_{nr} but also R, which serves as a key parameter for quantifying the elastic contribution within the binder structure. This parameter characterizes the ability of the binder to recover after load removal, thereby reflecting its viscoelastic behavior and playing a critical role in determining the long-term performance of asphalt pavements.

To further elucidate the transition in mechanical behavior from a predominantly viscous response to a more elastic-dominated state induced by modification, the percent recovery (R) was evaluated using the MSCR test. The results, presented in Figures 10 and Figure 11, illustrate the variation of R for five types of binders, including the 60/70 base asphalt, PMB III, and TPS-modified binders with additive contents of 6%, 13.6%, and 18%, over a temperature range from 52°C to 88°C.

$R_{0.1}$ reflects the recovery capability of the binder under low stress levels, thereby indicating the development and effectiveness of the elastic network structure within the asphalt. The results show that the 60/70 base asphalt is predominantly viscous in nature, exhibiting very low $R_{0.1}$ values, reaching 5.195% at 58°C and decreasing to nearly zero (0.151%) at 76°C, indicating negligible recovery upon unloading. In contrast, the incorporation of TPS significantly enhances the elastic response of the binder. At 58°C, the binders modified with 13.6% and 18%

TPS both achieve a recovery rate of 100%. Notably, the 18% TPS-modified binder maintains this level across the entire temperature range from 58°C to 76°C, outperforming PMB III, which reaches only 91.74% at 76°C. These results suggest the formation of a stable and continuous polymer network, enabling near-complete recovery after load removal.

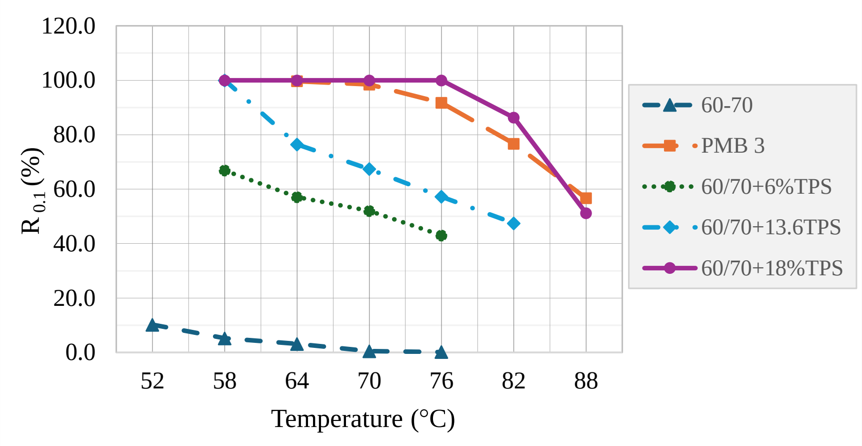

Figure 10. Percentage recovery (R) at a stress level of 0.1 kPa.

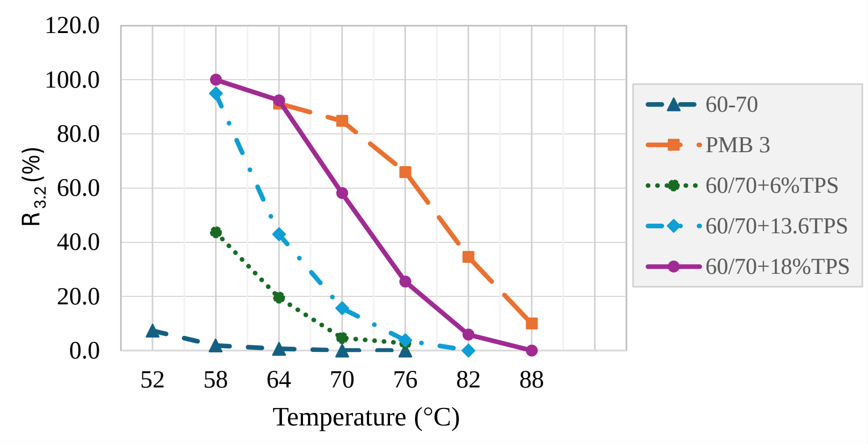

Figure 11. Percentage recovery (R) at a stress level of 3.2 kPa.

At the high stress level of 3.2 kPa, the recovery behavior of the binders exhibits a clear differentiation, reflecting the stability of the polymer network. At 58°C, the 18% TPS-modified binder maintains a recovery rate of 100%, whereas the 13.6% and 6% TPS samples decrease to 94.9% and 43.71%, respectively, highlighting the critical role of TPS dosage in sustaining elastic response under heavy loading. However, as the temperature increases to 76°C, the $R_{3.2}$ values of all binders decrease substantially. The 18% TPS sample drops to 25.46%, which is lower than that of PMB III (65.93%) under the same conditions. Nevertheless, compared to binders with lower TPS contents (6% and 13.6%), the 18% TPS-modified binder still demonstrates a noticeably higher recovery capability.

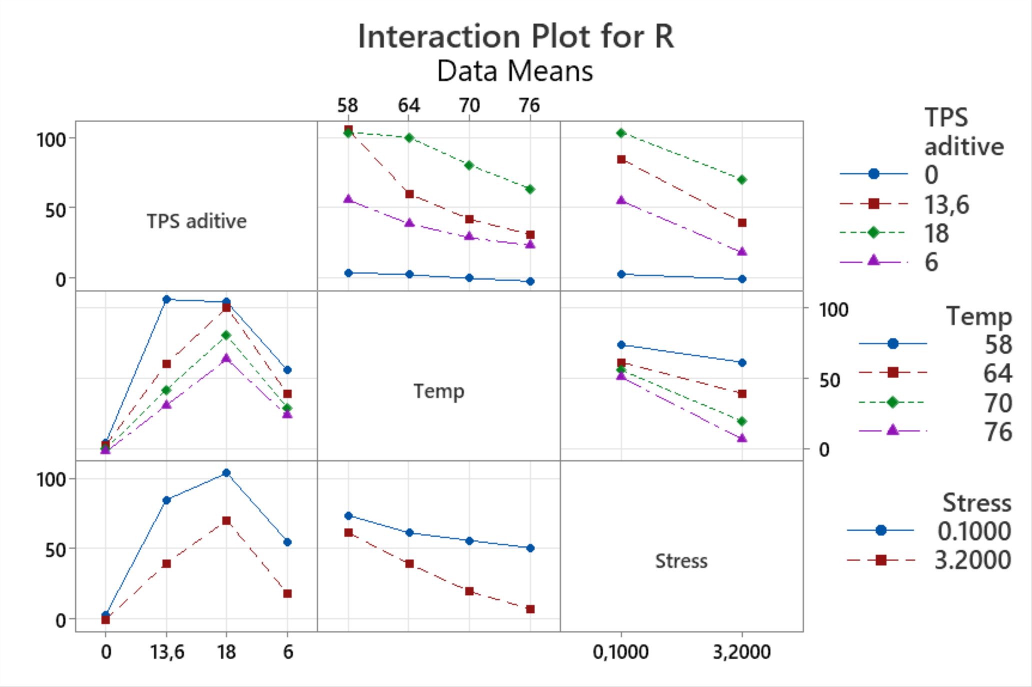

Figure 12. Interaction effects of temperature, stress level, and TPS additive content on percent recovery (R).

Figure 12 illustrates the interaction plots for R, indicating that temperature, stress level, and TPS additive content all significantly influence the elastic recovery behavior of the binder. Overall, R decreases markedly with increasing temperature, highlighting the reduced elastic response at high temperatures due to binder softening. Similarly, an increase in stress level from 0.1 to 3.2 kPa leads to a substantial reduction in R, confirming the stress sensitivity and nonlinear viscoelastic nature of the material under MSCR conditions.

The effect of TPS additive is pronounced, with higher additive contents resulting in significantly improved recovery, particularly at moderate temperatures. However, this beneficial effect diminishes at higher temperatures and stress levels, as indicated by the non-parallel trends in the interaction plots. Notably, strong interactions are observed between temperature and stress, as well as between additive content and temperature, suggesting that the elastic recovery performance is governed by the combined influence of thermal and loading conditions. These findings demonstrate that the evaluation of binder performance based on R should consider the coupled effects of temperature, stress, and modification level rather than relying on single-condition assessments.

Figure 13 presents the main effects plot for R as a function of TPS additive content, temperature, and stress level. The results indicate that TPS content is the most influential factor governing elastic recovery. Specifically, R increases sharply with the addition of TPS, reaching a maximum at 18% before decreasing at lower dosage levels, highlighting the critical role of adequate polymer content in developing an effective elastic network. Temperature also exhibits a pronounced negative effect, with R decreasing progressively as temperature increases from

58°C to 76°C, reflecting the reduced elastic response of the binder due to thermal softening. Similarly, an increase in stress level from 0.1 to 3.2 kPa leads to a significant reduction in R, indicating the degradation of elastic recovery under higher loading conditions. Overall, these results demonstrate that the elastic recovery of asphalt binders is strongly dependent on the combined effects of modification level, temperature, and applied stress, with TPS modification playing a key role in enhancing performance.

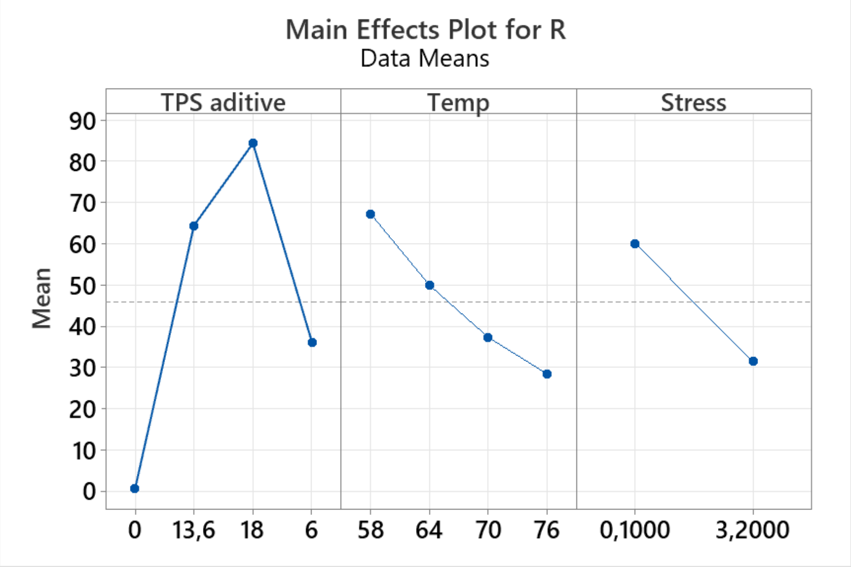

Figure 13. Main effects plot of percent recovery (R) as a function of TPS additive content, temperature, and stress level.

4. CONCLUSION

Based on the experimental findings and statistical analyses, some key conclusions of this study are summarized as follows:

- TPS additive exhibits a dominant effect in reducing J_{nr} of the base asphalt across all investigated temperature and stress conditions. Notably, at 76°C and a stress level of 3.2 kPa, the incorporation of 18% TPS reduces Jnr by up to 87% compared to the 60/70 base binder. This substantial improvement is attributed to the formation of a stable and well-developed polymer network within the asphalt matrix, which enhances stiffness and resistance to shear deformation at high temperatures. However, when compared to PMB III at the same stress level (3.2 kPa), TPS-modified binders still exhibit higher J_{nr} values, indicating relatively inferior resistance to non-recoverable deformation under high shear stress conditions.
- TPS modification fundamentally alters the mechanical response of the binder, shifting it from a predominantly viscous behavior to an elastic-dominated response, as evidenced by the significant increase in R. At the low stress level (0.1 kPa), the binder containing 18% TPS maintains complete recovery (100%) over the temperature range

from 58°C to 76°C, outperforming the reference polymer-modified binder. This behavior indicates the presence of a continuous and robust polymer network that enables near-complete strain recovery upon unloading.

- Non-recoverable deformation resistance and recovery characteristics of asphalt binders are governed by the coupled effects of temperature, stress level, and additive content. The results indicate that temperature is the most influential factor affecting Jnr, whereas TPS dosage is the primary parameter controlling R. Increasing the TPS content significantly reduces both temperature and stress susceptibility, thereby enhancing the stability of the binder under combined high-temperature and heavy loading conditions.

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