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RHEOLOGICAL CHARACTERIZATION OF RECLAIMED ASPHALT BINDER BLENDED WITH THE NEAT AND SBS-PMA BINDERS

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ABSTRACT

Reusing reclaimed asphalt pavement material guarantees a substantial optimization of non-renewable material resources, emissions reduction, and decreasing landfill space, along with the economic benefits associated with saving the costs of purchasing and transporting new aggregate and asphalt binder for asphalt concrete mixture production. This study aims to investigate the influence of aged asphalt binder from reclaimed asphalt pavement on the virgin asphalt binder's rheological properties. Therefore, different dosages of RAP binder (20%, 30%, and 40% by weight of the total mix) were blended with neat asphalt binder (40-50), penetration grade (P40), and SBS polymer asphalt (SBS-PMA) binder. Using both traditional and Superpave performance testing methods, the effects of RAP on the blend's consistency, viscosity, softening, elastic recovery, rutting (permanent deformation), fatigue cracking, and low temperature cracking were evaluated. The results revealed that the RAP binder decreased the penetration value of both neat and SBS-PMA binders. The neat asphalt binder's viscosity and softening point increased with the increase in RAP content, whereas they decreased for SBS-PMA. The RAP binder decreases the SBS-PMA elastic recovery. where the neat asphalt experienced a little improvement in elastic recovery when blended with the RAP binder. The Superpave test results revealed that the RAP binder deteriorates the performance of the SBS-PMA binder at high, intermediate, and low testing temperatures. With the addition of 20%, 30%, and 40% RAP, the high-temperature PG grade of SBS-PMA blends decreased by 0.64%, 0.95%, and 1.10%, respectively, while the low-temperature PG grade increased by 23%, 31%, and 32%, respectively. In contrast, the RAP improves the neat asphalt blend's high-temperature performance grade and deteriorates intermediate and low-temperature performance grades. The addition of 20%, 30%, and 40% RAP increased the neat asphalt blends' high-temperature properties by 1.5%, 3.3%, and 4.5%, respectively. whereas the neat asphalt low-temperature PG grade increased by 5%, 11%, and 15% with the addition of 20%, 30%, and 40% RAP, respectively. In summary, the performance of virgin and RAP binder blends depends on the individual characteristics of the blended asphalt binders.

***KEYWORDS**:* Reclaimed asphalt pavement (RAP); Superpave performance grade; Rheology; SBS polymer modified asphalt;

1. INTRODUCTION

Recycling asphalt pavements is one of the important achievements in the highway construction industry. It started a hundred years ago, but it came into practice in the late 1970s after the increase in asphalt prices due to the embargoing of the Arab oil [1-3]. Recycling asphalt pavement materials using both reclaimed aggregate and binder is widely known as Reclaimed Asphalt Pavement (RAP).

The importance of reusing RAP in the asphalt pavement industry is economic and has environmental benefits in addition to technical advantages. The environmental merits comprise emissions and energy reduction associated with the production and transportation of new materials, saving non-renewable material resources, and decreasing the landfill area required for disposing of the waste materials. Economic benefits include saving on the costs of purchasing and transporting neat aggregate and asphalt binder for a new mixture[2]. Despite these benefits, the main challenge of using RAP in pavement construction is the stiffness of the RAP binder, which results from the gradual aging of the asphalt binder, which oxidizes and alters its viscoelastic properties[4, 5].However, mixtures with high RAP contents are not commonly used.

The RAP proportion in new hot mix asphalt (HMA) mixtures is typically limited to between 15 and 30%, but in practice, less than 25 % is allowed in the wearing course [2, 6]. Within these limits, the RAP binder's aging can be restored using a softer asphalt binder. The virgin binder grade selection is based on the RAP binder grade, the percentage of RAP to be added, and the regional performance grade (PG) requirements of the asphalt binder [5]. The effect of the RAP binder on the performance of the blended binders (Virgin + RAP) is proportional to the RAP proportion in the mixture. At low rates, the effect is minimal, and RAP acts as a “black rock” (pure inert aggregate) that influences the asphalt concrete mixture's volumetric properties only through aggregate gradation and mechanical properties. While at high RAP rates, the RAP and virgin binder bind with each other in such a way that the blended binder properties are significantly altered.[6].

Most State road authorities and country guidelines assumes the blending that’s occur between the virgin and RAP binders is 100% [7]. In contrast to this common practice, numerous studies have revealed that only a portion of the RAP binder functions as an effective binder in the new asphalt mixture formulation[8, 9]. With the addition of a high RAP percent, softening agents or rejuvenators might be required for the restoration of the aged binder properties[10]. The introduction of the softening agents to the asphalt mixtures represents an additional mix design variable that requires the selection of the optimum doses and compatible agent [9].

The high stiffness and brittleness of the aged binder is the main challenge with increasing the recycled asphalt material amount in hot-mix asphalt (HMA) mixtures, which raises the concern of premature pavement cracking [6, 11-13]. A stiffer asphalt concrete mixture might be more susceptible to fatigue, reflection, and thermal cracking, which are considered the main reasons for the unwillingness of the road authorities to use RAP mixtures.

Numerous studies highlight that the addition of RAP to well-designed asphalt concrete mixtures makes the resulting mixes more resistant to permanent deformations [10, 14]. Flexible pavements constructed with neat asphalt binder (unmodified) are not strong enough to resist the increased traffic loading and extreme environmental conditions. Several pavement deteriorations are related to the asphalt binder rheological properties. To mitigate the deficiencies in neat asphalt, polymer modification has been introduced for improving the asphalt binder rheology to enable pavement made with polymer-modified asphalt to resist the stresses and strains induced by heavy traffic loads and environmental conditions [15]. For better performance of the asphalt pavement, Polymer-Modified Asphalt (PMA) has long been studied. The Styrene-butadiene-styrene (SBS) copolymer-modified asphalt was primarily developed for the fact that it could improve the rutting resistance, resistance to fatigue cracking, low-temperature cracking resistance and stripping resistance [16-20]. However, the polymer modification benefits may be reduced with the addition of a RAP binder, especially for low-temperature cracking. Therefore, the usage of RAP is limited to about 20% with the use of PMA [5, 21].

The asphalt binder from the RAP affects the physical and rheological properties of virgin asphalt in the RAP asphalt concrete mixtures. The penetration of virgin asphalt blended with reclaimed asphalt binder decreases with the increase of RAP [22, 23].Both the softening point and the viscosity of the blended binder increase with the addition of reclaimed asphalt to the virgin asphalt binder. [22, 24-26]. The addition of RAP to virgin asphalt improves the elastic recovery of the blended binder [23, 24], while the RAP reduces the elastic recovery of the SBS-PMA binder [24, 27].

Only a few studies were conducted during the last decade on the impact of RAP content on SBS-modified asphalt binders with and without rejuvenators.

Hossain, Zaman [25]used RAP binder from different sources mixed with asphalt binder grade (PG64-22) to investigate the rheological performance of the blended binder. The Superpave performance grade (PG) and rotational viscosity were used to identify the low and high PG temperatures and binder viscosity. The results showed an increase in the high PG temperature and viscosity with the increase in RAP content, while the low PG temperature reduced significantly with the RAP increase .**Zhou, Gu [28],**used neat high penetration asphalt binder (PG 64-22), two SBS-modified binder grades (3% and 3.5% SBS), three rejuvenator dosages (2%,4%, and 6% by weight of RAP), and four RAP contents to assess the permanent deformation and fatigue cracking performance of blended binders. The results showed an increase in the rutting performance of binders and a deterioration in their elastic recovery behavior.

Khan, Koting [29]evaluated asphalt mixtures containing 20%, 40% and 50% of (RAP) using virgin and SBS-PMA binder. The investigation concluded that the 20 percent RAP mixture performed approximately similar to a mixture with virgin asphalt and virgin aggregate. Furthermore, the SBS polymer modification improves mixture properties even at high RAP contents. **Izaks, Rathore [30**]examined the performance of a high modulus asphalt concrete mixture (HMAC) produced from reclaimed asphalt pavement material (0–70%) and SBS-modified binder. The performance of the mixtures was tested using the wheel tracking test, the semi-circular bend test, the thermal stress restrained specimen test, the water sensitivity test, and the four-point bending test. The study outcomes demonstrated the possibility of production HMAC with satisfactory performance from a mixtures incorporating high RAP content using SBS polymer modified binder, which can be used successfully in extreme cold extreme cold regions.

According to the literature and the author’s knowledge, there is a lack of studies regarding the effect of RAP on the low penetration asphalt binder (i.e., 40–50) and SBS-modified asphalt binder performance without using the rejuvenators. Therefore, the aims of this study are to investigate the effects of different RAP percentages on the low penetration grade neat asphalt binder(P40) and SBS modified asphalt binder (P40asphalt binder with 4% SBS) performance using conventional and Superpave Performance Grading (PG) tests.

2. METHODOLOGY

This study is an investigation of the laboratory performance characterization of low penetration grade neat (i.e.,40–50) and SBS-PMA binders blended with different percentages of RAP using conventional and Superpave performance tests.

2.1. Materials

In addition to the reclaimed asphalt binder that is recovered from RAP, neat asphalt and SBS-PMA binders were used in this study.

The RAP material was collected from the top 6 cm of the 10-year-old binder layer of the Ibrahim Khalil–Duhok highway using the cold milling process. The neat asphalt (40-50) penetration grade and the SBS polymer modified asphalt binder (4% SBS) are the most commonly used in the Kurdistan region of Iraq for the construction of HMA mixtures. Therefore, these two types of binder were selected for this study. Table **(1** summarizes the characteristics of neat and SBS-PMA binder, while the SBS polymer properties are presented in Table (**2**.

Table (1): Characteristics of Neat and SBS-PMA Binder:

Test properties	Results		Standard Code
	Neat Binder	**SBS PMA binder**	
Penetration @ 25 °C (0.1 mm)	43.8	31.0	AASHTO T- 49
Softening Point (Ring-and-Ball) C	52.60	72.5	AASHTO T- 53-09
Ductility@ 25 °C (cm)	>100	>100	ASTM D113
Rotational Viscosity @ 135 °C (Pa.s)	0.556	2.472	AASHTO T-316
Elastic Recovery@ 25 °C (%)	4.75	76.45	AASHTO: T- 301
Asphaltene Content (%)	25	-	ASTM D6560
Superpave PG Grade(°C)	70-16	82-22	AASHTO R 29

Table (2): SBS Polymer Properties

Property	Unit	Value
Styrene	%By mass	30
Specific Gravity		0.94
Hardness, Shore A (15 sec)	Shore A	70
Melt Flow Rate, 200C/5kg	g/10min.	<1

2.2. Experimental Plan And Test Procedures

This investigation is part of a larger study to assess the effect of different RAP percentages on the performance of hot mix asphalt (HMA) mixtures produced with both neat asphalt (NA) and SBS-PMA binder. Different RAP parentages (0%, 20%, 30%, 40%, and 100%) were considered for the preparation of the asphalt concrete mixture for each binder type (neat and SBS-PMA). Nine asphalt binder blends, including the neat and SBS-PMA binder (NA+0%RAP, NA+20%RAP, NA+30%RAP, NA+40%RAP, SBS+0%RAP, SBS+20%RAP, SBS+30%RAP, SBS+40%RAP, and 100% RAP), were prepared based on the RAP Binder Replacement Ratio (RBRR).

The RBBR is the percentage of the binder from RAP that replaces the virgin binder in HMA mixtures. Table (3 presents the RBRR for each RAP percentage used in the study.

The conventional properties (penetration, softening point, rotational viscosity, and elastic recovery) were laboratory measured. Similarly, the Superpave performance tests were conducted to evaluate the rheological properties of the asphalt binder blend. Fig. (1 presents the experimental plan of this study.

Table (3): RAP Binder Replacement Ratio (RBRR)

Blend Name	RAP%	RBRR % (percent of RAP binder from total binder)
0%RAP	0	0
20%RAP	20	17.1
30%RAP	30	24.1
40%RAP	40	28.3
100%RAP	100	100

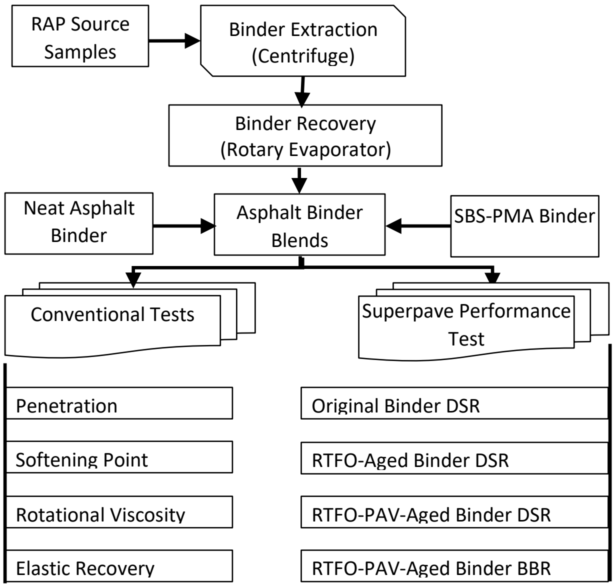

Fig. (1): Experimental Plan Flow Chart

2.3. rap binder extraction and recovery.

The binder was extracted from the RAP materials using AASHTO T-164-13[31] (Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)) by means of centrifuge extractor at 3600 r/min and toluene as a solvent. To remove the remaining filler materials, the extracted solution is subjected to multiple centrifuging processes using a continuous flow rate of 100 to 150 mL/min using three filter papers. Following asphalt extraction, the asphalt binder is recovered from the solvent using a rotary evaporator as per ASTM D7906−14 [32]without significantly altering the recovered asphalt binder properties as shown in Fig. (2.

Fig. (2): Rotary Evaporator

2.4. Preparation Of Binder Blends

The neat and SBS-PMA asphalt binders were mixed with the specified percentage of RAP binder using a high-shear mixer for 30 minutes at 150 °C for the neat binder and 175°C for the SBS-PMA binder [33]. The 0%RAP and 100%RAP blends were subjected to the same blending conditions (temperature, duration, and shear rate) for a fair comparison with the other blends.

2.5. Blended Asphalt Binder Rheological Characterization

Different conventional and superpave asphalt binder tests were performed to characterize the asphalt binder's rheological properties.

A penetration test was conducted to measure the effect of RAP on the hardness and consistency of asphalt binder blends, using the AASHTO T-49 [29] test procedure.

The Softening point was used to measure the effect of RAP on asphalt binder viscosity transition temperature and temperature susceptibility. The softening point test was performed as per AASHTO T- 53-09[31] using the Ring and Ball apparatus.

Elastic recovery (ER) by a ductilometer was used to measure the rate at which a material returns to its original shape after application and releasing of the stresses. A higher elastic recovery value is desirable in flexible pavement to prevent permanent deformation (Rutting).The test was conducted as per (AASHTO:T-301)[31].

The Rotational Viscosity (RV) test at 135 °C , according to AASHTO T316[31] was used to determine the asphalt binder's high-temperature flow characteristic. The test result shall be less than 3.0 Pa.s as specified in AASHTO M230 [31].

To evaluate the rheological performance of the asphalt binder, blends were tested using the Superpave performance according to the requirements of the AASHTO M 320 [31] procedures. The tests were conducted to measure the critical temperature where the specifications are exactly met. The measured temperature is called the critical temperature (continuous grade or true grade). The critical temperature determination requires performing the tests at two temperatures bracketing the specification limits [34].

To measure the rutting performance of the asphalt binder blends, high-temperature (T_C ($High$)) was calculated by performing a Dynamic Shear Rheometer (DSR) test on the original binder without any aging processes. The T_C ($High$) was calculated based on a test result where the G*/sinδ is equal to a value of 1.00 kPa as shown in Fig. (3 using the following Equation:

$$T_c = T_1 + \left(\frac{\log(G_2\ ) - \log\ (G_1\ )}{\alpha}\right) \qquad \text{Eq. 1}$$

Where
T_C = High critical temperature
T_1 = Lower value of the two-test temperatures
$G_1 = G^*/\sin\delta$ at T_1
G_2=1.00 kPa

α = Stiffness-Temperature curve slope and determines as per the following Equation

$$\alpha = \Delta \log\left(\frac{G^*}{Sin\delta}\right)/\Delta T \qquad \text{Eq. 2}$$

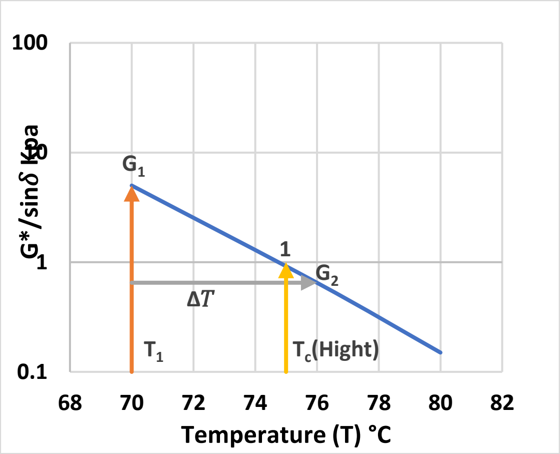

Fig. (3): Critical Temperature Determination

The asphalt binder blends were aged using a rolling thin-film oven (RTFO) as per AASHTO T-240[31].Then the critical high temperature (T_C (*High*)) of the RTFO- aged binder, corresponding to the $G^*/\sin\delta$ value of 2.2 kPa ,is calculated utilizing DSR ,using Eq.3 and Eq.2 for G_2 =2.2 kPa .

The lowest high critical temperature T_C (*High*) value from the original DSR and RTFO-DSR is to be selected to represent the high critical temperature of the asphalt binder blend.

To address the effects of long-term in-service aging on the blend's fatigue performance, the residue from RFTO was further aged in a pressure aging vessel (PAV) at 110 °C for 20 hours, pressurized with 2.1 MPa air pressure as per AASHTO R28.

The vacuum degassing oven (VDO) was used to precisely and accurately degas PAV-aged binder samples and to rapidly remove the entrapped air bubbles in asphalt binder specimens. The asphalt binder samples were immediately placed in the VDO at a maintained temperature of 170±5°C for15 ± 1 min. at the required 15 ±1.0kPa vacuum pressure.

The DSR intermediate critical temperature T_C *(Int.)* of asphalt binder blends was determined for the PAV-aged specimens. The T_C *(Int.)* corresponds to $G^*.\sin\delta$ value of 5000 kPa calculated using Eq.4 and Eq.2

$G_1 = G^*.\sin\delta$ at T_1
G_2=5000 kPa

To identify the cracking resistance capability of the blended binders, the Bending Beam Rheometer (BBR) test as specified in AASHTO T 313 [31]was used to measure the blends' low critical temperature based on the creep stiffness T_c *(S)*, and the asphalt binder relaxation or creep rate properties (*m*-Value) T_c *(m)* .

Using the following equations, T_c *(S)* and T_c *(m)* were calculated at temperatures corresponding to the stiffness of 300 MPa and an m-Value of 0.3, respectively.

$$T_c(S) = T_1 + \left(\frac{\log(300) - \log(S_1)}{\alpha}\right) \qquad \text{Eq. 3}$$

Where
T_C (*S*)= Stiffness Low critical temperature
T_1 = = Lower value of the two-test temperatures
S_1 = the stiffness value at temperature T1
α = Stiffness-Temperature curve slope and determines as per the following Equation

$$\alpha = \Delta \log(S)/\Delta T \qquad \text{Eq. 4}$$

T_C (*m*) was determined as follows

$$T_c(m) = T_1 + \left(\frac{0.3 - m_1}{\alpha}\right) \qquad \text{Eq. 5}$$

Where

$T_C\,(m)$= m-Value Low critical temperature
m_1 = m-Value at temperature T_1
α = m-Value-Temperature curve slope and determines as per the following equation

$$\alpha = \Delta\, m\text{Value}\;/\Delta T \qquad \text{Eq. 6}$$

The higher temperature measured from stiffness T_C (S) and creep rate T_C (m) was selected as a blend's low critical temperature that the pavement can resist without experiencing thermal cracking at low in-service temperatures.

2.6. Statistical analysis

In order to investigate the significant difference between the mixture's performance, many researchers have used, One-way ANOVA (Analysis of Variance) and Tukey Pairwise comparison between the means[35-37] .

A One -way ANOVA was used to investigate whether the mixes are significantly different. Throughout the analysis, a significance level of 0.05 was used to investigate a null hypothesis. Statistical analysis frequently uses the 0.05 level of confidence, which denotes a 5% probability of assuming that an effect occurs when it does not. A null hypothesis is rejected when the P-values are below 0.05, indicating that statistically, the tested mixes performed differently (had statistically different means) from what was predicted by the performance test.

A Tukey pairwise comparison of means was performed to determine statistically different groups of data in order to rank and compare the mixtures. The means are ranked, and each mean is assigned a litter. that do not share a letter are significantly different. The effect of RAP asphalt binder on the performance of neat and SBS-PMA asphalt binder was evaluated using Minitab (Version 21.1.1).

3. RESULT AND DISCUSSION

This section prescribes the results from the tests performed using conventional and Superpave rheological characterization tests.

Conventional Tests Rheological Characterization/

The effect of the RAP binder on the penetration value of both neat and SBS-PMA binder blends is presented in

Figure 4.(a). The penetration values of all blends decrease with the increase in RAP binder percentage due to the stiffer nature of the RAP binder[27]. The decrease in penetration values of neat binder blends were observed to be 18.8%, 20.4%, and 23.5% with the addition of 20%, 30%, and 40% of RAP, respectively. While the decrease for SBS-PMA binder blends was found to be 17.6%, 22.6%, and 24.6% for the same RAP%.

Similar results were reported by other authors [22-24, 38].

The statistical analyses showed a significant difference in the penetration values of the neat and SBS-PMA blends. Also, the difference was significant within the RAP blends, except between 20% and 30% RAP of neat asphalt blends and between 30% and 40% RAP of SBS-PMA binder blends, as presented in Table (**4**.

The softening point values of the neat asphalt binder blends were found to have increased with the addition of RAP binder content, showing the stiffer nature of the RAP binder compared to the neat binder, as shown in

Figure 4.(b). This indicates more rutting resistance and less temperature susceptibility. The findings are consistent with the findings reported by Gottumukkala, Kusam [22] . On the other hand, the softening point of the SBS-PMA binder blends decreases with the increase of the RAP binder percent due to the stiffer nature of the SBS-PMA binder.

Figure 4: Effect of RAP on Asphalt Physical Properties of neat and SBS-PMA asphalt binder: (a)penetration, (b)Softening Point, (c), Elastic Recovery, (d) Rotational Viscosity these indicating a decrease in rutting resistance and more temperature susceptibility of the SBS-PMA blends[39, 40]. As presented in

Figure 4.(b) the softening point of the neat asphalt increased by 2.8% as the RAP content increased from 0% to 40 %. Similar trends were achieved by Kumar [24] .Conversely, the SBS-PMA softening point was reduced by 17.2% as the RAP content increased at the same above-mentioned rates.

The statistical analysis of the neat asphalt blends showed a significant difference in the softening point only after the addition of 40% RAP, while in the SBS-PMA binder blends, increasing RAP did not cause any significant change after increasing the RAP % by more than 20%, as presented in Table (**4**.

The elastic recovery of neat blends was found to be increased with the addition of RAP binder, as it increased by 52% with the addition of 40 % of the RAP as presented in

Figure 4.(c). In contrast, the addition of the RAP binder to the SBS-PMA binder led to the reduction of the blend's ER. The SBS-PMA asphalt binder blend's elastic recovery was reduced by 21% with the addition of 40% RAP, as shown in

Figure 4. (c). This is due to the reduction in SBS polymer concentration and the disturbance of the SBS polymer interlinkage and network within the PMA binder, which leads to a decrease in the permanent deformation resistance of the SBS-PMA blends. Similar patterns were found in other studies [24, 27].

Statistically, the addition of the RAP binder to the neat asphalt binder does not cause any significant changes in its elastic recovery.

On the other hand, the addition of 20% RAP significantly reduces the elastic recovery of the SBS-PMA binder, and an insignificant reduction was found for the other RAP percentages as presented in Table (**4**.

The introduction of the RAP binder into the neat asphalt binder resulted in a higher viscosity of the blended binders due to the higher stiffness of the RAP asphalt binder. While introducing RAP binder into SBS-PMA binder led to a viscosity reduction due to the relatively lower viscosity of the RAP binder as compared to SBS-PMA viscosity, the influence was relatively small compared to neat binder blends, as shown in

Figure 4.(d). The viscosity values of all binder blends are lower, indicating the capability of binders to be mixed and pumped[41].

From the statistical analysis, it was found that the neat asphalt blends were significantly different, while the 20%, 30%, and 40% RAP of SBS-PMA blends were not significantly different, as presented in Table (**4**.

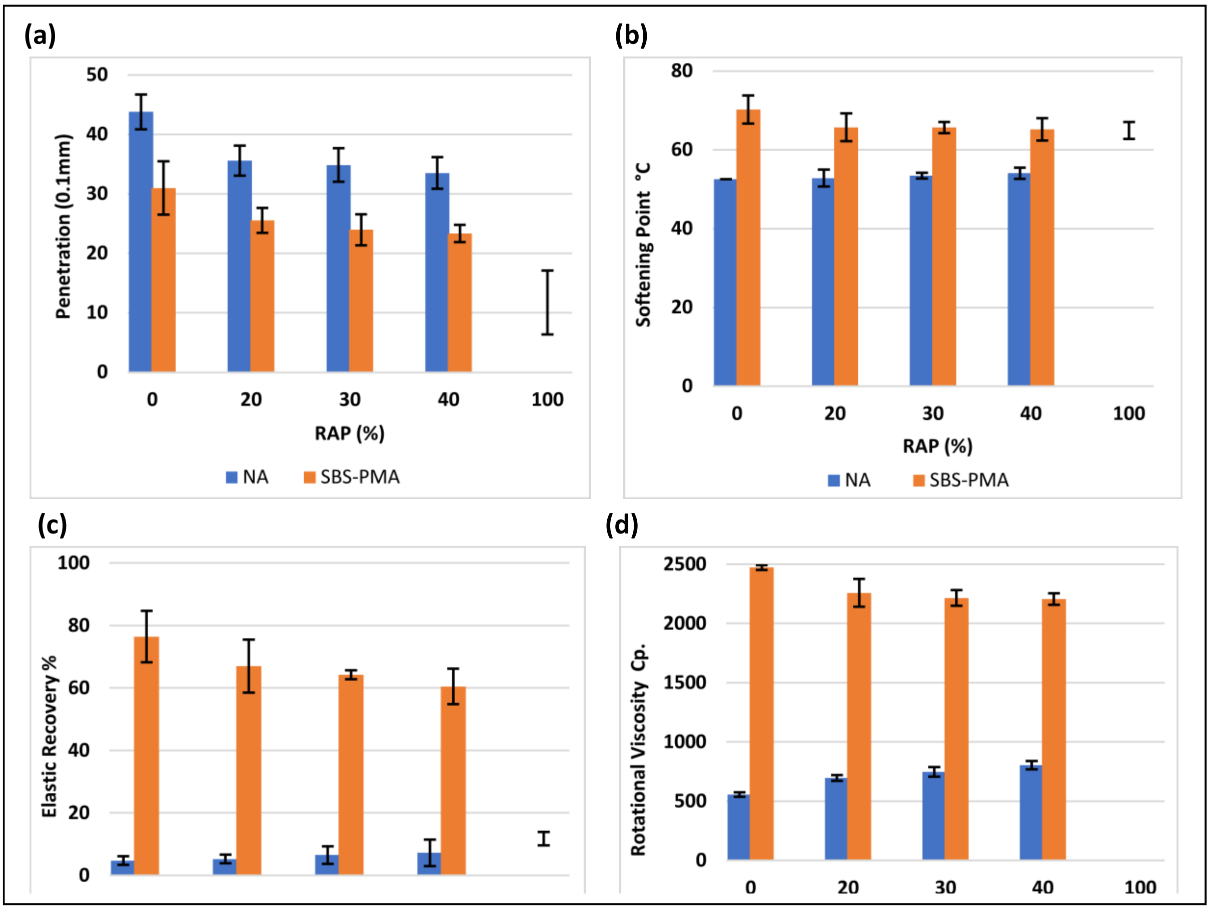

Fig. (5): Effect of RAP on Asphalt Physical Properties of neat and SBS-PMA asphalt binder: (a)penetration, (b)Softening Point, (c), Elastic Recovery, (d) Rotational Viscosity

Table (4): Statistical Analysis for Blendes Physical Properties

	Penetration `		**Softening Point**		**Elastic Recovery (ER)**		**Rotational viscosity**	
Parameter	***P-Value***		***P-Value***		***P-Value***		***P-Value***	
Asphalt Type	<0.001		<0.001		<0.001		<0.001	
Rap %	<0.001		<0.001		<0.001		<0.001	
Asphalt Type x RAP %	<0.001		<0.001		<0.001		<0.001	
Tukey Pairwise Comparisons of Asphalt Binder*RAP %								
					Asphalt Type			
RAP%	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**
0	A	D	D	A	E	A	H	A
20	B	E	D	B	E	B	G	B
30	B	F	C D	B	E	B C	F	B C
40	C	F	C	B	D E	C	E	C
100	G		B		D		D	
**Rows that do not share a letter are significantly different*								
Tukey Pairwise Comparisons of Asphalt Binder								
Asphalt Type	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**
Mean (Group)	31.91 (A)	23.12 (B)	55.59(B)	66.37 (A)	7.1(B)	55.99(A)	989.0 (B)	2258.8(A)

*Columns that do not share a letter are significantly different

3.1. Superpave Rheological Characterization

This section describes the findings from the Superpave performance tests.

3.1.1. Unaged Blend Dsr Results

The high critical temperatures of the asphalt binder blend for original (unaged) asphalt samples are shown in Table (**5** and Table 6 for neat and SBS-PMA binder blends, respectively. The test was conducted at a strain level of 12% and a mean frequency of 10 rad/s (1.59Hz). As can be seen, T_C (*High*) increases with the increase in RAP % for neat asphalt binder. This indicates the improvement in rut resistance due to the increase in asphalt binder stiffness[2, 11]. In contrast, the T_C *(High)* of the SBS- PMA blends decrease with the addition of the RAP binder. This indicates less rut resistance due to lower RAP binder stiffness compared with the SBS-PMA binder stiffness. The effect of the RAP binder on the SBS-PMA is less due to the relatively close true grade of these two binders.

Furthermore, Table (**5** and Table 6 show that the measured T_C (*High*) values are very close to the predicted values obtained from blending charts recommended by McDaniel& Anderson [6]for both neat and SBS-PMA blends. Thus, it can be concluded that the recommended blending charts could be reliably used to determine the high critical temperature of the RAP mixture based on the RBRR and the true grades of both RAP and virgin asphalt binders.

The rutting parameter G*/sinδ of the neat asphalt binder samples increases with the increase of the RAP % and decrease of the test temperature. The change in G*/sinδ is not strong at high temperatures up to 40% RAP. Although the G*/sinδ is strongly affected by test temperature as shown in Fig. (6.(a). These trends are consistent with what has been found by Kennedy, Tam [42].In contrast, the G*/sinδ parameter of SBS-PMA blends decreases with the increase in RAP% and the decrease in the test temperature .The RAP content effect on the SBS-PMA blends' G*/sinδ parameter is less noticeable compared to neat asphalt binder blends, as shown in Fig. (6.(b).

The statistical analysis results revealed a significant difference between the T_C (*High*) of the original neat and SBS-PMA asphalt binder blends. Similarly, there was a significant effect of RAP content on the neat asphalt binder as presented in Table 7. Also, there is no significant difference in T_C (*High*) for the SBS-PMA binder blend, except for the 20% RAP.

Table (5): Measured and Predicted Critical Temperatures of Neat Asphalt Binder Blends

PG True Grade	NA +0% RAP	NA +20%RAP	NA +30%RAP	NA +40%RAP	100% RAP
Measured T_c (High)@ G*/sinδ=1 kPa	73.01	74.13	75.41	76.31	85.55
Predicted T_c (High)@ G*/sinδ=1 kPa	-	75.16	76.04	76.56	-
Measured T_c (High)@ G*/sinδ=2.2 kPa	74.77	74.96	76.51	78.05	86.73
Predicted T_c (High)@ G*/sinδ=2.2kPa	-	76.81	77.66	78.15	-
Measured T_c (Int.)@ G*. sin δ =5000 kPa	27.82	28.88	29.33	30.30	37.53
Predicted T_c (Int.)@ G*. sin δ =5000 kPa	-	29.48	30.16	30.57	-
Measured low temp T_C (S) @S= 300 MPa	-25.66	-24.09	-23.32	-23.01	-18.38
Predicted low temp T_C (S) @S= 300 MPa	-	-24.42	-23.90	-23.60	-
Measured low temp T_C (m) @m= 0.3	-20.79	-20.52	-19.59	-17.49	-13.95
Predicted low temp T_C (m) @m= 0.3	-	-19.62	-19.14	-18.85	-
PG Grade	70-16	70-16	70-16	76-16	82-10

Table 6: Measured and Predicted Critical Temperature of SBS-PMA Binder Blends

PG True Grade	SBS-PMA +0%RAP	SBS-PMA +20%RAP	SBS-PMA +30%RAP	SBS-PMA +40%RAP	100% RAP
Measured T_c (High)@ G*/sinδ=1 kPa	86.91	86.36	86.09	85.96	85.55
Predicted T_c (High)@ G*/sinδ=1 kPa	-	86.68	86.58	86.53	-
Measured T_c (High)@ G*/sinδ=2.2 kPa	88.19	87.37	86.95	86.86	86.73
Predicted T_c (High)@ G*/sinδ=2.2kPa	-	87.94	87.84	87.87	-
Measured T_c (Int.) @ G*. sin δ =5000 kPa	25.69	27.77	28.21	30.30	37.53
Predicted T_c (Int.) @ G*. sin δ =5000 kPa	-	27.71	28.54	29.04	-
Measured low temp T_C (S) @S= 300 MPa	-27.73	-24.81	-22.98	-21.39	-18.38
Predicted low temp T_C (S) @S= 300 MPa	-	-26.21	-25.55	-25.16	-
Measured low temp T_C (m) @m= 0.3	-23.06	-17.88	-16.00	-15.68	-13.95
Predicted low temp T_C (m) @m= 0.3	-	-21.50	-20.86	-20.48	-

3.1.2. Rtfo-Aged Blends Dsr Results

The high critical temperature of RTFO-aged blends exhibited similar trends to that of the unaged blends using DSR at a strain level of 10% and a mean frequency of 10 rad/s(1.59Hz). The T_C (*High*) of RTFO-aged neat asphalt binder blends increased with the increase of RAP binder, as presented in Table (**5** .While it showed a decrease for the SBS-PMA binder as presented in Table 6.The T_C (*High*) of the neat asphalt binder increased by 4.4% with an increase of 40% RAP. In the case of the SBS-PMA, it was reduced by 1.5% for the same RAP %. Similarly, for unaged blends, the measured T_C (*High*) values were close to the predicted values calculated from blending charts.

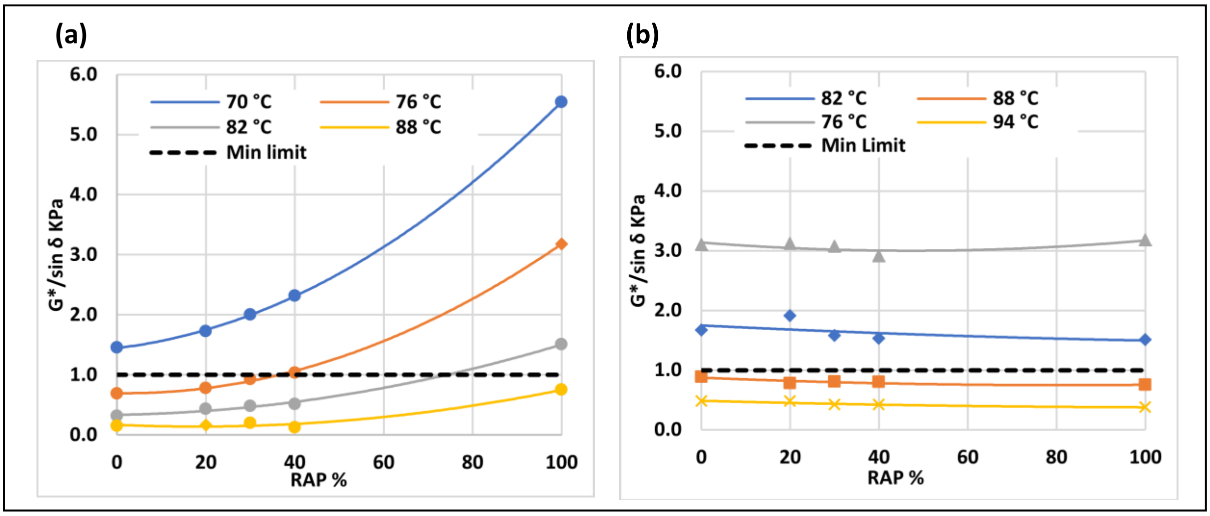

Fig. (6):G*/sinδ trends for original (Unaged) blends:(a). neat asphalt, (b). SBS-PMA.

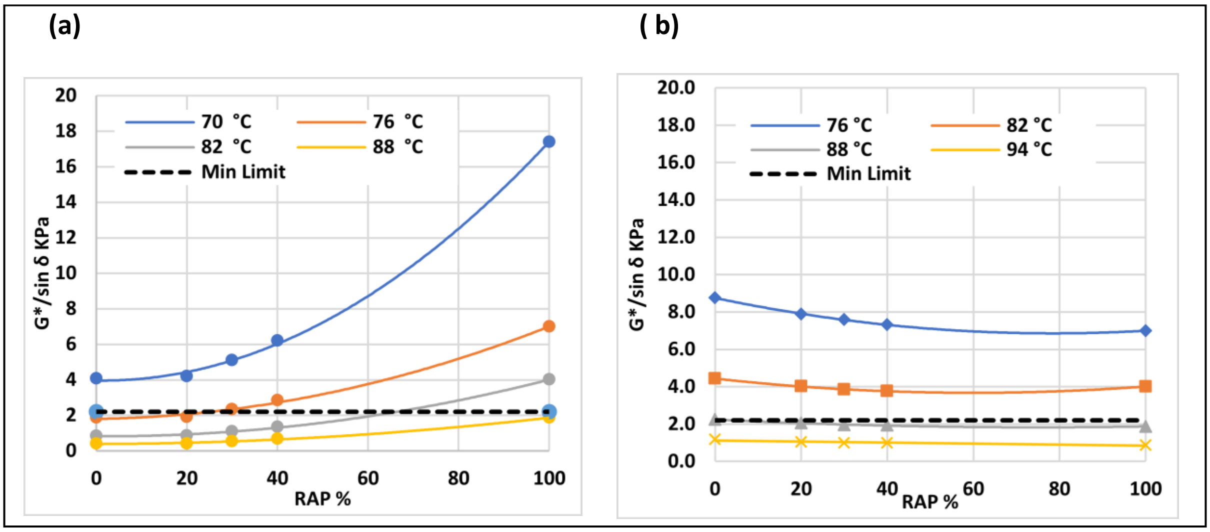

Fig. (7): G*/sinδ trends for RFTO-Aged blends:(a). neat asphalt, (b). SBS-PMA.

The measured G*/sinδ of RTFO aged samples showed similar trends to that of unaged binder blends for both neat and SBS-PMA asphalt binders. Fig. (7.(a) shows that the higher RAP percentages and lower test temperatures increase the G*/sinδ of neat asphalt binder blends. These findings are consistent with previous studies showing that the neat asphalt stiffness increases with the increase of RAP%[22, 40, 41].

In comparison to neat asphalt, the G*/sinδ of SBS-PMA binder blends decreased with the increase in RAP% and increased with the increase in test temperature. This is due to the higher G*/sinδ of the SBS-PMA binder compared to the RAP G*/sinδ.

However, the effect of testing temperatures is similar to that of neat asphalt binder blends, as shown in Fig. (7. (b). The RAP effect on the G*/sinδ value is less noticeable in SBS-PMA blends as compared to neat asphalt binder blends.

From the statistical analysis, a significant difference was found between RTFO T_C *(High)* of neat and SBS-PMA asphalt binder. The addition of 20% RAP did not significantly increase the T_C *(High)* of neat asphalt binder, but the effect was strong after 30% RAP. In contrast, the RAP is not significantly reducing the T_C *(High)* of RTFO-aged SBS-PMA binder blends, as shown in Table 7.

3.1.3. Rtfo-Pav-Aged Blend Dsr Results

The intermediate critical temperatures were measured using DSR for RTFO-PAV-aged asphalt samples at a strain level of 1% and a mean frequency of 10 rad/s (1.59Hz). As shown in Table (**5** for neat and Table 6 for SBS-PMA. The intermediate critical temperatures T_C (*Int.*) increase with the increase of RAP content, indicating a decrease in fatigue cracking resistance of the blended binder. Similar to the unaged and FTFO-aged samples, the measured T_C *(Int.)* values were close to the predicted values measured from the blending charts. The fatigue cracking parameter G*. sinδ of the neat and SBS-PMA binder blends is shown in Fig. (8.(a) and Fig. (8.(b), respectively. The high RAP percent and lower test temperature increase the G*. sinδ of both binder-type blends. However, the rate of change in G*. sinδ concerning RAP content is more pronounced in SBS-PMA blends as it increases immediately after the addition of the RAP binder .Similar patterns were obtained by Singh and Girimath [27].

The statistical analysis of the T_C *(Int.)* showed a significant effect of the RAP binder on the neat and SBS-PMA binder except for 30% RAP, which was not significantly different from 20% RAP for both types of asphalt as presented in Table 7.

3.1.4. Pav-Aged Blend Bbr Results

The low critical temperatures for PAV-aged blends were measured using BBR at different temperatures (-10, -16, and -22) °C. The results of blends at low critical temperatures based on creep stiffness T_C (S) and creep rate T_C (m) are presented in Table (**5** and Table 6 for neat and SBS-PMA asphalt binder blends, respectively.

The RAP hardens and stiffens due to oxidation and chemical modification in the asphalt binder components (more susceptible to fracture, less stress relaxation)[43]. The RAP aged binder increases the stiffness and brittleness of the NA and SBS-PMA binder[44]. Consequently, the low critical temperature of the two binder blends increases with the increase in RAP binder content. These results indicate a decrease in thermal cracking resistance. The effect of RAP on SBS-PMA blends was more pronounced than that of the neat asphalt binder blends, as the low critical temperature increased at a greater rate with the addition of the RAP binder. The low critical temperature was controlled by *(m-value)* for both types of binders as the blends failed at the creep rate(m-value) threshold (0.3) at a warmer temperature compared to the creep stiffness temperature to reach the failure threshold (300 MPa).

The measured low critical temperature values were close to the predicted values from the blending charts recommended by McDaniel and Anderson [6]for the neat asphalt binder blends. In contrast, the error in predicting low critical temperatures increased in SBS-PMA binder blends. Thus, it can be concluded that the recommended blending charts could be reliably used to determine the low critical temperature of RAP mixtures with neat asphalt binder, while they're not consistently applicable for the RAP mixtures containing SBS-PMA asphalt binder.

The creep stiffness of the neat asphalt increases with the increase in RAP content and with the decrease in test temperature, as shown in Fig. (9. (a). The creep rate (*m-value*) of neat asphalt binder blends decreases with the increase in RAP% and with the decrease of test temperature, as shown in Fig. (9. (b).

The SBS-PMA blends showed similar trends to those of neat asphalt blends for both creep stiffness and creep rate (*m-value*), as shown in Fig. (9.(c)and Fig. (9 (d)respectively. The only difference in SBS-PMA blends is that stiffness is affected at a greater rate with the increase in RAP %. Overall, these findings are similar to the findings reported by other authors [22, 24, 27, 41, 42].

Table 7. shows the statistical analysis results of the low critical temperature of both neat and SBS-PMA binder blends. The results indicated that there was no significant difference between T_C (S) of neat and SBS-PMA asphalt binder blends, whereas the difference was significant for TC (m). The effect of more than 30% of RAP on the T_C *(S)* of the neat asphalt was not significant. In contrast, the RAP rate significantly increased the T_C *(S)* of SBS-PMA binder blends.

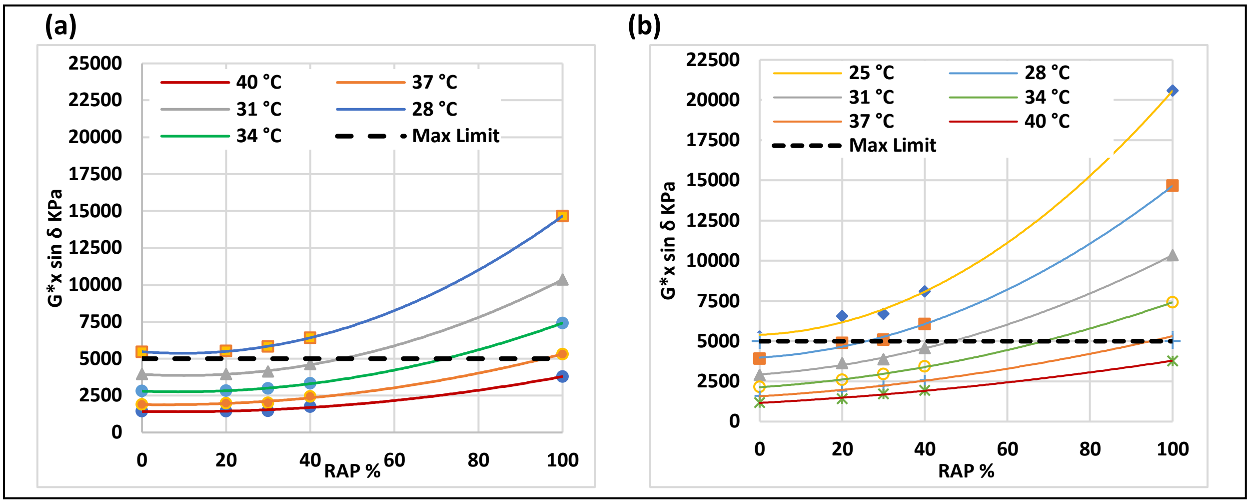

Fig. (8): G* x sin δ trends for PAV-Aged Blend: (a). Neat Asphalt, (b). SBS-PMA.

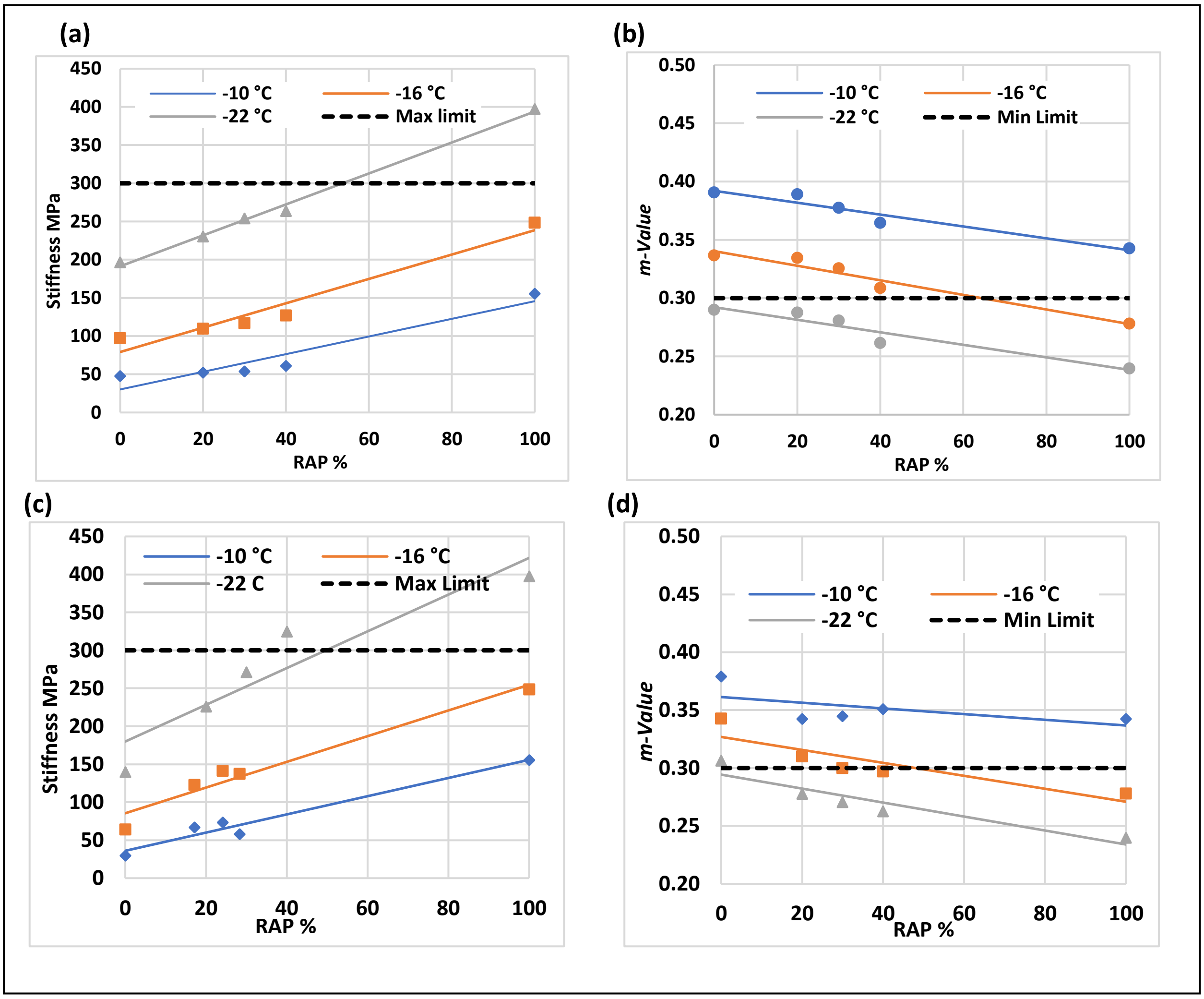

Fig. (9):PAV-Aged Blend BBR Trend: (a). Neat Asphalt Stiffness, (b). Neat Asphalt Creep Rate(c). SBS-PMA Stiffness, (d). SBS-PMA Creep Rate.

Table 7:Statistical Analysis for Blends Rheological Properties

Analysis of Variance

	T_C (*High*)Original	T_C (*High*)RFTO	T_C (*Int.*)	T_C (*S*)	T_C (*m*)
Parameter	**P-Value**	**P-Value**	**P-Value**	**P-Value**	**P-Value**
Asphalt Type	<0.001	<0.001	<0.001	0.005	<0.001
Rap %	<0.001	<0.001	<0.001	<0.001	<0.001
Asphalt Type x RAP %	<0.001	<0.001	<0.001	<0.001	<0.001

Tukey Pairwise Comparisons of Asphalt Binder*RAP %

	Asphalt Type									
RAP%	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**
0	G	A	E	A	F	G	E	F	E	F
20	F	B	E	A B	D E	F	D	D	D E	C
30	E	B	D	B	C D	E F	C	C	D	B
40	D	B C	C	B	B	B C	C	B	C	B
100	C		B		A		A		A	

*Rows that do not share a letter are significantly different

Tukey Pairwise Comparisons of Asphalt Binder

Asphalt Type	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**	**NA**	**SBS-PMA**
Mean (Group)	31.91 (A)	23.12 (B)	55.59(B)	66.37 (A)	7.1(B)	55.99(A)	989.0 (B)	2258.8(A)	-18.47(B)	-17.32(A)

*Columns that do not share a letter are significantly different

4. CONCLUSIONS

This paper evaluates the RAP binder effect on the rheological properties of the neat (unmodified) and SBS polymer-modified asphalt binders. The reclaimed asphalt binder recovered from the RAP was blended with SBS-modified asphalt and unmodified (neat) asphalt (penetration 40–50). Different percentages of the RAP (0%, 20%, 30%, and 40% by weight of the total mix) were blended with the two asphalt binder types. The rheological characterization of blended binders was carried out using conventional and Superpave standard test methods. Based on the results, the following main conclusions were drawn:

- The RAP binder increased the NA binder's penetration, softening point, elastic recovery, and viscosity.
- The addition of RAP to SBS-PMA led to a decrease in penetration, softening point, elastic recovery, and viscosity of the blended binder.
- The addition of 20%, 30%, and 40% RAP to the neat asphalt binder increases the true high-temperature performance grade (PG) by 1.5%, 3.3%, and 4.5%, respectively. Indicate an improvement in rutting resistance with the addition of RAP.
- The true high-temperature performance grade (PG) for SBS-PMA was reduced by 0.64%, 0.95%, and 1.10% with the addition of 20%, 30%, and 40% RAP, respectively, indicating a slight decrease in rut resistance with the addition of RAP.
- The true intermediate Superpave critical temperature increases by 3.8%, 5.4%, and 9% for neat asphalt blends with the addition of 20%, 30%, and 40% RAP, respectively, demonstration of a decrease in fatigue cracking performance of the neat asphalt binder with the addition of RAP binder.
- The addition of 20%, 30%, and 40% RAP led to a decrease in the true intermediate Superpave critical temperature for SBS-PMA binder by 8.1%, 9.8%, and 16.9%, respectively. Indicating a reduction in the fatigue performance of the blended binders.
- The low-Temperature true PG increases by 5%, 11%, and 15% for the neat asphalt binder and by 23%, 31%, and 32% for the SBS-PMA binder with the addition of 20%, 30%, and 40% RAP, respectively. Indicating a remarkable decrease in blends' low-temperature cracking performance.
- The predicted continuous PG from blending charts recommended by McDaniel& Anderson [5] was close to the measured continuous PG for high, intermediate, and low-performance temperatures, except for the low temperate grade of SBS-PMA. Thus, the blending charts can be reliably used for the selection of virgin binder grades for different rates of RAP.

Generally, from the previous explanations, the performance of the SBS polymer-modified asphalt binder deteriorated with the addition of RAP at high, intermediate, and low testing temperatures. whereas the performance of neat asphalt binder improves at high testing temperatures, and deteriorates at intermediate and low testing temperatures.

In summary, the performance of the RAP and virgin binder blends primarily depends on the individual characteristics of the blended binders. However, to figure out the potential behavior of RAP in new asphalt concrete mixtures, further work is needed to study the performance of the asphalt mixtures containing RAP.

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