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PARALLEL PLATE GAP HEIGHT EFFECT ON DSR MEASUREMENTS OF GTR MODIFIED BINDERS

Zeine Elabidine Boudnani, FIMAS Laboratory, Tahri Mohammed University, Bechar B.P 417, Bechar, 08000 Algeria.
Glaoui Bachir, FIMAS Laboratory, Tahri Mohammed University, Bechar B.P 417, Bechar, 08000 Algeria.
Merbouh M'hammed, FIMAS Laboratory, Tahri Mohammed University, Bechar B.P 417, Bechar, 08000 Algeria.
Francisco Silva, CONSULPAV, Consultores e Projectistas de Pavimentos, Lda., Rua da Zona Industrial, Nº6 A, Casais da Serra. 2665-305 Milharado, Mafra, Portugal
Jorge B Sousa, CONSULPAV, Consultores e Projectistas de Pavimentos, Lda., Rua da Zona Industrial, Nº6 A, Casais da Serra. 2665-305 Milharado, Mafra, Portugal

Abstract

The current Superpave performance grade (PG) specification uses a dynamic shear rheometer (DSR) with a 1-mm gap height to determine the high-temperature performance grade of asphalt rubber binders. Concerns have arisen that rubber particulates exceeding 25% of the gap height might skew the measurements, leading to properties that do not accurately represent the actual behavior of ground tire rubber modified binders. This study explores adjusting the 1-mm gap height to better measure the high-temperature performance properties of these binders and minimize the interaction effects between the asphalt binder and rubber particles on PG grading results. A trial gap height of 2 mm was used to test three different ground tire rubber modified (GTR) binders. Both the standard Superpave high temperature grading test and the multiple stress creep and recovery (MSCR) test were employed. Results indicated a consistent trend for binders with 15% GTR, while notable differences were observed for 18% and 20% GTR. The 2 mm gap provided more stable results over several days compared to the 1 mm gap, likely due to reduced particle interaction at the increased concentration. Based on these findings, a 2 mm gap height is recommended for GTR modified binders.

Keywords: Dynamic Shear Rheometer, Ground tyre rubber, Binder, MSCR, Gap height

1. INTRODUCTION

The improved engineering properties of various modified binders in asphalt applications are well-documented. Rubber-modified binders, for instance, exhibit superior rutting resistance compared to unmodified bitumen [1]. At intermediate temperatures, CRM (Crumb Rubber Modified) binders are less stiff, and in cold climates, such as in Russia, these materials perform well [3].

During 1987-1993, the Strategic Highway Research Program (SHRP) initiated a significant research effort to develop the Superpave performance-based specifications and testing methods for asphalt binders [4], as well as similar tests and mix design practices for hot mix asphalt (HMA) mixes. These specifications were designed to be agnostic of binder source, making them applicable to all binders, irrespective of their source, type, or modifications [6].

Following Superpave protocols to evaluate the rheological properties of asphalt binders presents challenges, particularly in obtaining accurate test results. The presence of rubber particles in ground tire rubber (GTR) modified binders can interfere with testing configurations and pose potential issues during asphalt binder testing [5]. According to AASHTO T315, the gap spacing during testing is set at 1 mm for 25-mm plates and 2 mm for 8-mm plates [8-11]. The size and concentration of residual ground tire rubber particles in the asphalt binders make it challenging to characterize GTR modified binders using the standard Superpave test procedure, which utilizes a 1-mm gap height in the dynamic shear rheometer (DSR). Researchers examined a 2-mm gap height and found that the multiple stress creep and recovery (MSCR) protocol with a 2-mm gap height best correlated with the flow number measured in the asphalt mixture performance tester (AMPT), as well as with rutting performance in the asphalt pavement analyzer (APA) [7-12].

Studies demonstrated that altering the gap height for crumb rubber modified binders significantly affects both the $G^*/\sin\delta$ value and the parameters measured during the Multiple Stress Creep and Recovery (MSCR) test [2-15]. The study also noted higher variability at the 2-mm gap height compared to the 3-mm gap height. Despite the gap height differences and test methods, the MSCR test showed less sensitivity to variations in production day [6].

Researchers have addressed concerns regarding the particle sizes of ground tire rubber (GTR) and questioned the adequacy of standard Superpave protocols for evaluating GTR-modified binders [14]. One of the pioneering studies highlighted that testing crumb rubber binders resulted in significantly higher variability in test results compared to the acceptable limits for conventional binders [16-17]. Another early study investigated various rheological properties of crumb rubber binders, such as rotational viscosity, modulus, phase angle, low-temperature creep stiffness, and m-value. To minimize the impact of rubber particle sizes, they increased the DSR gap height to 2 mm. Their findings indicated that the high-temperature properties of crumb rubber binders depended on CRM particle sizes, and that the linear elastic limits achieved with the 2-mm gap height testing geometry were comparable to those obtained with the 1-mm gap height [13]. Researchers in South Carolina also adjusted the DSR gap height from 1 mm to 2 mm to better accommodate the larger rubber particles in the crumb rubber binders during testing. Through a strain frequency sweep test, they demonstrated that despite the altered testing geometry, the binders maintained their behavior within the linear viscoelastic region [18].

The current study tries to improve the state of the practice with evaluating the DSR gap height and its sensitivity in regard to measured rheological properties in order to fulfill the following objectives:

1. Evaluate the impact of gap height on high-temperature performance parameters and compare to variability between replicates associated with different binders.
2. Evaluate the impact of gap height on MSCR performance parameters and compare to variability between replicates associated with different binders;

2. MATERIALS AND TEST METHODS

2.1 Materials

An unmodified penetration grade 50/70 neat binder, which is a typical binder in Portugal where this project was done, has been modified with ambient Ground Tire Rubber (GTR), sourced from recycled waste tires, was utilized. The composition of the GTR consisted of 80% from truck tires and 20% from car tires, reflecting a blend commonly available in the recycling Algerian market. The GTR was characterized by a fine gradation of 0/0.6 mm (fig 1), suitable for the intended modification of bituminous mixes. The density of the GTR was measured at 1.15 tons per cubic meter, indicating its suitability for use in bituminous compositions.

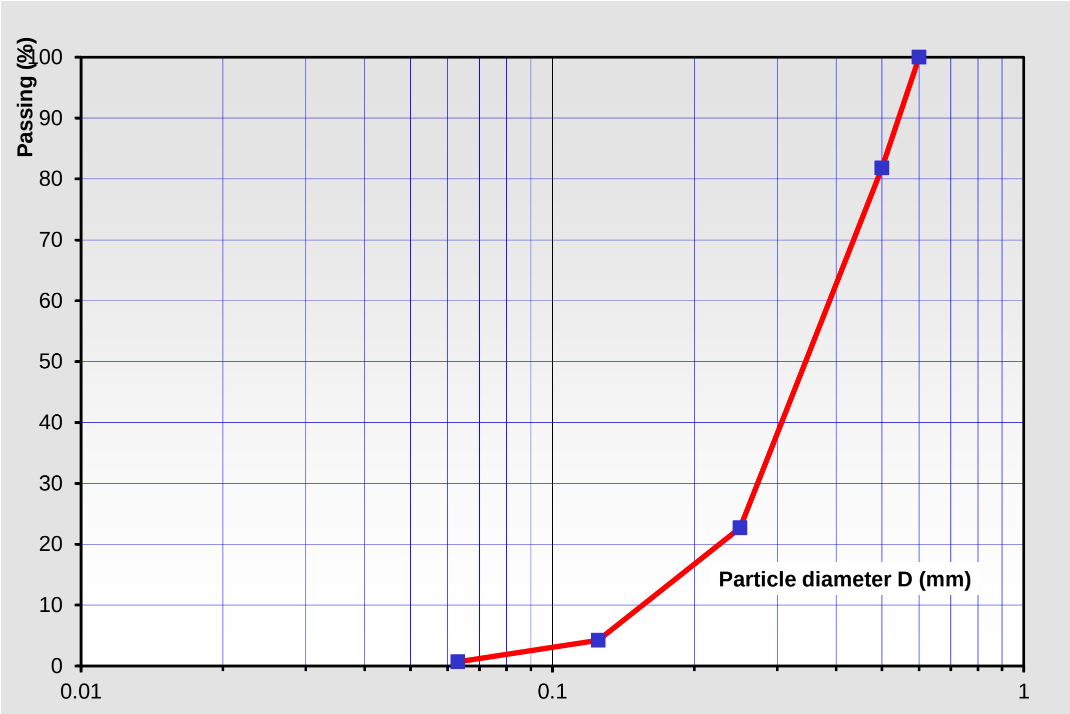
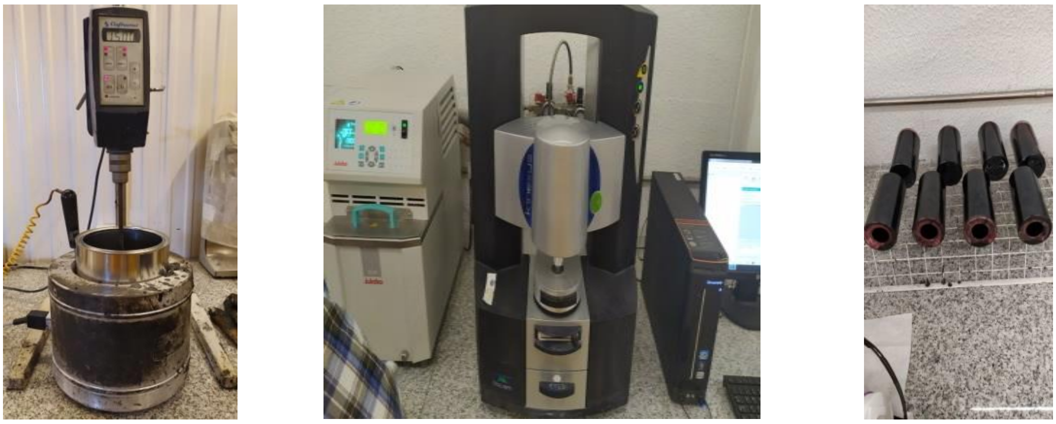


Figure 1: Gradation of Ground Tyre Rubber

To prepare the modified GTR binders, the base bitumen was heated to 180°C. Ground Tire Rubber (GTR) was then incrementally added at different percentages relative to the weight of the binder 15%, 18%, and 20%. These mixtures were blended using a high-shear mixer at 1500t/min for 45 minutes [19-20]. A high-precision laser thermometer monitored and maintained the mixing temperature consistently at 180°C (fig 2).



a b c

Figure 2: Used instruments for the experience (a=high shear mixer, b= dynamic shear rheometer, c= RTFO sample bottles)

Three different production days of each ground tire rubber modified binder were selected as asphalt binders tested in this study. The applicability of using different production days as replicates was evaluated as part of the investigation. Three replicates were tested from different production days and different GTR contents.

2.2 TEST METHODS

2.2.1 High-Temperature Performance Graded Testing

All the modified asphalt binders in this study were graded for high-temperature performance according to AASHTO M320 (AASHTO 2010a). The primary issue with this specification concerns the prescribed 1-mm gap height, which poses challenges in terms of the accuracy and repeatability of Dynamic Shear Rheometer (DSR) measurements. This complication arises because residual particles of ground tire rubber within the asphalt binder could potentially interfere with these measurements, leading to inconsistent results.

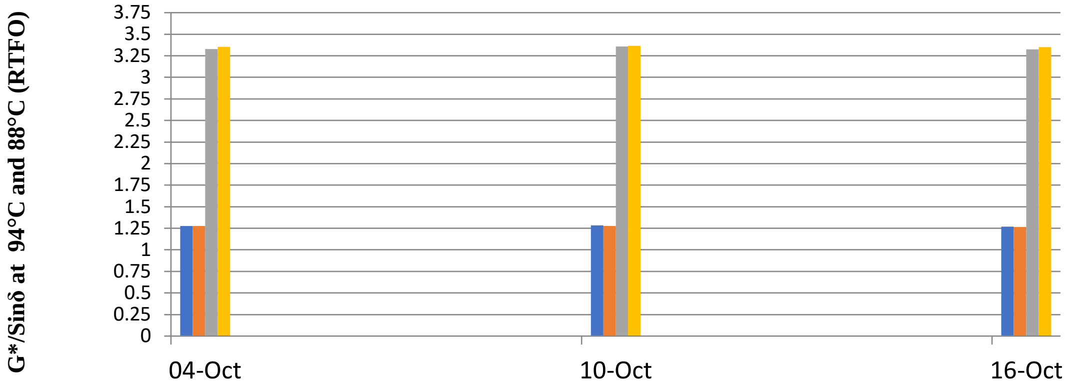
2.2.2 Multiple Stress Creep and Recovery (MSCR) Testing

The Multiple Stress Creep Recovery (MSCR) test was conducted on all binders at 64°C as specified in AASHTO TP70 (AASHTO 2009b). This temperature was chosen to sufficiently reflect the three-grade increment typically resulting from crumb rubber modification. The MSCR test evaluates the binder at the specified climatic grade temperature and applies different specification thresholds based on traffic levels to gauge the degree of modification. During the test, stress levels of 0.1 and 3.2 kPa were applied, each consisting of 10 cycles, with a loading time of 1 second and a recovery time of 9 seconds. The outcomes measured included the average non-recoverable creep compliance (Jnr) and the average percentage of recoverable strain, thereby assessing the binder’s response to repeated loading and its recovery capability.

3. RESULTS AND ANALYSIS

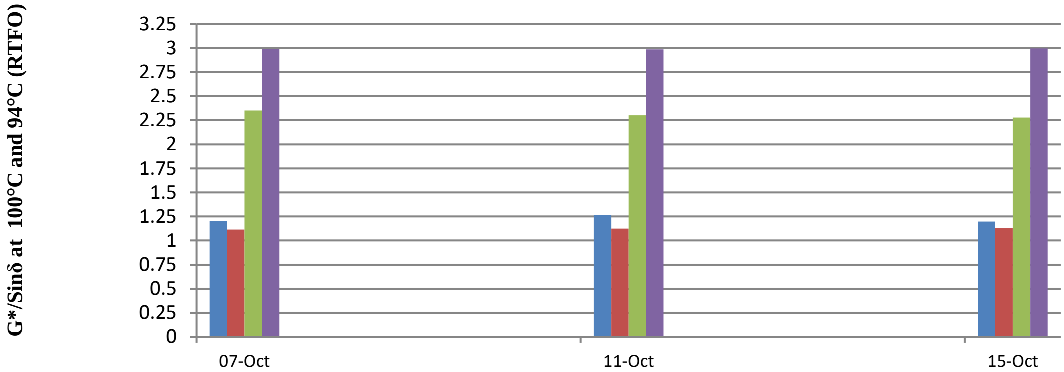
3.1 Analysis of the Superpave High-Temperature Parameter

The purpose of this study was to evaluate the quality of the data collected and analyze the impacts of variations in gap height and production day on the $G^*/\sin\delta$ parameter. Quality was assessed through the repeatability among replicate tests.



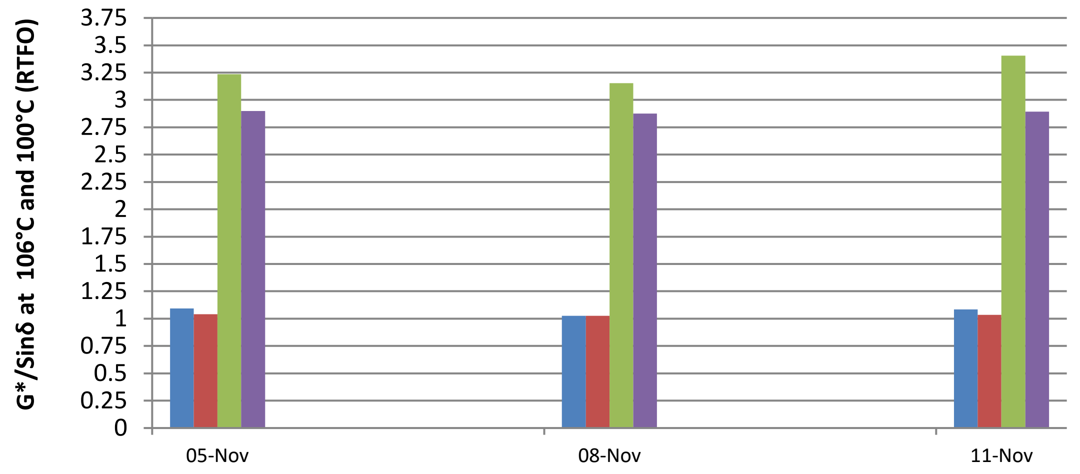
	04-Oct	10-Oct	16-Oct
Unaged 1mm gap	1.276	1.283	1.268
Unaged 2mm gap	1.275	1.275	1.264
RTFO aged 1mm gap	3.327	3.356	3.324
RTFO aged 2mm gap	3.355	3.366	3.349

(a)



	07-Oct	11-Oct	15-Oct
Unaged 1mm gap	1.201	1.263	1.198
Unaged 2mm gap	1.116	1.125	1.129
RTFO aged 1mm gap	2.351	2.301	2.278
RTFO aged 2mm gap	2.991	2.986	2.998

(b)



	05-Nov	08-Nov	11-Nov
Unaged 1mm gap	1.093	1.025	1.085
Unaged 2mm gap	1.041	1.025	1.035
RTFO aged 1mm gap	3.234	3.154	3.405
RTFO aged 2mm gap	2.9	2.875	2.894

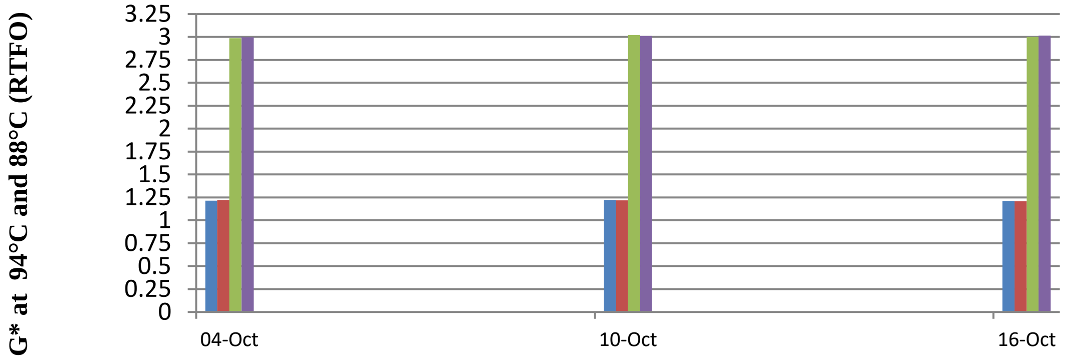
(c)

Figure 3: G/sin δ versus production day for 1- and 2-mm gap heights and GTR contents: (a) 15 GTR; (b) 18 GTR; (c) 20 GTR.

For the 15% GTR modified binder, production day variability shows minimal impact on the un-aged binder for both gap heights, indicating that the effect of different gap heights is negligible based on the data collected. Additionally, aging appears to have a lesser effect on the variance in G*/sin δ values for the 1mm gap, particularly in the un-aged binder state. The data reveal that production day has a negligible effect on the RTFO-aged binder when using a 1mm gap. However, a 2mm gap displays higher G*/sin δ values and shows more significant differences as the production day changes as showed in fig 3.

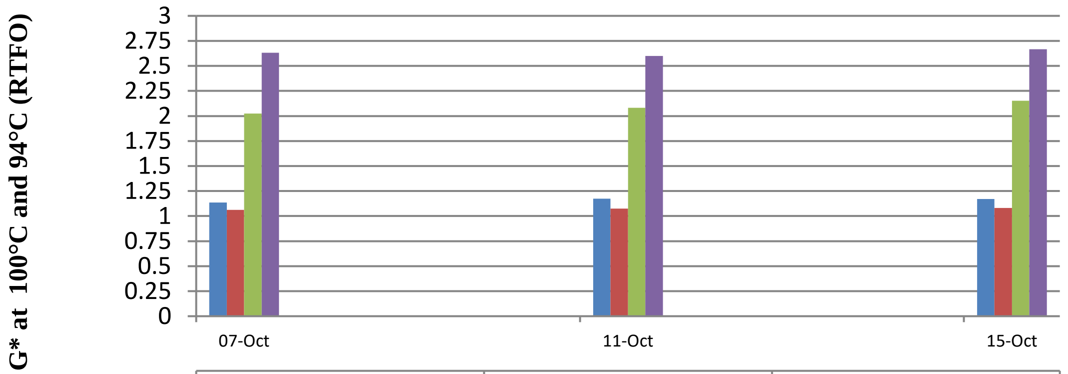
For the 18% GTR modified binder, the data indicate a noticeable sensitivity to the production day at a 1mm gap height for both un-aged and RTFO-aged binders. This sensitivity is attributed to the increased concentration of GTR, which enhances the likelihood of undispersed rubber particles interfering between the plates, potentially skewing the performance output data. Conversely, a different trend is observed for the 2mm gap height for both un-aged and RTFO-aged binders, where the experimental data demonstrate a stable consistency in results. Notably, the impact of the production day is insignificant for both aging states at this gap size, suggesting higher repeatability compared to the 1mm gap. This consistency in the 2mm gap results suggests it may provide more reliable data for un-aged and RTFO-aged binders across different production days.

For the 20% GTR modified binder, the influence of the production day is more pronounced on the G*/sin δ values at a 1mm gap height than at a 2mm gap height for both un-aged and RTFO-aged binders. Specifically, the 1mm gap height exhibits higher G*/sin δ values compared to the 2mm gap, particularly for the RTFO-aged state. This is expected due to the higher concentration of GTR particles within this binder, which can increase interaction between the particles and the test plates over various production days. The results from the 1mm gap height for the 20% GTR binder demonstrate a lack of consistency when compared to the 15% and 18% GTR binders, highlighting the significant impact of GTR particle concentration on obtaining reliable data.



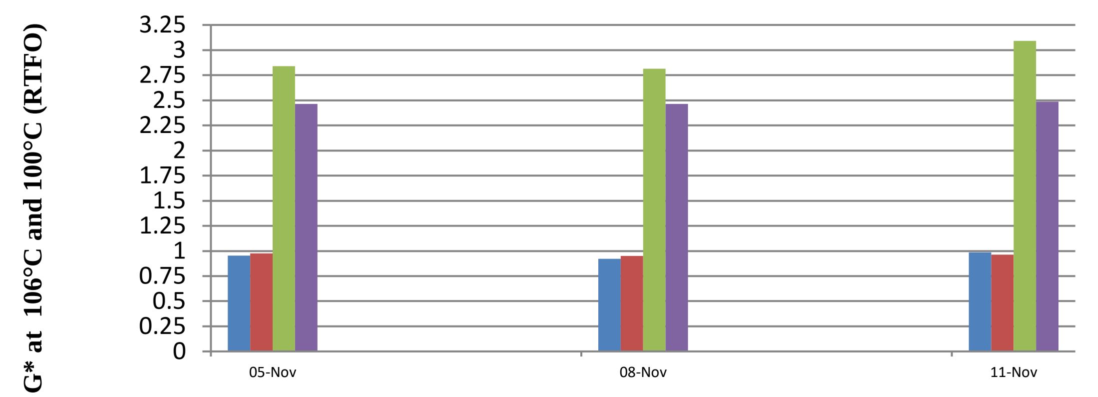
	04-Oct	10-Oct	16-Oct
Unaged 1mm gap	1.215	1.22	1.212
Unaged 2mm gap	1.223	1.218	1.209
RTFO aged 1mm gap	2.988	3.02	3
RTFO aged 2mm gap	2.997	3.01	3.013

(a)



	07-Oct	11-Oct	15-Oct
Unaged 1mm gap	1.134	1.173	1.172
Unaged 2mm gap	1.062	1.075	1.08
RTFO aged 1mm gap	2.025	2.083	2.151
RTFO aged 2mm gap	2.63	2.598	2.665

(b)



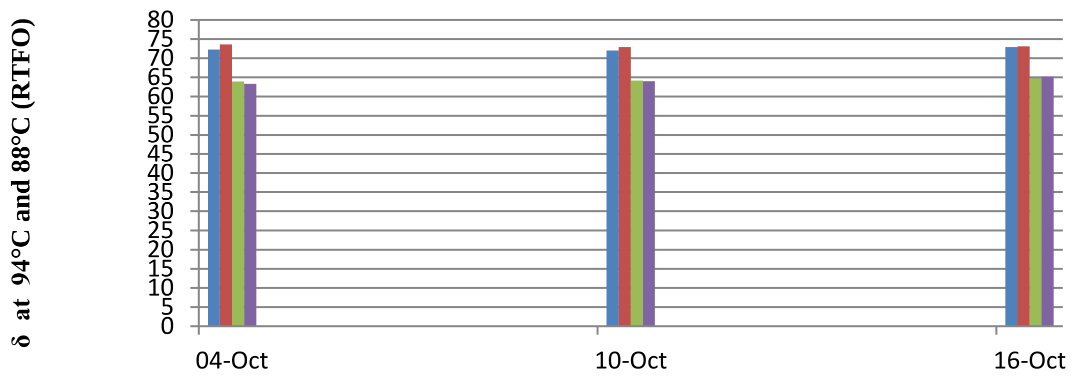
	05-Nov	08-Nov	11-Nov
Unaged 1mm gap	0.954	0.9232	0.9861
Unaged 2mm gap	0.9746	0.951	0.9627
RTFO aged 1mm gap	2.839	2.813	3.091
RTFO aged 2mm gap	2.463	2.464	2.487

(c)

Figure 4: G* versus production day for 1- and 2-mm gap heights and GTR contents: (a) 15 GTR; (b) 18 GTR; (c) 20 GTR.

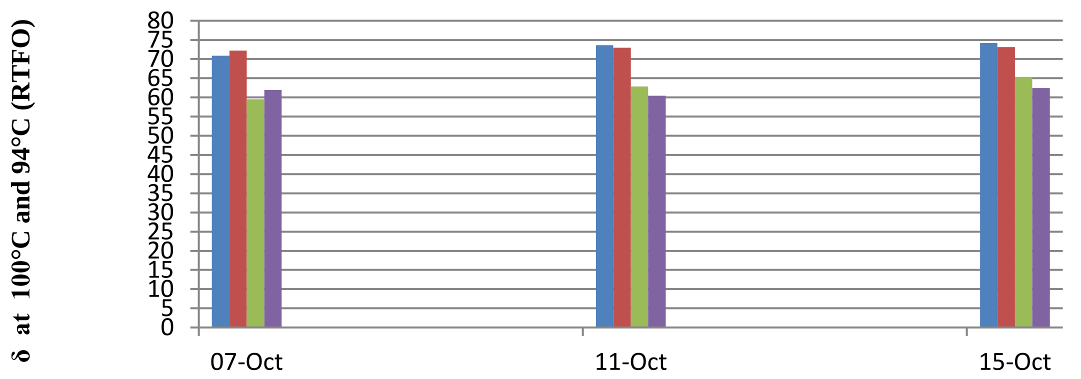
Figure 4 demonstrates that the impact of production day on the complex modulus is minimal for both gap heights across various aging states, particularly for the 15% and 18% GTR binders, which reinforces the repeatability factor for these configurations. Conversely, the 20% GTR binders exhibit different behavior at the 1mm gap height across different aging states, showing inconsistent data especially for the RTFO-aged binder. This inconsistency suggests that higher GTR concentrations may adversely affect the reliability of test outcomes at smaller gap settings.

For the 20% GTR modified binder, data at the 1mm gap height during the RTFOT aging state showed outcomes that were inconsistent with those for the 15% and 18% GTR binders. This variance is primarily attributed to the high concentration of rubber in the binder, which leads to the continuous contact and overlapping of rubber particles within the 1mm gap. The arrangement of these densely packed particles contributes to irregular and unreliable results.



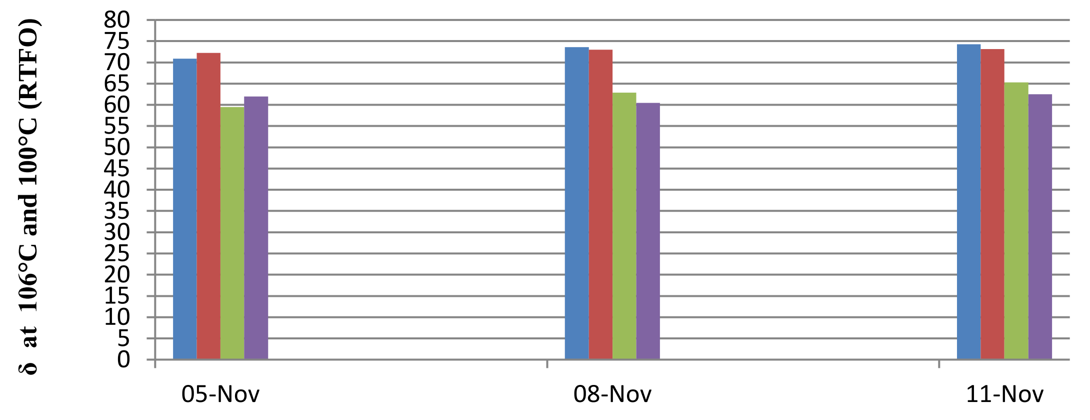
	04-Oct	10-Oct	16-Oct
Unaged 1mm gap	72.22	71.98	72.95
Unaged 2mm gap	73.6	72.9	73.05
RTFO aged 1mm gap	63.91	64.15	64.75
RTFO aged 2mm gap	63.32	64.02	65.2

(a)



	07-Oct	11-Oct	15-Oct
Unaged 1mm gap	70.89	73.6	74.25
Unaged 2mm gap	72.24	72.98	73.15
RTFO aged 1mm gap	59.48	62.85	65.32
RTFO aged 2mm gap	61.95	60.48	62.47

(b)



	05-Nov	08-Nov	11-Nov
Unaged 1mm gap	70.89	73.6	74.25
Unaged 2mm gap	72.24	72.98	73.15
RTFO aged 1mm gap	59.48	62.85	65.32
RTFO aged 2mm gap	61.95	60.48	62.47

(c)

Figure 5: δ versus production day for 1- and 2-mm gap heights and GTR contents: (a) 15 GTR; (b) 18 GTR; (c) 20 GTR.

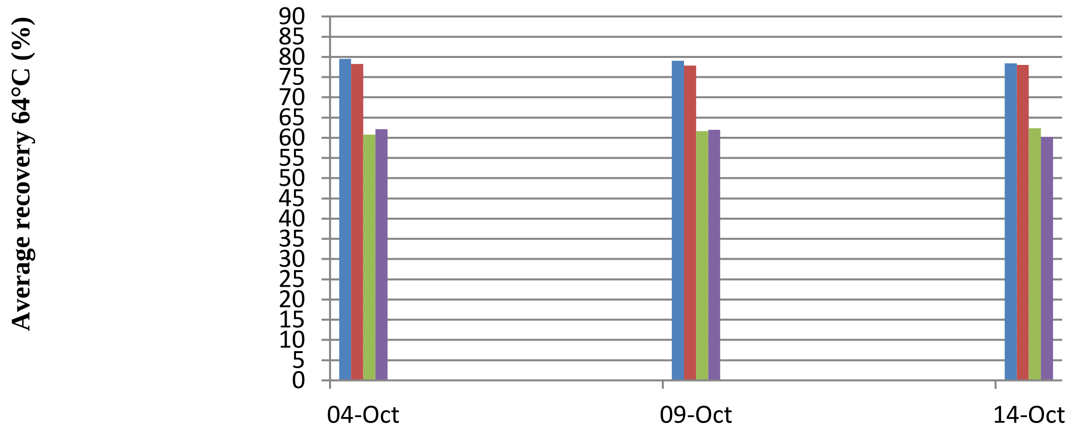
The data presented in Figure 5 indicate a consistent trend for the 15% GTR across both aging states and gap heights, demonstrating that the effect of production day on the overall results is negligible (fig 5). These findings confirm that a gap height of either 1 mm or 2 mm does not significantly affect the phase angle results for this particular GTR content at different aging states.

For 18% GTR, the production day significantly influenced the results, particularly on October 7 compared to October 11 and 15. This variation is likely due to the complexities associated with higher concentrations of modified binders. The data from October 11 and 15 display more consistency than those from October 7, indicating a repeatable testing process for these days. Additionally, the effects of aging follow a similar pattern. An increase in gap height generally resulted in slightly lower values of the phase angle -δ- across different aging states. Figure 5-b illustrates the significant impact of gap heights and production days, underscoring their roles as critical factors in the variability of phase angle -δ- measurements.

The data depicted in Figure 5-c demonstrate a consistent trend across both gap heights. It's observed that higher gap heights result in lower values of the phase angle -δ-. Despite the high concentration of rubber, the phase angle values for both the 1mm and 2mm gap heights were not significantly affected. This consistency suggests that the phase angle -δ- is relatively stable across different gap settings, even in the presence of a high concentration of rubber.

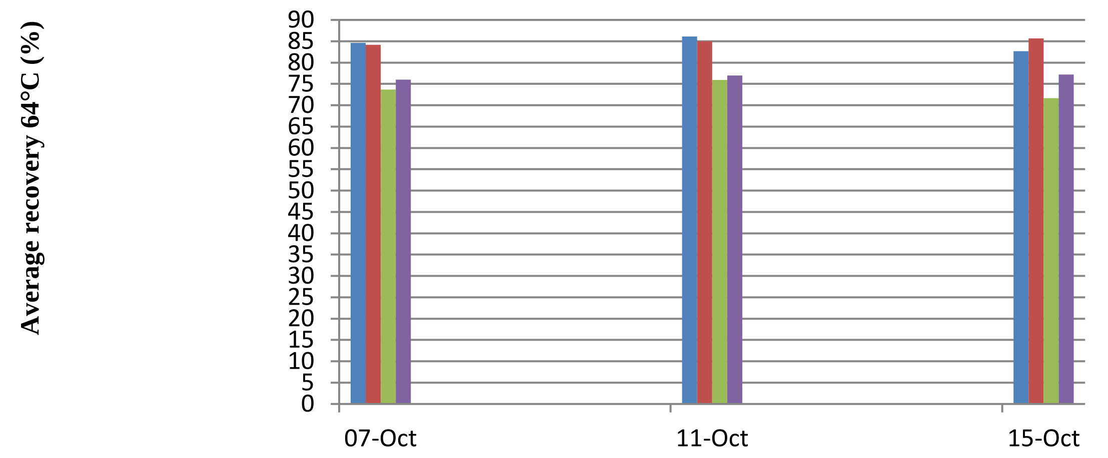
3.2 Analysis of Multiple Stress Creep And Recovery

The Multiple Stress Creep Recovery (MSCR) test is a relatively recent addition to asphalt binder characterization tools, primarily utilized to assess the rutting resistance of modified binders. This test focuses on measuring non-recoverable creep compliance (Jnr) and the percentage of recovery, with computational specifics outlined in AASHTO TP70. In an approach mirroring the analysis used for the G/sin δ parameter, MSCR results were scrutinized to observe how they respond under different test conditions. The specifications for Jnr are detailed and vary according to stress levels due to changes in the limits set by the standards. According to the results depicted in Figure 5, it is evident that the gap height significantly influences the outcomes of the MSCR test, particularly at the lower stress level of 0.1 kPa.



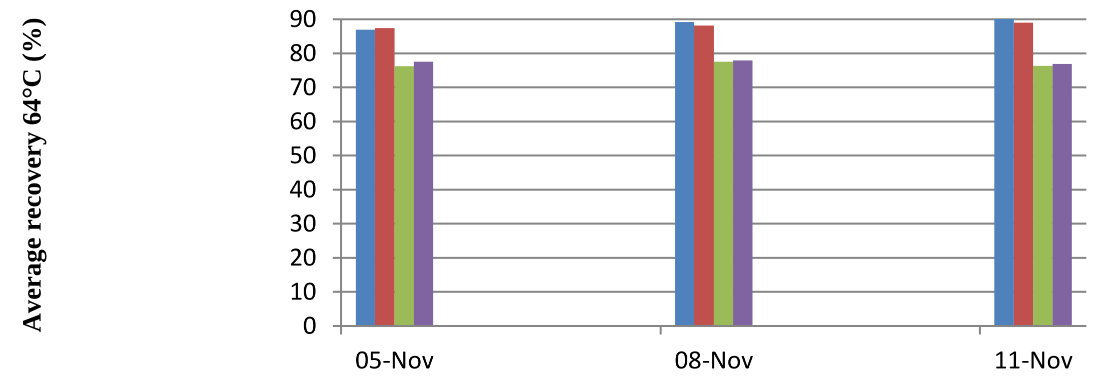
	04-Oct	09-Oct	14-Oct
Average % recovery at 0.1 kPa (1mm)	79.5	79	78.4
Average % recovery at 0.1 kPa (2mm)	78.24	77.89	77.98
Average % recovery at 3.2 kPa (1mm)	60.75	61.65	62.35
Average % recovery at 3.2 kPa (2mm)	62.12	61.98	60.23

(a)



	07-Oct	11-Oct	15-Oct
Average % recovery at 0.1 kPa (1mm)	84.63	86.12	82.65
Average % recovery at 0.1 kPa (2mm)	84.17	85.02	85.64
Average % recovery at 3.2 kPa (1mm)	73.67	75.89	71.68
Average % recovery at 3.2 kPa (2mm)	76.01	76.99	77.18

(b)



	05-Nov	08-Nov	11-Nov
Average % recovery at 0.1 kPa (1mm)	86.9	89.15	91.36
Average % recovery at 0.1 kPa (2mm)	87.39	88.13	89.01
Average % recovery at 3.2 kPa (1mm)	76.2	77.54	76.28
Average % recovery at 3.2 kPa (2mm)	77.55	77.9	76.89

(c)

Figure 6: Recovery (%) versus production day for 1- and 2-mm gap heights and GTR contents: (a) 15 GTR; (b) 18 GTR; (c) 20 GTR.

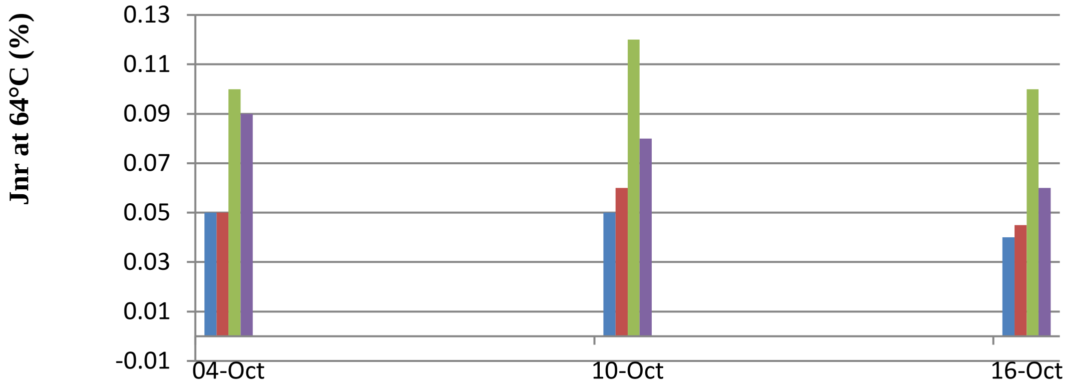
The analysis of the recovery percentages at the 0.1 kPa stress level shows that for 15% GTR-modified binders (fig 6-a), changes in gap height from 1mm to 2mm produce acceptable variations in recovery across different production days. At the higher stress level of 3.2 kPa, there's a clear trend where increasing the gap height from 1mm to 2mm enhances recovery, reflecting expected differences in binder stiffness at these settings. This suggests that the 3.2 kPa stress level is more sensitive to changes in gap height compared to the 0.1 kPa level.

For 18% GTR, Figure 6-b indicates that changes in gap height do not significantly affect the recovery percentage at the 0.1 kPa stress level, with most data points showing that an increase in gap height leads to a decrease in recovery percentage, except for an anomaly on October 15th. At the 3.2 kPa stress level, like the 15% GTR, increasing the gap height generally leads to increased recovery percentages. This consistent trend across different GTR concentrations and stress levels highlights the critical influence of gap height on the mechanical behavior of GTR-modified binders under varied loading conditions.

For the 20% GTR modified binder, the results displayed in Figure 6-c illustrate those variations in gap height at the lower stress level of 0.1 kPa across different production days, with the exception of November 5th, generally do not significantly impact the percentage of recovery. Notably, at this stress level, a 2mm gap results in slightly lower recovery percentages compared to the 1mm gap, which aligns with expectations given the smaller applied stress and the associated differences in binder stiffness.

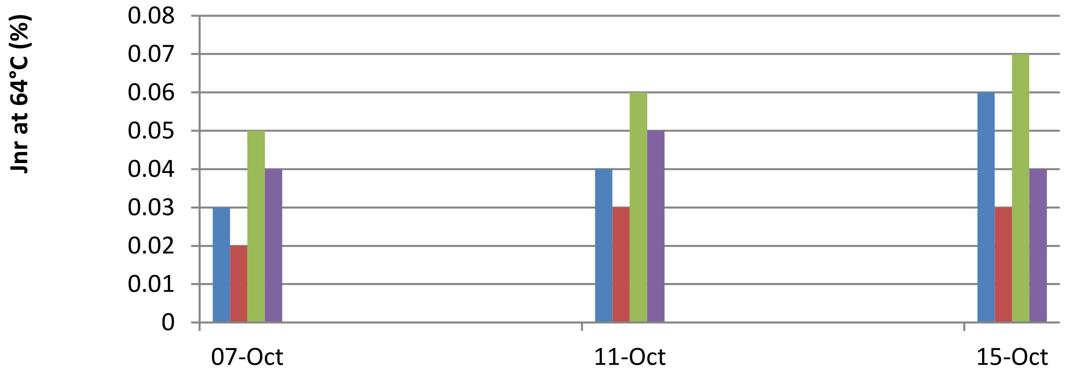
Conversely, at the higher stress level of 3.2 kPa, the 1mm gap height consistently shows lower recovery percentages compared to the 2mm gap. This indicates that the binder's response at 3.2 kPa is more sensitive to changes in gap height, suggesting that the binder's stiffness characteristics are more critical under higher stress conditions.

From the overall trends observed in Figure 6, it's apparent that the concentration of GTR has minimal influence on recovery percentages at the 0.1 kPa stress level for any gap height across different production days. However, the same GTR concentration exhibits more pronounced differences at the 3.2 kPa stress level, influenced by both production day and gap height. This highlights the need for careful consideration of gap height in testing protocols, especially at higher stress levels where binder properties and particle interactions become more influential.



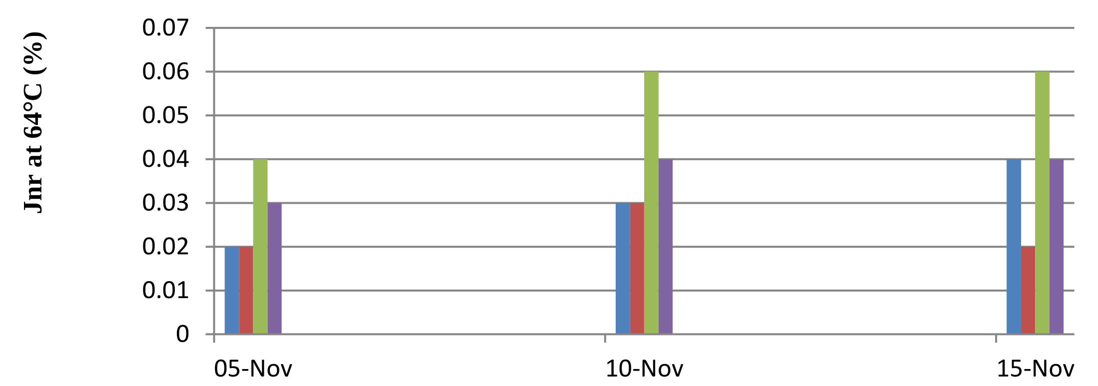
	04-Oct	10-Oct	16-Oct
Jnr at 0,1kPa(1mm)	0.05	0.05	0.04
Jnr at 0,1 kPa (2mm)	0.05	0.06	0.045
Jnr at 3,2 kPa (1mm)	0.1	0.12	0.1
Jnr at 3,2 kPa (2mm)	0.09	0.08	0.06

(a)



	07-Oct	11-Oct	15-Oct
Jnr at 0.1 kPa (1mm)	0.03	0.04	0.06
Jnr at 0.1 kPa (2mm)	0.02	0.03	0.03
Jnr at 3.2 kPa (1mm)	0.05	0.06	0.07
Jnr at 3.2 kPa (2mm)	0.04	0.05	0.04

(b)



	05-Nov	10-Nov	15-Nov
Jnr at 0.1 kPa (1mm)	0.02	0.03	0.04
Jnr at 0,1 kPa (2mm)	0.02	0.03	0.02
Jnr at 3,2 kPa (1mm)	0.04	0.06	0.06
Jnr at 3.2 kPa (2mm)	0.03	0.04	0.04

(c)

Figure 7: Non-recoverable creep compliance -Jnr- (%) versus production day for 1- and 2-mm gap heights and GTR contents: (a) 15 GTR; (b) 18 GTR; (c) 20 GTR.

For the 15% GTR modified binder, the analysis demonstrates minimal sensitivity of the Jnr (%) values to changes in gap height at the lower stress level of 0.1 kPa. This indicates that the non-recoverable creep compliance at this stress level is less affected by the variations in gap spacing between the DSR plates, suggesting robustness in the binder's performance under milder stress conditions (fig 7).

The influence of the production day on the test outcomes is notable; highlighting those day-to-day variations in production can impact the rheological properties of the modified binder. At the 0.1 kPa stress level, the 2mm gap height consistently resulted in higher Jnr (%) values compared to the 1mm gap. This trend persisted at the higher stress level of 3.2 kPa, where the larger gap also demonstrated higher Jnr (%) values relative to the smaller gap.

These findings imply that the stiffness of the binder, influenced by the gap height, plays a crucial role in determining the non-recoverable creep compliance of the material. The increased gap height appears to accommodate the rubber particles more effectively, thereby reducing the interference in the measurement and resulting in higher Jnr values. This suggests that for 15% GTR modified binders, utilizing a larger gap height could enhance the accuracy and repeatability of high-stress level MSCR testing, accounting for the inherent variability introduced by rubber modification and production conditions.

Results showed that Jnr (%) at 3.2 kPa has higher sensitivity to gap heights changes compared to Jnr(%) at 0.1 kPa, the production day effect on data stability has been observed as contribution factor for Jnr (%) at 3.2 kPa.

For the 18% GTR modified binders, the observed data trends highlight how the concentration of ground tire rubber affects the rheological properties of the asphalt binders, particularly in terms of non-recoverable creep compliance (Jnr) at different stress levels and gap heights.

At the lower stress level of 0.1 kPa, the 2mm gap height consistently demonstrates lower Jnr(%) values across different production days, suggesting that the increased gap height may help reduce the measurement interference caused by larger rubber particles, thus providing a clearer picture of the binder's actual viscoelastic properties. This reduction in Jnr(%) values at a larger gap height indicates better rutting resistance potential at mild stress conditions, which is beneficial for the performance longevity of asphalt pavements under normal traffic loads.

At the higher stress level of 3.2 kPa, the trend remains consistent with that observed for 15% GTR binders, where increasing the gap height leads to decreased Jnr (%) values. This suggests that the modified binder with higher rubber content maintains its performance integrity even under increased loading, reflecting its capacity to withstand significant traffic stresses without substantial deformation.

The consistency in the trend of Jnr (%) values across different production days for both stress levels indicates a stable production process for the 18% GTR modified binder. However, it also underscores the importance of considering production variability when assessing the performance of rubber-modified asphalt binders, as slight changes in production conditions can influence the viscoelastic properties of the binder.

Overall, the findings for the 18% GTR modified binder reinforce the utility of adjusting the DSR gap height to better evaluate the performance characteristics of GTR modified binders, especially at varying stress levels that simulate different traffic conditions. This approach allows for a more accurate assessment of the binder's rutting resistance potential and durability under real-world conditions.

For the 20% GTR modified binders, the results presented reflect the complexities introduced by a higher concentration of ground tire rubber in the asphalt mix. At a 0.1 kPa stress level, the increase in gap height from 1mm to 2mm shows limited influence on the non-recoverable creep compliance (Jnr) values. This observation suggests that the dense concentration of rubber particles in these binders might be leading to mechanical interference within the measurement system, particularly at smaller gap heights where particle contact is more probable. The inconsistency across different production days, except for November 15th, underscores the variability introduced by such high levels of rubber modification.

At the higher stress level of 3.2 kPa, the behavior of the 20% GTR modified binder aligns more closely with that of the 18% GTR, where increasing the gap height reduces the Jnr values. This suggests that at higher stress levels, the binder's viscoelastic properties are less affected by particle interference and more reflective of the binder's inherent characteristics. The reduction in Jnr values at a 2mm gap height underlines improved binder performance due to decreased sensitivity to particle interference, enhancing the binder's ability to recover after loading.

These findings reinforce the concept that higher GTR concentrations can complicate the evaluation of binder properties due to the physical presence and distribution of rubber particles. It also highlights the importance of selecting appropriate gap heights in dynamic shear rheometer testing to obtain reliable data, especially when dealing with heavily modified binders. Adjusting the gap height not only helps in accommodating the physical size of the rubber particles but also in achieving more accurate assessments of the binder's performance under conditions that reflect real stresses.

4. Conclusion and recommendations

This study aimed to evaluate how gap height and production day influence the test parameters obtained from standard Superpave grading and the Multiple Stress Creep Recovery (MSCR) test on ground tire rubber (GTR) modified binders. While the research is limited to specific types of GTR binders, it provides valuable insights into refining test methodologies for GTR modified binders. Based on the findings, the following conclusions are drawn:

1. Impact of Gap Height: The gap height in dynamic shear rheometer (DSR) testing significantly affects the measured parameters, particularly $G^*/\sin\delta$ and Jnr values. A 2-mm gap height generally results in higher $G^*/\sin\delta$ values, indicating increased stiffness, and lower Jnr values, suggesting better performance against rutting. This is attributed to reduced particle interference at this larger gap height, which likely provides a more accurate assessment of the binder's viscoelastic properties. For complex modulus, the data variance is primarily attributed to the high concentration of rubber in the binder, which leads to the continuous contact and overlapping of rubber particles within the 1mm gap. The arrangement of these densely packed particles contributes to irregular and unreliable results. For phase angle, despite the high concentration of rubber, the phase angle values for both the 1mm and 2mm gap heights were not significantly affected. This

consistency suggests that the phase angle -δ- is relatively stable across different gap settings, even in the presence of a high concentration of rubber. The concentration of GTR has minimal influence on recovery percentages at the 0.1 kPa stress level for any gap height across different production days. However, the same GTR concentration exhibits more pronounced differences at the 3.2 kPa stress level, influenced by both production day and gap height.

2. Production Day Variability: The study highlights significant variations in binder properties depending on the production day, particularly for the G*/sin δ parameter. This variation underscores the need for careful quality control in production and testing processes. The MSCR test exhibited less sensitivity to production day variations, suggesting it might be a more reliable method for assessing the performance characteristics of GTR modified binders under varying production conditions.
3. Recommendation for Gap Height: For the types of GTR binders tested—considering their specific gradation and rubber content, a 2-mm gap height is recommended for both PG grading and MSCR tests. This recommendation is based on the observed reduction in measurement anomalies likely caused by particle interference at the conventional 1-mm gap height.

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