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Investigation of rutting, fatigue and cracking resistance parameters of CR modified warm asphalt binders compare with SBS modified binders

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Abstract: This study compares the rutting and cracking resistance and fatigue parameters of crumb rubber (CR) modified warm asphalt binders, which were determined by viscoelastic continuum damage (VECD) theory. The effect of the combination of CR modification and Sasobit, a warm mix additive, was investigated. Performance of CR + Sasobit compound was compared with styrene-butadiene-styrene (SBS) modification. Newly developed rheological tests such as multi stress creep recovery (MSCR), lineer amplitude sweep (LAS) and conventional tests were applied to modified binders. It was determined that the CR + Sasobit modified binders improved the rutting parameter better in comparison to SBS-added binders. Although the CR additive improved the rheological properties of the binder at low and medium temperatures, this effect was reduced when used with Sasobit additive. Sasobit additive increased the stiffness and decreased the fatigue parameter at low temperatures. Besides, the results of the LAS test revealed that at high strain values (i.e.> 6%), the fatigue life of CR and Sasobit modified binders was lower than the fatigue life of the pure binder. In other words, CR and Sasobit modified binders could not preserve material integrity.

Keywords: Modification, rheology, warm mix additive, rutting, cracking, fatigue parameter.

1. Introduction

Fatigue and rutting or permanent deformation are among the frequent pavement deterioration types in hot bituminous mixtures (Rahi et al. 2015; Behbahani et al. 2017; Nasr and Pakshir 2019) Rutting and fatigue parameters of the binders are determined in accordance with the Superpave specification criterion under high and medium temperatures, respectively. However, it is stated that the rutting parameter under high temperatures (G*/sinδ) is not a performance-based parameter and that the performance-based multi stress creep recovery (MSCR) test provides a better correlation with the rutting of the mixture (D'Angelo 2009; Zhang et al. 2015; Lv et al. 2019). The fatigue damage of asphalt mixtures reveal that they are mostly affected by the mechanical characteristics of asphalt binders' mastic phase.

The current Superpave specification criterion (G*/sinδ) is based on the linear viscoelastic characteristics of the material. It is expressed that this approach is insufficient for characterizing the real damage resistance (Bahia et al. 2001). For this reason, Bahia and his team have developed the linear amplitude sweep (LAS) test to determine the fatigue performance of the binder

(Hintz and Bahia 2013). It is stated that LAS test has a good correlation with the fatigue crack field data of long-term pavement performance (LTPP) (Hintz et al. 2011). In another study, it is determined that LAS test has a strong relationship with the four-point beam bending (FBB) test (Hasan et al. 2019), but does not have a good correlation with G*.sinδ parameter and that it is a widely used (Hu et al. 2020) and effective test method for detecting the fatigue parameter of the binders (Sabouri et al. 2018; Norouzi et al. 2019).

Bituminous binders or mixtures need to be modified with various additives to improve their characteristics under high, medium, and low temperatures. In studies conducted over the recent years, it is expressed that additives such as styrene-butadiene-styrene (SBS) and crumb rubber (CR) significantly improve the rutting performance and fatigue resistance of bituminous binders and mixtures (Kök et al. 2013; Behnood and Olek 2017a; Cao and Wang 2019; Chen et al. 2019). However, such additives reduce the workability by increasing the viscosity of the binder (Kök and Çolak 2011), and for this reason, their workability and high-temperature characteristics can be improved when they are combined with warm asphalt additives such as Sasobit (Kök et al. 2016).

In a study examining the effect of CR, SBS, and CR/SBS composition usage on the rutting and fatigue life of the binder (Ye et al. 2019), it is stated that the usage of CR in the SBS modified binder improves the thermal and fatigue crack formation under low temperatures. According to the LAS test results, it is also determined that the CR modified binder increases the fatigue life under low-stress levels thanks to the elasticity it provides, but this effect is not observed under high-stress levels. In a study conducted on various polymer-modified binders, it is expressed that additives such as SBS, CR, and polyethylene reduce the fatigue damage of the bitumen and increase the fatigue life (Hassanpour-Kasanagh et al. 2020).

In recent years, warm asphalt technology has frequently been used since it reduces the carbon emissions and production temperature and energy of asphalt pavements (Aktaş, Aytekin, & Aslan, 2019; Herrera de la Rosa, Alonso Aenlle, & Villegas Muñoz, 2018). One of the most common warm asphalt additives is Sasobit. In studies using Sasobit additive, it is stated that Sasobit provides high rutting resistance by improving the performance of binders under high temperatures and increases the rigidity under low temperatures (Abed et al. 2020; Behnood et al. 2020).

It is stated that the use of Sasobit WMA additive in recycled binders significantly increases rutting resistance, however, it also has some adverse effects on resistances to fatigue and low temperature cracking (Li et al. 2021). Besides, it is stated that Sasobit additive in recycled asphalt pavement (RAP) will increase the rigidity and brittleness of the mixture (Ayazi et al. 2017). It is stated that with the use of organic (like Sasobit) and chemical-based warm asphalt additives in polymer and CR modified binders, the elastic recovery percentages go up; but as the warm asphalt additive rates increase, the fatigue lives get shorter (Kleizien and Vaitkus 2020).

Kataware and Singh examine the effect of warm asphalt additive (FT-wax additive) in CR modification with MSCR and LAS test. They conclude that the organic warm asphalt additive reduces the creep compliance values of the binder and provides high rutting resistance by improving the recovery values. Besides, according to the LAS test results, they determine that it increases the fatigue life (Nf) and the optimum additive ratio is 2% in terms of binder weight (Kataware and Singh 2019). In this study, rutting resistances of CR modified warm asphalt binders are determined by performing newly developed rheological tests such as MSCR and LAS, and their fatigue lives by viscoelastic continuum damage (VECD) theory; and then they are compared to the SBS modified binders. In addition, critical low temperature (ΔTc) and Glover-Rowe (G-R) parameters used to determine the crack resistance of binders or mixtures were determined.

2. Materials and methods

2.1. *Materials and preparation of modified binders*

This study examines the variances seen in Figure 1 and the rheological effects of various asphalt additives on the binders. Additive materials used in the study are as follows: (1) SBS block copolymer (Kraton D1101), (2) Crumb rubber (from

Samsun Akın Kauçuk company) with the dimension to pass a No. 40 sieve (3) Sasobit (from Sasolwax company), which is used as a warm asphalt additive, obtained by Fischer Tropsch synthesis.

All modified binders are prepared by using a high shear mixer device with B 50/70 penetration class pure binders supplied from TÜPRAŞ refinery. The preparation scheme of the modified binders is given in Figure 1. As applied in previous studies, modified binders are prepared with a mixing speed of 2000 rpm, a temperature of 170 °C, and a time of 45 minutes (Akpolat et al. 2020). Besides, pure binders are also subjected to the same mixing procedure to eliminate the aging during mixing with the binders.

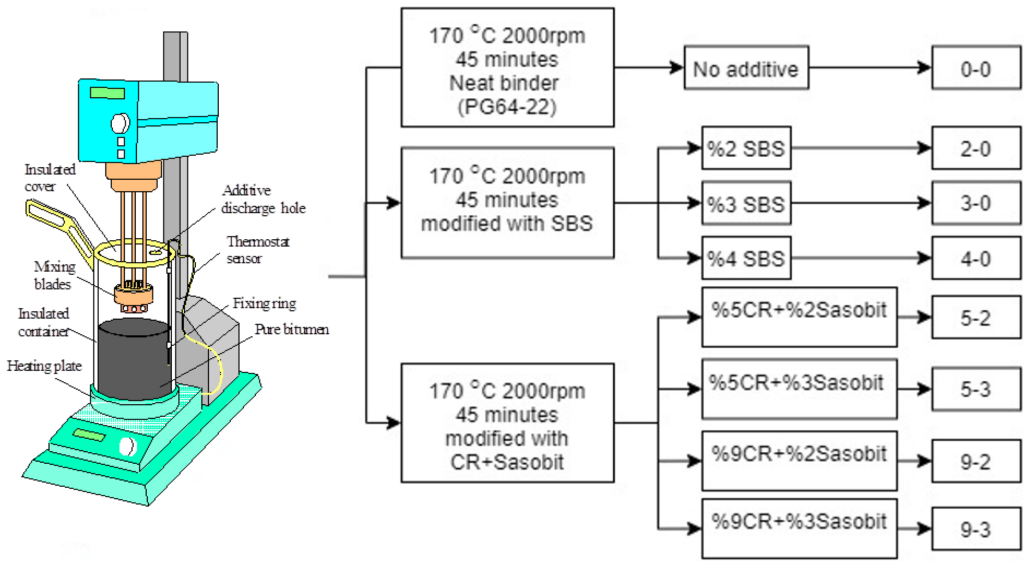

Figure 1. High shear mixer and binder IDs used in the study.

2.2. *Method*

The experimental plan used in the study is given in Table 1. The MSCR and LAS tests applied on the bituminous binders in this study are adopted since they are stated to provide a better correlation with rutting and fatigue resistances in many studies (Wasage et al. 2011; Gibson et al. 2012; Hintz and Bahia 2013; Golalipour et al. 2017; Lv et al. 2019).

Table 1. Experimental plan.

Experiment	Standard	Equipment	Test temperature range (°C)	Aging condition
Softening point	AASHTO T 53			Unaged
Viscosity	AASHTO T 316	Rotational viscometer	135 and 165	Unaged
Performance grade (PG)	AASHTO T315	DSR	58-88	Unaged
Frequency sweep	ASTM 7175	DSR	40, 50, 60 and 70	Unaged
Multi stress creep and recovery (MSCR)	AASHTO T350	DSR	58-88	RTFOT
Frequency sweep for G-R parameter	ASTM 7175	DSR	10, 15, 20, 25 and 30	RTFOT+PAV
Linear amplitude sweep (LAS)	AASHTO TP 101-14	DSR	15 and 20	RTFOT+PAV
Low temperature creep stiffness	AASHTO T 313	BBR	-6, -12, -18	RTFOT+PAV

2.2.1. Frequency sweep test

Frequency sweep test was applied to unaged binders with Malvern DSR+ rheometer device at 40-70 °C temperature with an increase of 10 °C temperature. The experiment was carried out with 25mm parallel plate and 1mm gap geometry. The test was performed within the linear viscoelastic (LVE) region of the binder. During testing, the frequency was set in the range of 0.1-100 rad/sec. The master curves of the complex modulus (G*) and phase angle (δ) values obtained to determine the viscoelastic behavior in a wider frequency range at the reference temperature of 40 °C were created according to the Time Temperature Superposition Principle (TTSP).

2.2.2. Multi stress creep recovery (MSCR) test

In accordance with the AASHTO T350 (AASHTO T350 2012) standard, MSCR test is conducted on an RTFOT residue under temperatures between 58 and 88 °C (by increasing 6 °C at a time) by using a 25 mm plaque and pure and modified binders prepared as per the AASHTO T315 standard. As per AASHTO M332, two parameters are obtained with the MSCR test. These are (1) percent recovery (R) and (2) non-recoverable creep compliance (Jnr). The mean recovery percent values for asphalt binders are figured up according to Equations 1 and 2 at shear stress levels 0.1 kPa (R0.1) and 3.2(R3.2) kPa (AASHTO M332 2015).

$$R_{0.1} = \frac{\sum_{N=11}^{20} [\varepsilon_r(0.1, N)]}{10} \quad (1)$$

$$R_{3.2} = \frac{\sum_{N=20}^{30} [\varepsilon_r(3.2, N)]}{10} \quad (2)$$

Here, ε_r (0.1, N) and ε_r (3.2, N) are the percent recoveries in N cycle numbers at shear levels 0.1 and 3.2 kPa respectively, and N is the number of cycles in each shear level.

In the AASHTO M332 standard, it is stated that the percent recovery (R) is not currently being used as a grading parameter (Behnood and Olek 2017b). However, this parameter serves as an indicator for the existence of the modified additives in the binder. On the other hand, it is determined that the Jnr parameter has a better correlation with the rutting resistance as per the Superpave PG criteria (Wasage et al. 2011; Behnood et al. 2016). The binder classification methodology is defined as (a) mean non-recoverable creep compliance value under 3.2 kPa at a certain traffic level (b) the difference between non-recoverable creep compliances (Jnrdiff) under a stress value of 3.2 kPa and 0.1 kPa, whose maximum value is 75%. The different traffic load categories considered within the standard are standard (S), heavy (H), very heavy (V), and extremely heavy (E). The formula for non-recoverable creep compliance values at 0.1 kPa (Jnr0.1) and 3.2 (Jnr3.2) kPa are given in Equations 3 and 4, and the formula for Jnrdiff value is given in Equation 5.

$$Jnr_{0.1} = \frac{\sum_{N=11}^{20} [Jnr(0.1, N)]}{10} \quad (3)$$

$$Jnr_{3.2} = \frac{\sum_{N=20}^{30} [Jnr(3.2, N)]}{10} \quad (4)$$

$$Jnr_{diff} = \frac{(Jnr_{3.2} - Jnr_{0.1})}{Jnr_{0.1}} * 100 \leq 75 \quad (5)$$

As a result of the MSCR test performed on crumb rubber modified binders, it is stated that while an improvement in the rutting is expected due to high recovery values, the specification criterion Jnrdiff ≤ 75 value is not met, and therefore it is not suitable since there is a contradiction between these two findings (Behnood and Olek 2017a). For this reason, Jnrslope values are also determined in the study and compared with Jnrdiff values. The study states that the Jnrslope parameter indicates the expected change in rutting better than the Jnrdiff. Besides, the performance-based Jnrslope boundary equation is given in the study (Stempihar et al. 2018). The formula for the Jnrslope parameter is given in Equation 6.

$$Jnr_{slope} = \frac{dJ_{nr}}{d_{\tau}} = \frac{(Jnr_{3.2} - Jnr_{0.1})}{3.1} * 100 \tag{6}$$

2.2.3. Linear amplitude sweep (LAS) test

The LAS test is applied as per the AASHTO TP 101-14 (AASHTO TP 101-14 2016) standard on RTOFT+PAV. Test protocol contains two successive tests. The first test is frequency sweep to determine the rheological characteristics of the binder, and the second one is amplitude sweep to find out the binder's fatigue life and damage.

In this study, frequency sweeps are performed within a frequency range varying between 0.2 and 30 Hz with a strain amplitude of 0.1%. Amplitude sweep test, on the other hand, is comprised of a linearly increasing load application from zero to 30% with a fixed frequency of 10 Hz. All the tests are conducted on a parallel plaque 8 mm in diameter with a gap of 2 mm by using a Kinexus DSR+ device. Safaei and Castorena state that the test temperatures should be selected such that linear dynamic shear moduli fall within the range of 12 to 60 mPa to avoid the confounding effects of flow or adhesion loss (Safaei and Castorena 2016).

Besides, it is stated that the test temperature is important for the results obtained from the fatigue life and the mechanism of sample damage during the LAS test, so the temperature choice should be clearly stated (Kleizien and Vaitkus 2020). Thus, based on the relationship between test temperature and fracture mechanics of G*LVE given in Table 2, the test temperature is determined to be between 15 °C and 20 °C.

Table 2. Relationship between G*LVE, test temperature, and fracture mechanism.

Temperatures	G*LVE (MPa)							
	0-0	2-0	3-0	4-0	5-2	5-3	9-2	9-3
5	65.23	80.78	83.16	84.87	74.75	82.45	66.15	70.77
10	46.48	48.84	51.28	52.47	47.28	52.47	42.97	46.86
15	27.59	33.48	34.49	36.26	30.21	32.47	28.85	29.89
20	17.73	18.85	21.40	21.72	19.90	22.32	19.07	21.71
25	9.02	11.50	14.01	14.16	13.66	14.32	12.53	13.54
30	6.34	7.44	8.15	8.95	9.03	9.81	8.26	8.54

NOTE: blue color= adhesion loss, green color= cohesive fracture and red color= instability flow.

The analysis scheme of the LAS test is based on viscoelastic continuum damage (VECD) mechanics concepts and it calculates fatigue life as per Equation (7):

$$N_f = A \times (\gamma_{\max})^{-B} \tag{7}$$

where Nf is the fatigue life or number of cycles to failure; γmax is the maximum expected asphalt binder strain for a specific pavement structure (i.e: asphalt layer>4": use 2.5% strain, asphalt layer<4": use 5% strain); and A and B parameters are VECD model coefficients. Being directly connected with the storage modulus in the course of loading cycles, parameter A indicates the binder's capability to maintain its integrity. A decrease in storage modulus would lower parameter A, which remarks a weaker resistance of the binder in maintaining the integrity. The binder's sensitivity to change in strain level is designated by parameter B. A greater absolute value of parameter B represents larger percentages of fatigue life reduction in case of increasing strain level amplitude. There is an association between greater A values and smaller absolute B values, and the binders with greater fatigue resistance (Ameri et al. 2016; Sabouri et al. 2018; Hassanpour-Kasanagh et al. 2020).

Frequency sweep data were used to derive the damage element of alpha. Alpha is a function of slope G’ (storage modules) and ω while G’ can be calculated from Equation (8):

$$\log G'(\omega) = |G^*|(\omega) \times \cos\delta(\omega) \tag{8}$$

Then the alpha parameter was derived from the inverse of the slope of the plot of log G’ versus log ω based on Equation (9) and Equation (10):

$$\log G'(\omega) = m\log(\omega) + b \tag{9}$$

$$\alpha = \frac{1}{m} \tag{10}$$

The damage intensity at failure point (Df) is calculated using the material integrity at peak shear strain (Cf) as follows:

$$D_f = \left(\frac{C_0 - C_f}{C_1}\right)^{\frac{1}{C_2}}$$

where C1 and C2 are curve fitting coefficients and C0 is the initial value of C, equals to one.
Finally, the parameters A and B are defined as:

$$A = \frac{f \cdot D_f^{\,1+\frac{\alpha}{1-C_2}}}{[1+\alpha(1-C_2)](\pi \cdot C_1 C_2)^{\alpha}}$$

$$B = 2\alpha$$

where f is the loading frequency (10 Hz); and all the other terms are as previously described.

2.2.4. Bending beam rheometer (BBR) test

To determine the low temperature performance of bituminous binders, a beam bending rheometer (BBR) test is performed. The test was carried out on PAV samples at -6 °, -12 °C and -18 °C according to the AASHTO T313 standard. Also, the ΔTc parameter was selected from the BBR test data (Equation (11)). ΔTc is known as the difference between critical low temperatures of the asphalt binder Tc,S (Equation (12)) and Tc,m (Equation (13)) designated from the BBR test (Anderson, Phillip B. Blankenship, & Zeinali, Alireza, 2014; Asphalt Institute, 2019). It is assumed that this parameter is related to the durability of asphalt binder and presents the non-load associated cracking potential of asphalt binders. A more negative value of ΔTc identifies loss of asphalt binder relaxation properties (Arshadi et al., 2017). Form a limit of $\Delta Tc \leq -2.5$°C as an indication for identifiable risk of cracking (Anderson, King, Hanson, & Blankenship, 2011). Then, (Rowe, 2011) suggested, immediate remediation should be taken into account, as soon as ΔTc≤ -5 °C equation comes true,

$$\Delta T_c = T_{c,S} - T_{c,m} \tag{11}$$

$$T_{c,S} = T_1 + \left(\frac{(T_1 - T_2) \times (Log300 - LogS_1)}{LogS_1 - LogS_2}\right) - 10 \tag{12}$$

$$T_{c,m}=T_1+\left(\frac{(T_1-T_2)\times(0.300-m_1)}{m_1-m_2}\right)-10 \tag{13}$$

where, S1=creep stiffness at T1 (MPa), S2=creep stiffness at T2 (MPa), m1=creep rate at T1, m2=creep rate at T2, T1=temperature at which S and m passes, °C, and T2 = temperature at which S and m fails, °C.

3. Experimental results and analysis

3.1. Conventional and performance grade test results

Conventional and performance grade test results are given in Table 3. According to the softening point results, the binders' softening points increase with the use of Sasobit additive together with SBS and CR. While 4% SBS addition increases the softening point of the pure binder by 17.84%, the softening point raises by 48.52% by using 3% Sasobit additive with 9% CR. It is also determined that each addition of 1% Sasobit additive provides an increase of approximately 3 °C in the softening point. Rotational viscometer values of SBS and CR+Sasobit modified binders increase in comparison to the pure binders. As the SBS ratio at 135 °C increases, the viscosity value goes up by 100%, 180%, and 271% in comparison to the pure binder. 5% CR+3% Sasobit and 9% CR+3% Sasobit modified binders reveal similar viscosity values with 2% and 4% SBS, respectively. It has been determined that CR+Sasobit modified binders met the criteria in terms of workability (Vis@135 °C< 3 Pa.s).

In the CR modification, a reduction of 8% in viscosity is achieved by increasing the Sasobit additive from 2% to 3%, PG test is applied on unaged, RTFO-aged (AASHTO T240), and PAV-aged (ASHTO R28) samples of pure and modified binders. According to the results of non-aged and short-term aged binders at 64°C, 9% CR+3% Sasobit modified binder provides the highest rutting parameter by approximately 6.5, 3.56, 2.5 and 1.74 times more than pure, %2 SBS, %3 SBS and %4 SBS modified binders respectively. Besides, performance levels are given in Table 4 together with the MSCR results.

Table 3. Conventional and performance grade test results

Binder type	0-0	2-0	3-0	4-0	5-2	5-3	9-2	9-3
Unaged								
Softening point (°C)	54.1	59.0	62.8	63.8	73.9	76.6	76.5	80.4
Rotational Viscosity(η)@135 °C (cP)	700	1400	1963	2600	1475	1350	2888	2675
Rotational Viscosity(η)@165 °C (cP)	187.5	350	487.5	650	362.5	350	687.5	637.5
Modification index@135°C (ηmodified/ηneat)	1.00	2.00	2.80	3.71	2.11	1.93	4.13	3.82
Modification index@165°C (ηmodified/ηneat)	1.00	1.87	2.60	3.47	1.93	1.87	3.67	3.40
G*/sinδ@64 °C (kPa)	3.06	5.32	8.46	11.52	9.19	10.59	19.44	19.99
RTFO-aged								
G*/sinδ@64 °C (kPa)	13.47	24.09	35.15	48.89	41.37	49.63	75.21	87.25
PAV-aged								
G*.sinδ@25 °C (kPa)	2669	3783	3828	3930	3422	3787	3612	4066
Sm @-12 °C	196.40	155.01	160.35	167.72	176.26	202.75	155.02	180.75
m-value@-12 °C	0.3150	0.3100	0.3062	0.3027	0.3046	0.2699	0.3134	0.2869

3.2. Frequency sweep test results

In Figure 2, the master curves of the complex module and phase angles of all binders at a reference temperature of 40 °C are depicted. While the complex modulus values of the pure and SBS modified binders were lower than the complex modulus values of the CR+Sasobit added binders, the phase angle values were higher. With the use of Sasobit additive in CR, the complex module values of the binder increase, while the phase angle values decrease significantly. This reveals that a more flexible behavior will be provided to the binders with the use of Sasobit additive at high temperatures.

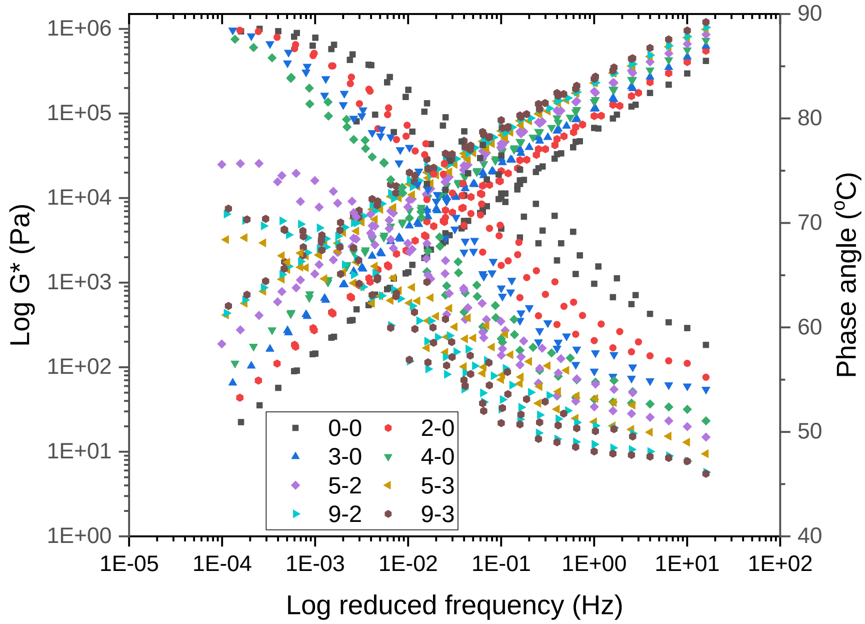

Figure 2. Complex module and phase angle master curves of pure and modified binders at 40 °C reference temperature.

The black space diagram represents the phase angle corresponding to the complex shear modulus obtained from the dynamic rheological data. The plot is typically used to measure the validity of time-temperature superposition and thermorheological simplicity (Qin, Farrar, Turner, & Planche, 2015). In general, a higher complex modulus value versus a lower phase angle value illustrates increased flexibility of the binder. In Figure 3, a black space diagram is drawn using the frequency scan data of pure and modified binders. Considering the same complex module values here, it can be seen that CR+Sasobit modified binders exhibit a more flexible behavior with lower phase angles. In addition, while SBS modified binders demonstrated similar performance with pure binder at low complex modulus values, the use of warm asphalt additive with CR provided no decrease in phase angles.

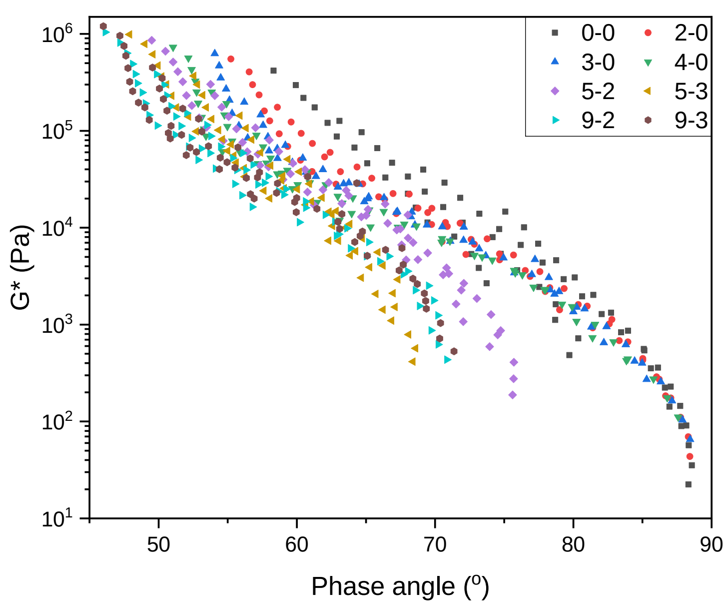

Figure 3. Black diagram.

Figure 4 presents the variation of the loss factor (tan δ) with frequency. The low loss factor calculated according to Equation 14 indicates that the binder will exhibit more flexible behavior.

$$\tan\delta = \frac{G"}{G'} \tag{14}$$

As detailed in figure, the loss factors of pure and SBS modified binders are high at low frequencies, while those of CR and Sasobit modified binders are low. This justifies that CR+Sasobit modified binders will exhibit a more elastic behavior than SBS modified binders, especially at low frequencies.

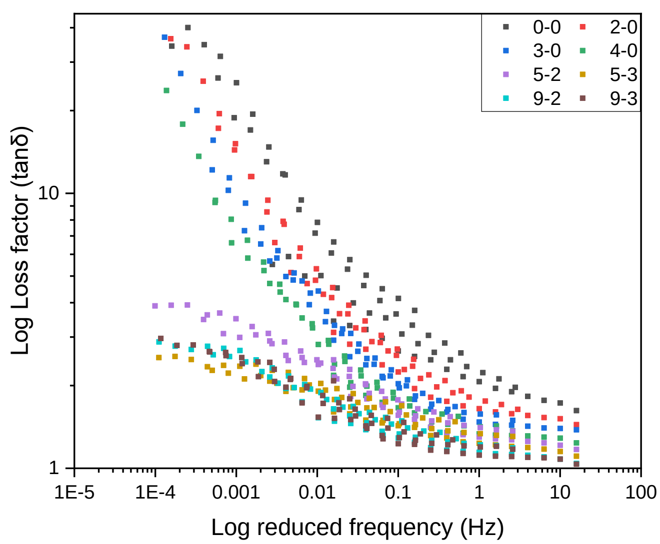

Figure 4. Frequency dependence of loss tangent at reference temperature.

In this study, the Glover-Rowe (G-R) parameter was also valued as a rheological aging index property. The G-R parameter was introduced by Rowe, and was based on the evaluation of Glover et al.'s (Glover et al., 2005) study on low ductility temperature (King, G. Anderson & Hanson, D. Blankenship, 2012). In their study, Glover et al. utilized the Maxwell mechanical analog model to obtain a rheological parameter of ductility ($G'/(\eta'/G')$), which was later called the "Glover parameter" (Glover et al., 2005). Glover et al. proposed this parameter as a indicator of pavement cracking potential (Glover et al., 2005). Rowe et al. (Rowe, King, & Anderson, 2014) tried to simplify Glover's parameter. The findings of their study demonstrated the following:

$$G-R = \frac{G^*(\cos\delta)^2}{\sin\delta} \tag{15}$$

G* states that, dynamic shear modulus measured at 15°C and 0.005 rad/s (Pa) and δ, phase angle measured at 15°C and 0.005 rad/s (°). It is impossible to execute testing at 0.005 rad/s. Therefore, the G* and phase angle results at a decreased frequency that conform with 15°C and 0.005 rad/s were identified from the G* and phase angle master curves built from temperature– frequency sweep DSR testing and frequency– temperature shift factors.

The G-R parameters were calculated from the results of the Frequency Sweep Test performed on the PAV residue of pure and modified binders. Test results are given in Figure 5. According to the findings of this study, 9% CR + 3% Sasobit added binder gave the highest G-R parameter. With the addition of Sasobit additive to the CR modification, it was determined that the resistance to crack formation would decrease at medium and low temperatures. It also stated that the high G-R parameter was due to the high complex modulus values and increases the hardness of the binder. At the same time, as the ratio of SBS contribution increased, also the value of the G-R parameter increased. Nevertheless, this increased the possibility of crack formation at medium and low temperatures.

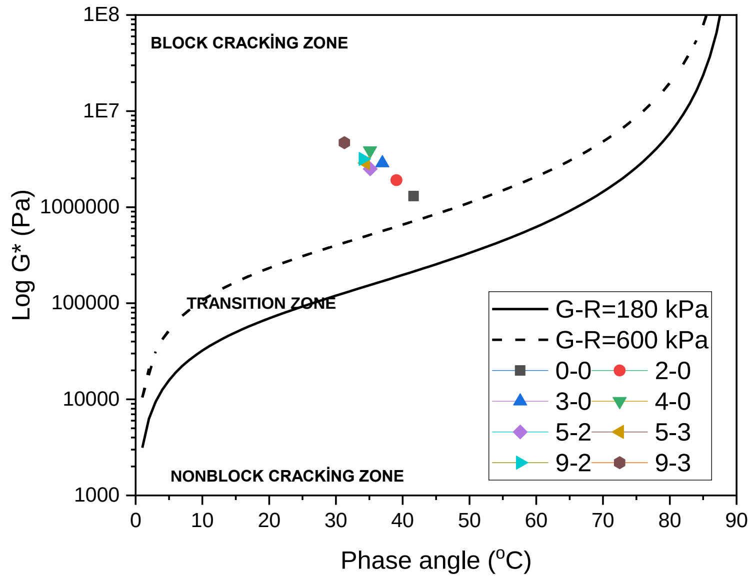

Figure 5. G-R parameter in black diagram.

3.3. MSCR test results

In Figure 6, the results of the MSCR test applied at different temperatures under 3.2 kPa and 0.1 kPa and the percentage differences between these stress levels are given according to two different criteria. As it can be seen in Figure 6(a) and (b), a significant decrease in Jnr values compared to pure binder is observed at both stress levels with the use of warm asphalt additive together with SBS and CR. It is determined that this decrease is respectively at a ratio of 82.5% and 97.2% for 4% SBS and 9%+3% Sasobit in Jnr3.2 at 64 °C. A similar ratio is observed in creep compliance values at 3.2 kPa at 70 ° C. By increasing the use of warm asphalt additives by 1% in 5% CR modified contents, an average reduction of 29% in Jnr3.2 values is achieved at all temperatures. It is determined that this ratio is 23.5% for 9% CR modified contents. In other words, creep compliance (Jnr3.2) values of CR at both stress levels decrease by using the Sasobit additive.

This effect of Sasobit addition is also determined in another study (Sadeq, Masad, Al-Khalid, Sirin, & Mehrez, 2018). Besides, considering the Jnr3.2 values especially at high temperatures, 4% SBS and 5% CR+2% Sasobit modified binders yield nearly similar creep compliance values, while 5% CR+2% Sasobit at 0.1 kPa stress level reveal lower creep compliance values. Just as another one, this study also achieves lower creep compliance values compared to SBS modified binders at a stress level of 0.1 kPa with the use of CR (Behnood and Olek, 2017b). As seen in Figure 6 (c), pure and SBS modified binders provide the Jnrdiff ≤ 75 value, the second criteria of MSCR protocol, under all temperatures. However, it is determined that the binders with CR+Sasobit additive do not meet this specification criterion especially under high temperatures (i.e., ≥76). In studies where CR is used as an additive material in asphalt binders, it is determined that this criterion cannot be met (Behnood & Olek, 2017b).

Figure 6 (d) provides the Jnrslope values determined by considering the study (Stempihar et al., 2018) which is stated to better describe the stress sensitivity. According to the obtained Jnrslope values, all binders except the test results of the binders with 9% CR+2% Sasobit and 9% CR+3% Sasobit additives at 88 °C, provided the limit values determined in the study (Stempihar et al., 2018). Besides, as seen in the binder performance grades determined according to the PG and MSCR test results given in Table 4, it is observed that especially the binders with CR and Sasobit additives do not meet the Jnrdiff specification criteria and give a low-performance level. According to Jnrslope values, 5% CR+2% Sasobit and 9% CR+3% Sasobit modified binders provide one and the other CR and Sasobit modified binders provide two upper grades of performance levels.

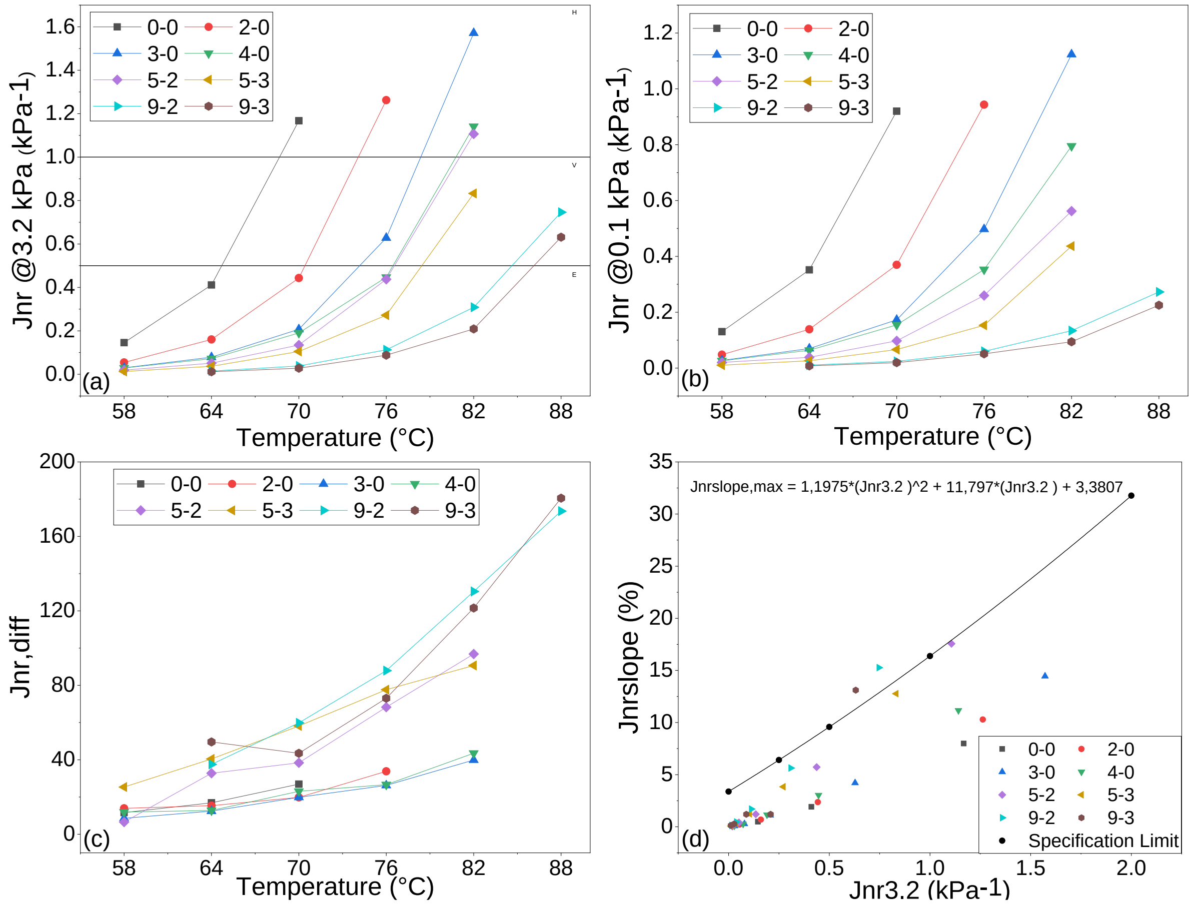

Figure 6. MSCR test results at different temperatures a) Jnr3.2; b) Jnr0.1; c) Jnrdiff; d) Jnrslope.

Figure 7 gives the average percent recoveries of pure and modified binders at different temperatures under 3.2 kPa and 0.1 kPa and their percentage differences in percent recoveries at these stress levels. As seen in Figure 7 (a) and Figure 7 (b), the percent recoveries decrease almost linearly ($R2 \geq 0.98$) as the temperature increases in both stress levels. It is determined that CR and Sasobit modified binders yield higher mean percent recovery values under all temperatures at both stress levels. This is an indication that CR and Sasobit modified binders will behave more flexibly than SBS modified binders under higher temperatures.

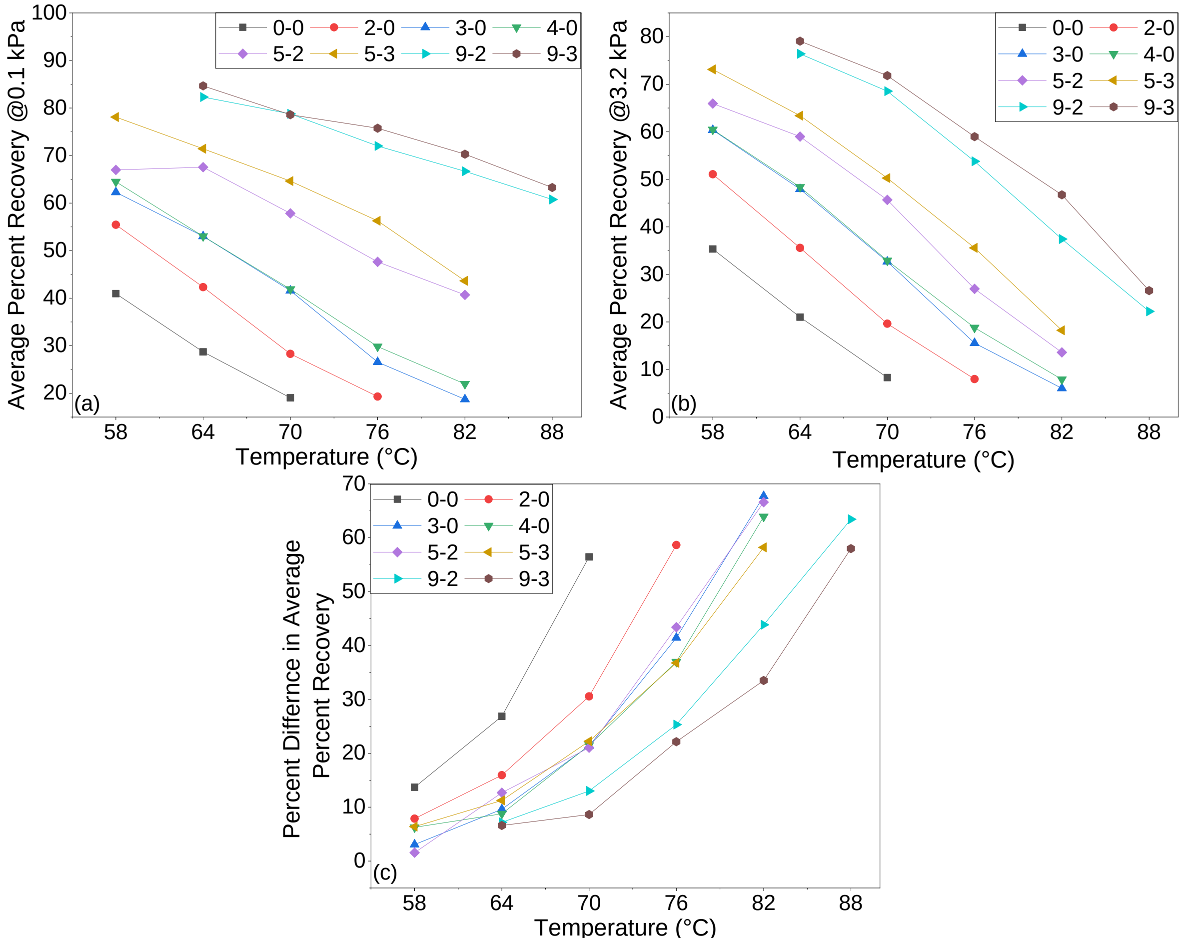

Figure 7. MSCR test results at different temperatures a) R3.2 b) R0.1 c) percent difference between averages percent recoveries at 3.2 kPa and 0.1 kPa.

Figure 8 shows the graphic of total strain versus time in the first cycles of 0.1 kPa and 3.2 kPa stress levels according to the MSCR test results under 64 °C. CR+Sasobit modified binders show more resistance to rutting than other binders. While 2%, 3%, and 4% SBS modified binders respectively yield 57.1%, 76.7%, and 78.6% less strain than the pure binder, the total strain of the 9% CR+3% Sasobit modified binder is the lowest, that is 17.12 times lower than the pure binder.

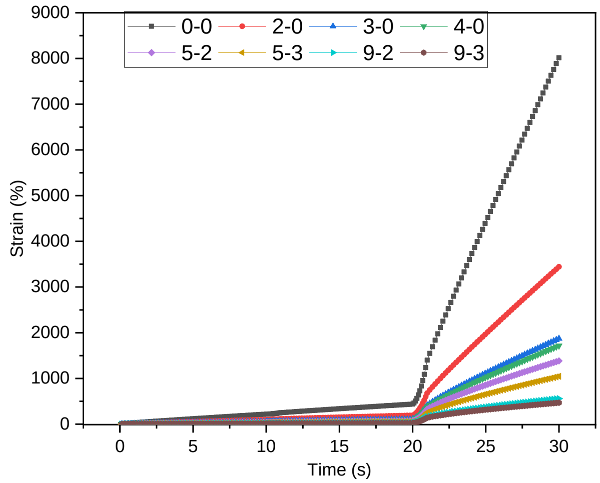

Figure 8. Total strain vs. time at 64 °C.

Table 4. Binder performance levels according to PG and MSCR tests.

Binder ID	Grade designation						
	PG system	MSCR system with Jnrdiff ≤ 75 criteria			MSCR System with Jnrslope criteria		
0-0	PG70-22	PG64E-22	PG70H-22		PG64E-22	PG70H-22	
2-0	PG76-22	PG70E-22	PG76H-22		PG70E-22	PG76H-22	
3-0	PG82-22	PG70E-22	PG76V-22	PG82H-22	PG70E-22	PG76V-22	PG82H-22
4-0	PG82-22	PG76E-22	PG82H-22	PG82H-22	PG76E-22	PG82H-22	
5-2	PG82-22	PG76E-22			PG76E-22	PG82H-22	
5-3	PG82-16	PG70E-16			PG76E-16	PG82V-16	
9-2	PG88-22	PG70E-22			PG82E-22		
9-3	PG88-16	PG76E-16			PG82E-16		

3.4. LAS test results

Table 5 shows the fatigue parameters calculated according to the VECD theory at 15 °C and 20 °C. Parameter A represents the ability of the binder to maintain its integrity and parameter B stands for its sensitivity to strain level change (Hassanpour Kasangh, Ahmedzade, & Günay, 2021). According to Table 5, as the SBS and CR content increase, the A parameter also goes up under both temperatures. However, with the increase of the percentage of Sasobit additive in CR modification, a fair amount of decrease is observed in parameter A. This indicates that the Sasobit additive impairs the integrity of the binder at medium temperatures and will yield a shorter fatigue life than other binders. Besides, the absolute increase in parameter B indicates that the fatigue life will shorten with the increase in the strain level. In other words, at high strain levels, CR+Sasobit modified binders are expected to yield short fatigue lives as can be seen in Nf-shear strain graphics.

Table 5. VECD fatigue parameter for 15 °C and 20 °C.

Binder Type	A		B		C1		C2		α		Damage level	
	15 C°	20 °C	15 C°	20 °C	15 C°	20 °C	15 C°	20 °C	15 C°	20 °C	15 C°	20 °C
0-0	1.45E+07	1.20E+07	-5.507	-5.062	0.111	0.119	0.425	0.393	2.753	2.531	0.566	0.566
2-0	2.95E+07	4.15E+07	-5.890	-5.465	0.187	0.170	0.298	0.309	2.945	2.733	0.540	0.575
3-0	4.40E+07	6.40E+07	-6.202	-5.847	0.192	0.196	0.296	0.288	3.101	2.923	0.540	0.587
4-0	9.99E+07	1.25E+08	-6.424	-5.851	0.192	0.196	0.295	0.286	3.212	2.926	0.554	0.617
5-2	8.03E+07	1.34E+08	-6.539	-6.348	0.222	0.207	0.272	0.288	3.270	3.174	0.570	0.612
5-3	7.57E+07	1.29E+08	-6.807	-6.343	0.203	0.246	0.305	0.251	3.403	3.172	0.574	0.616
9-2	2.39E+08	2.95E+08	-7.095	-6.563	0.259	0.261	0.245	0.241	3.547	3.281	0.599	0.646
9-3	2.34E+08	3.13E+08	-7.222	-6.746	0.276	0.285	0.236	0.226	3.611	3.373	0.606	0.651

Fatigue lives (Nf) at 2.5% and 5% strain levels under 15 °C and 20° C are given in Figure 9. According to Figure 9 (a), 2%, 3%, and 4% SBS modified binders respectively yield 1.43, 1.60, and 2.96 times longer fatigue lives than the pure binder at 15 °C, while this ratio is respectively 2.97, 3.22, and 6.27 at 20 °C. As seen in the figure, as the ratio of Sasobit additive increases, the fatigue life of the CR modification shortens at both temperatures. The 9% CR+2% Sasobit modified binder provides the best performance at a 2.5% strain level. As seen in Figure 9 (b), when the strain level increases, the CR+Sasobit modified binders reveal lower Nf values in comparison to the 4% SBS modified binder. This shows that the crumb rubber and warm asphalt additive undergo structural deteriorations at high strain levels.

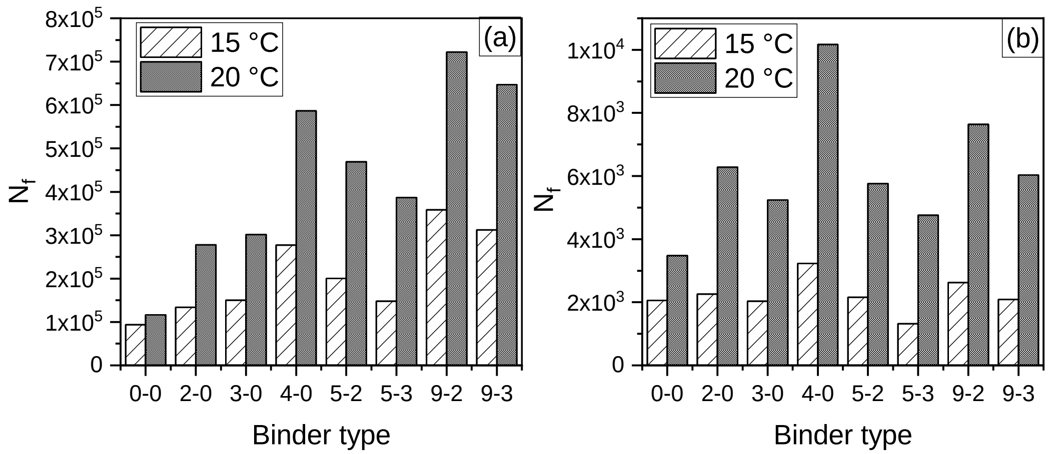

Figure 9. LAS test result: (a) fatigue life at 2.5% strain level and (b) fatigue life at 5% strain level.

Fatigue lives at different strain levels (from 1% to 10%) are given in Figure 10. As seen in Figure 10, binders with 9% CR+2% Sasobit and 9% CR+3% Sasobit modified binders yield the longest fatigue life at low strain levels under both temperatures. For example, these modified binders' fatigue lives are respectively 24.6 and 24.1 times longer than the pure binder at 1% strain level. However, at high strain levels, SBS modified binders yield longer fatigue lives than all binders.

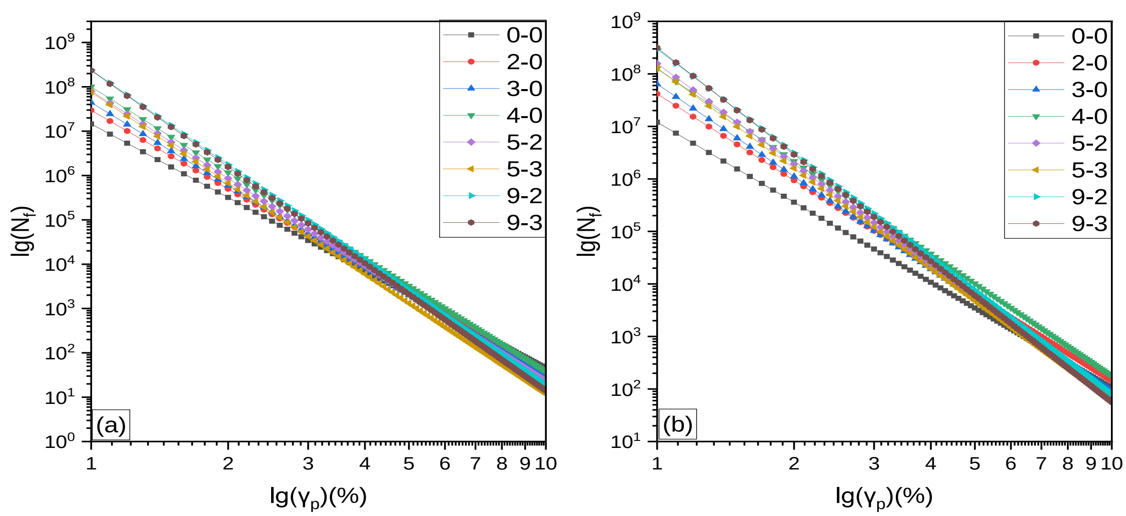

Figure 10. Fatigue lives at different strain levels (a) at 15 °C (b) at 20 °C.

The shear stress-strain graphics under two different temperatures are given in Figure 11. %4 SBS modified binder yields the highest shear stress under both temperatures. It is seen that as the Sasobit modification in CR increases, the shear stresses go up. The pure binder undergoes a sudden decrease as the strain increases after the maximum shear stress and this indicates that the sample is damaged.

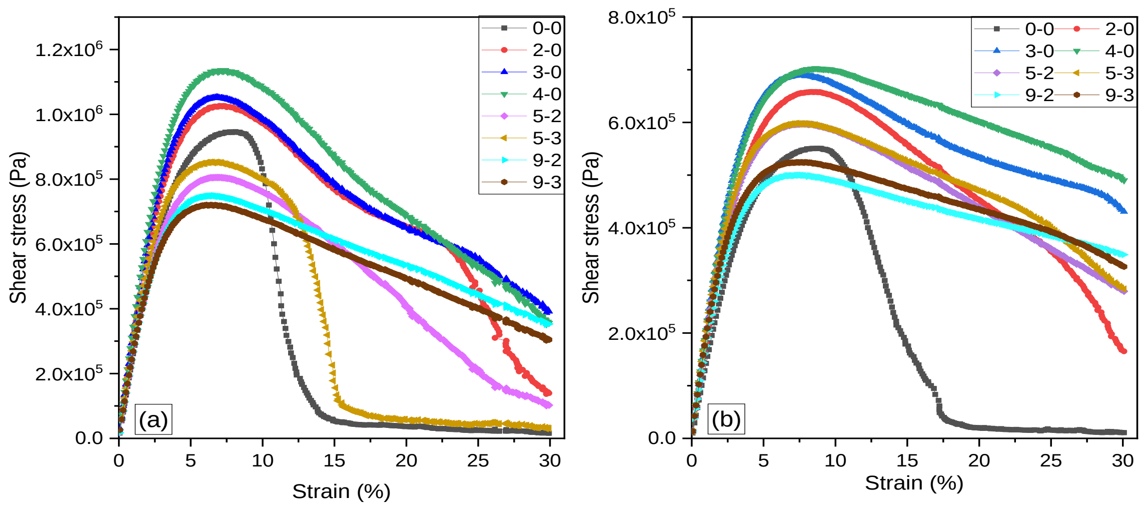

Figure 11. Shear stress versus strain curve of all modified (a) at 15 °C (b) at 20 °C.

Figure 12 provides the relationship between the binders' damage intensity (D) and integrity parameters (C). According to the figure, as the damage intensity increases, the integrity parameters of all binders reduce. It is detected that under a fixed damage intensity, the material integrity of the SBS modified binders is higher than all other binders'.

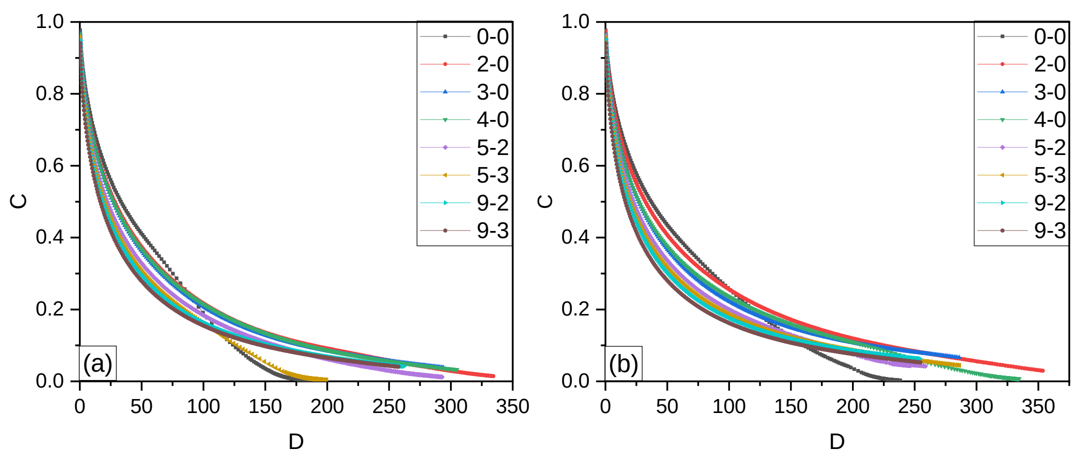

Figure 12. Damage characteristics curves with VECD theory (a) at 15 °C (b) at 20 °C.

3.5. BBR test results

In Figure 13, the stiffness and m-value values of the pure and modified binders are depicted. SBS additive reduces the stiffness and m-values of the binder. Warm asphalt additive significantly increases the stiffness of the binder, as in the medium temperature parameter. It has been observed that 3% Sasobit added CR modified binders do not meet the specification limits at -12 °C. According to the BBR black space diagram given in Figure 14, the performance level of pure and modified binders is PG XX-22, while the performance level of binders with 3% Sasobit additive is PG XX-16.

To better evaluate the behavior of binders against crack propagation at low temperatures, ΔTc values are detailed in Figure 15. As highlighted in the figure, it was determined that all binders except the pure binder became more sensitive to stresses. Among the modified binders, SBS added binders give lower ΔTc values. While CR modified binders are expected to give high ΔTc values (Behnood et al., 2020) it was revealed that they gave low ΔTc values due to Sasobit addition. This was an indicator of Sasobit additive's making the binder stiffer at low temperatures.

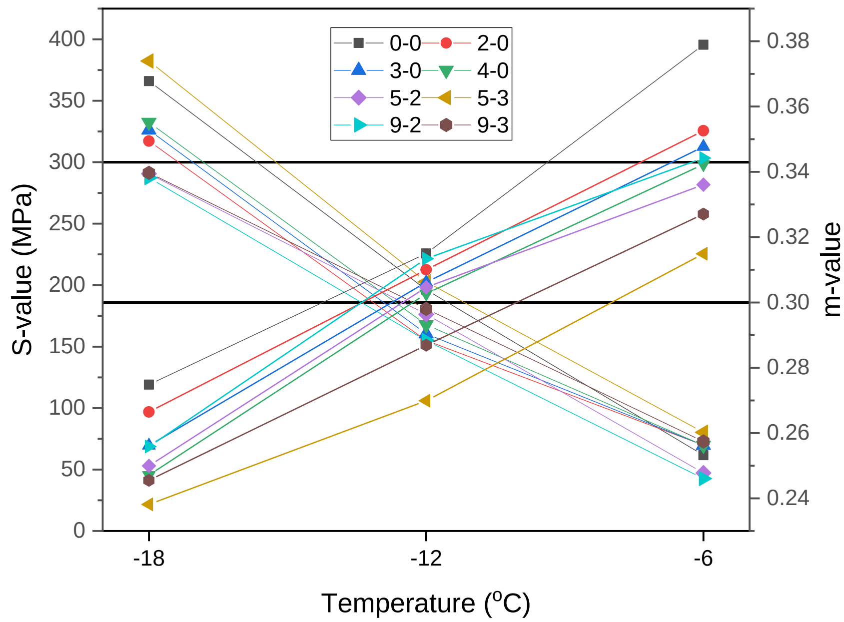

Figure 13. The stiffness and m-value values of pure and modified binders.

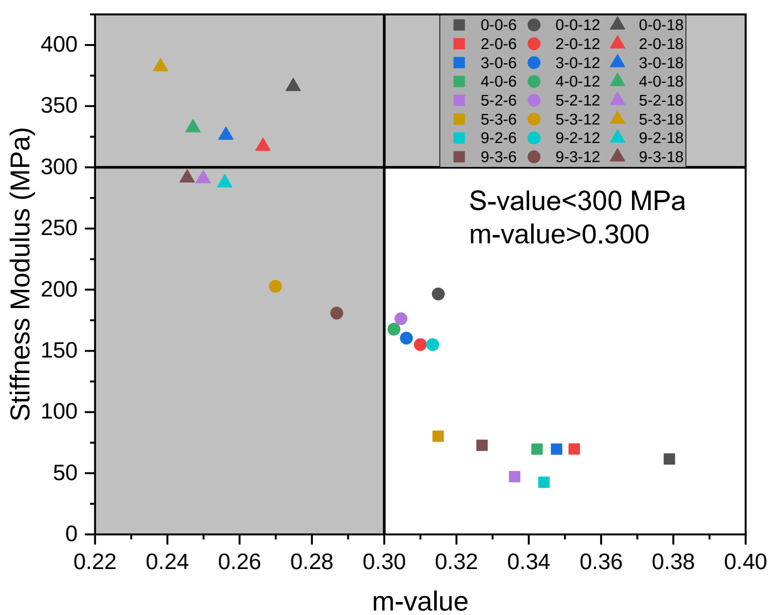

Figure 14. BBR black diagram.

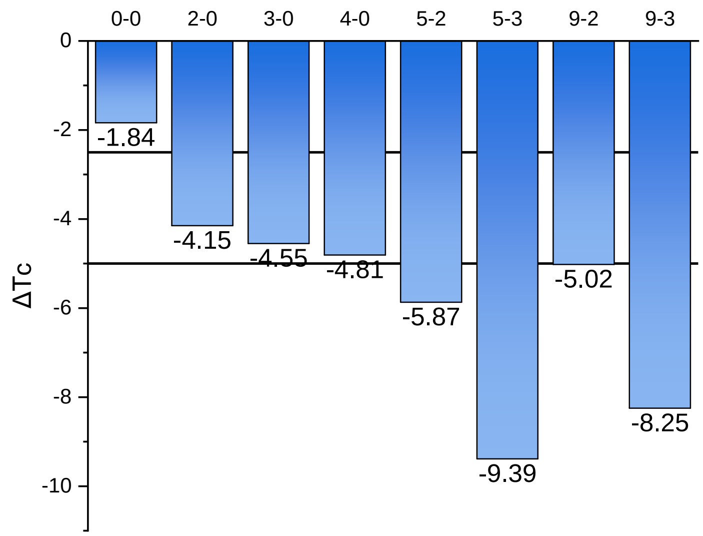

Figure 15. ΔTc values of pure and modified binders.

4. Conclusions and comments

1. In the DSR test it is determined that the binders with 4% SBS and 5% CR+3% Sasobit additives put down a similar performance in unaged, RTFO-aged and PAV-aged binders;
2. It is determined that the combination of CR and Sasobit improves the rheological characteristics of the pure binder at high temperatures, besides its viscosity reducing effect;
3. Although the CR additive improves the rheological characteristics of the binder at medium and low temperatures, this effect is reduced when it is used with Sasobit additive;
4. According to the frequency sweep test results, it has been determined that the use of Sasobit additive at high temperatures will provide a more flexible behavior to the binders;
5. It is determined that the CR+Sasobit modified binders do not meet the specification criteria Jnr,diff ≤75 at high temperatures. Instead, it is detected that with the determined Jnrslope value, the CR modified binders yield higher PG levels.
6. Fatigue lives shorten with the increase in the percentage of Sasobit in the CR modification;
7. According to LAS test results, the most suitable Sasobit rate is determined to 2% when used with CR (Kataware and Singh 2019);
8. According to the G-R parameter and ΔTc values, it was determined that the warm asphalt additive makes the binder more rigid and reduces the resistance against crack resistance at medium and low temperatures.

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