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Low-Temperature and Fatigue Characteristics of Degraded Crumb Rubber–Modified Bitumen Before and After Aging

Sheng Wang[1]; Weidong Huang[2]; and Peng Lin, Ph.D.[3]

Abstract: The high viscosity and poor storage stability of crumb rubber–modified asphalt (CRMA) can be partially addressed by the appropriate degree of degradation of the crumb rubber modifier. However, the low-temperature and fatigue characteristics of degraded crumb rubber–modified bitumen (DCRMB) in different aging states are not well understood. In this study, two types of DCRMB—namely, terminal blend rubberized asphalt (TBRA) and terminal blend hybrid asphalt (TBHA)—were prepared with sulfur, styrene-butadiene-styrene (SBS) polymer, and crumb rubber (CR). All DCRMB binders were short-term aged with a rolling thin film oven test (RTFOT) and long-term aged with a pressure aging vessel (PAV). Afterward, a bending beam rheometer (BBR) test and a linear amplitude sweep (LAS) test were conducted to characterize the low-temperature and fatigue properties of DCRMB binders at different aging degrees, respectively. Based on the rheological test results, several conclusions can be drawn. First, the BBR results indicated that the increase in CR content led to a slight increase in creep rate and a significant decrease in stiffness. Especially in PAV aging, the low-temperature properties of DCRMB were much better than those of neat asphalt. Meanwhile, DCRMB demonstrated an advantage over neat asphalt in integrity and fatigue resistance before and after aging. Finally, based on correlation analysis, the LAS test is recommended for evaluating the fatigue properties of DCRMB before and after aging. **DOI: 10.1061/(ASCE)MT.1943-5533.0004131.** © *2021 American Society of Civil Engineers.*

Author keywords: Degraded crumb rubber–modified bitumen (DCRMB); Short-term and long-term aging; Bending beam rheometer (BBR) test; Linear amplitude sweep (LAS) test; Correlation analysis.

Introduction

Pavement cracking due to the effects of low temperatures and fatigue cracking under repeated loading are the main forms of pavement distress and seriously affect the service life of asphalt pavement (Wang et al. 2019b, 2021a). The main cause of pavement cracking is the hardening and brittleness of the asphalt binder at low temperatures, resulting in a reduction in its stress relaxation capacity and the occurrence of tensile stresses over the ultimate tensile strength of the asphalt mixture under traffic loading (Chen et al. 2019). Also, asphalt binder as a complex compound is the main factor influencing pavement cracking, contributing 52% to fatigue cracking and 87% to low-temperature cracking (Poulikakos et al. 2019; Wang et al. 2019a). Adding modifiers to asphalt is the main way to improve the cracking resistance of asphalt. Crumb rubber–modified asphalt (CRMA) has attracted much attention because of its excellent high- and low-temperature cracking and fatigue resistance (Akisetty et al. 2009; Kim et al. 2001; Lee et al. 2008; Picado-Santos et al. 2020) and because it can consume much waste rubber from tires (Bressi et al. 2019; Lo Presti 2013). However, most of the CR in traditional CRMA swells in the asphalt and forms a solid-liquid two-phase system, which leads to unstable performance and poor storage stability. Moreover, the high viscosity of CRMA leads to greater construction difficulty, which limits its popularization. The terminal blend process can degrade CR in CRMA through high temperature, high speed, and long-time shearing (Chamoun et al. 2015; Hajj et al. 2011; Han et al. 2016; Wen et al. 2018); the desulphurization reaction produces small-molecule polymers, which reduce the viscosity of terminal blend rubberized asphalt (TBRA), thus improving CRMA workability.

Some studies have found that TBRA has excellent low-temperature cracking resistance, fatigue resistance, and storage stability (Huang et al. 2017; Li et al. 2017; Lin et al. 2018). The low-temperature performance of TBRA increases with rising CR content. This is due to the uniform mixing of CR and asphalt, which enhances TBRA integrity and low-temperature ductility. Moreover, TBRA has excellent fatigue and self-healing properties, and its antireflective cracking ability is better than that of styrene-butadiene-styrene–modified asphalt (SBSMA) (Huang and Huang 2016; Lv et al. 2017a, b). This is because the CR generates small molecules under the condition of high-speed shear and high temperature, and fully dissolves into the asphalt to generate a liquid-phase homogeneous colloidal structure. However, the high-temperature performance of TBRA is reduced due to breakage of long chains of molecules during CR degradation in desulfurization. Given this problem, some researchers have carried out composite modification of TBRA by adding polymer. The cross-linking between SBS polymer and TBRA forms a new space network structure (Wen et al. 2001, 2002), which improves the binder's elastic recovery and failure strength. While retaining low-temperature

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cracking resistance, this new structure greatly improves TBRA high-temperature performance. Asphalt is subjected to aging by heat, light, and oxygen during mixing, construction, and use, resulting in significant changes in its performance (Apeagyei 2011; Ghavibazoo et al. 2015; Zeng et al. 2018; Zhao et al. 2016). With the repeated effects of heat and oxygen, ultraviolet radiation, and traffic loads, asphalt performance deteriorates (Wang et al. 2021b), leading to fatigue and low-temperature cracking, which affect pavement life. It is known that DCRMB, as a relatively new material, ages less, and current research on modified bitumen is still mainly focused on high-temperature performance. However, because there is no systematic research on low-temperature cracking resistance and fatigue resistance, it is of great significance to study the low-temperature cracking resistance and fatigue resistance of DCRMB before and after aging.

In this study, the low-temperature and fatigue characteristics of DCRMB before and after aging were measured. The bending beam rheometer (BBR) test was performed to study low-temperature cracking resistance before and after aging. The changes in fatigue characteristics before and after aging were analyzed using linear amplitude scanning (LAS) and fatigue factor tests. Additionally, correlations between DCRMB's low-temperature performance indicators and fatigue performance indicators were investigated.

Materials and Methods

Materials

In this study, there were two DCRMBs, TBRA and TBHA. Five TBRAs were prepared using different amounts of CR and neat asphalt (PG 64-22). Sulphur, linear SBS polymer, and the five TBRAs were selected to prepare the TBHA binders. The average molecular weight of the linear SBS polymer was 120,000 g/mol. The −30 mesh CR, containing 54% natural and synthetic rubber was produced in China. The specific preparation of the TBRA and TBHA is shown in Fig. 1 (Wang and Huang 2021). Three percent SBS content allowed the asphalt binder to form a stable polymer network structure. The addition of no more than 0.3% sulfur to the crumb rubber and SBS composite–asphalt helped to ensure the homogeneity of the binder network structure; the SBSMA was 0.15% sulfur (Tang et al. 2016). Details of the composition of TBRA and TBHA are provided in Table 1. With the increase in CR content, the penetration of TBRA increased and the softening point decreased. However, TBHA penetration and softening point increased with the increase in CR. The reasons are as follows: due to the desulfurization of CR and the degradation of rubber molecules in the bitumen after high-temperature degradation, TBRA lost part of the elasticity of the CR, and the serious degradation of the rubber molecular chain produces a large number of small molecular polymers with molecular weight less than asphalt. This may have had a diluting effect on the bitumen, resulting in a lower softening point of the TBRA binder (Tang et al. 2016). In addition, in the presence of sulfur the small polymers produced by the degradation of the molecular chains of the TBHA CR formed a network structure by cross-linking with SBS, which led to a TBHA higher softening point.

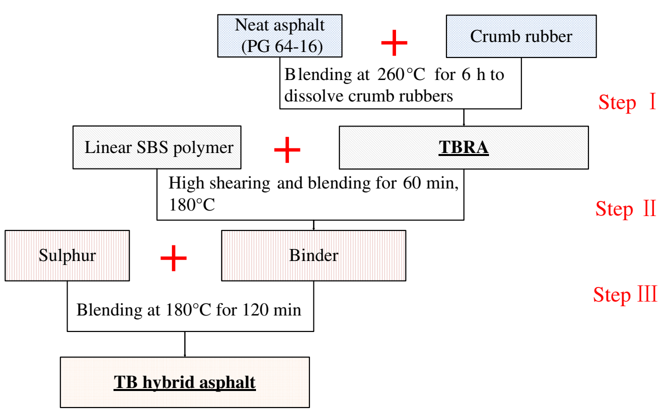

Fig. 1. Schematic of binder preparation.

Aging

Rolling thin film oven tests (RTFOTs) and pressure aging vessel (PAV) tests were performed on TBRA and TBHA according to AASHTO M 320-14 (AASHTO 2014).

Bending Beam Rheometer Test

The BBR test was used to investigate the low-temperature performance of DCRMB before and after short-term and long-term aging according to ASTM D6648 (ASTM 2001). Stiffness (S) and creep rate (m-value) before and after aging at −12°C, −18°C, and −24°C were measured. For reliability reasons, all binders were replicated three times. An Increasing S value and a decreasing m-value indicated that the asphalt was brittle and easy to crack and damage (Chen et al. 2019; Li et al. 2017). Under PAV aging conditions, when S was 300 MPa or the m-value was 0.3, low-temperature performance grade (PG) was used to evaluate low-temperature binder cracking resistance. PG temperature judged by S under PAV aging (Tsp) represented PG low temperature when S was 300 MPa in the PAV aging state, and PG temperature judged by m-value under PAV aging (Tmp) represented PG low temperature when the m-value

Table 1. Binder modifications and physical properties

Binder type	Modification plan			Physical properties	
	CR (%)	Sulphur (%)	SBS polymer (%)	Penetration (0.1 mm)	Softening point (°C)
0TB	0	0	0	64	50.1
5TB	5	0	0	71	49.5
10TB	10	0	0	103	48.2
15TB	15	0	0	115	47.9
20TB	20	0	0	120	47.5
0TB_3SBS_0.15S	0	0.15	3	55.4	80.5
5TB_3SBS_0.3S	5	0.3	3	59	72.8
10TB_3SBS_0.3S	10	0.3	3	63.8	78.2
15TB_3SBS_0.3S	15	0.3	3	65.6	78.4
20TB_3SBS_0.3S	20	0.3	3	77.2	79

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was 0.3. The higher value of Tsp and Tmp was selected as the DCRMB PG low-temperature grade (Lin et al. 2017, 2018).

Linear Amplitude Sweep Test

The linear amplitude sweep (LAS) test was used to evaluate the fatigue properties of DCRMB before and after short-term and long-term aging. It was conducted at 25°C according to AASHTO TP 101 and was divided into two parts: frequency sweep and amplitude sweep (AASHTO 2012). In the frequency sweep test, the binders were scanned from 0.2 to 30 Hz with a strain level of 0.1% to determine the asphalt damage analysis parameter (α). The amplitude sweep test used viscoelastic continuum damage (VECD) with a loading frequency of 10 Hz and a linear increase in loading amplitude from 0.1% to 30%.

Fatigue Factor

The dynamic shear rheometer (DSR) test was carried out on the DCRMB before and after aging at a fixed frequency of 10 rad/s with an 8-mm parallel plate and a 2-mm gap to obtain the fatigue factor ($G^* \sin\delta$) while the temperature was 25°C.

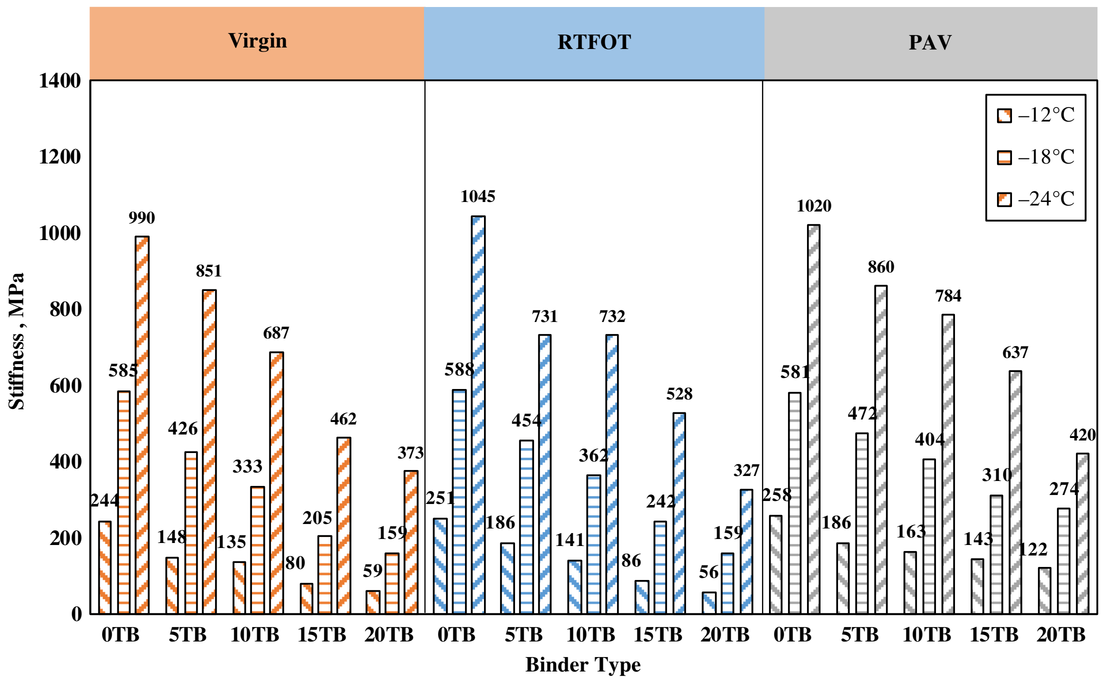

Fig. 2. TBRA stiffness before and after aging.

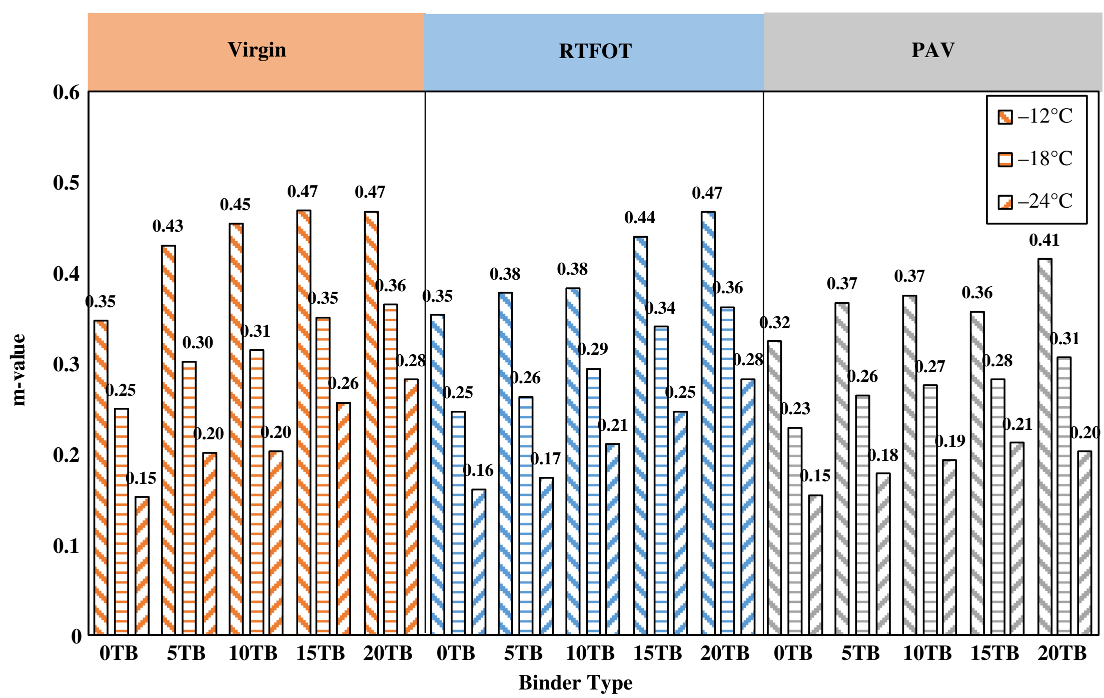

Fig. 3. TBRA m-value before and after aging.

Results and Discussion

Low-Temperature *S* and *m*-Value Analysis

Changes in TBRA *S* and *m*-value before and after aging at −12°C, −18°C, and −24°C are shown in Figs. 2 and 3. As shown in Fig. 2, compared with 0 TB, *S* before aging decreased at −12°C, −18°C, and −24°C. With the increase in CR content, it gradually decreased before aging, ranking in the virgin condition as 0TB > 5 TB > 10 TB > 15 TB > 20 TB, which indicated that the increase in CR improved TBRA low-temperature cracking resistance. The main reason for this was that the CR underwent desulfurization and degradation in the TB process, which resulted in its partial cleavage and the entry of antiaging agents, cross-linking agents, and carbon

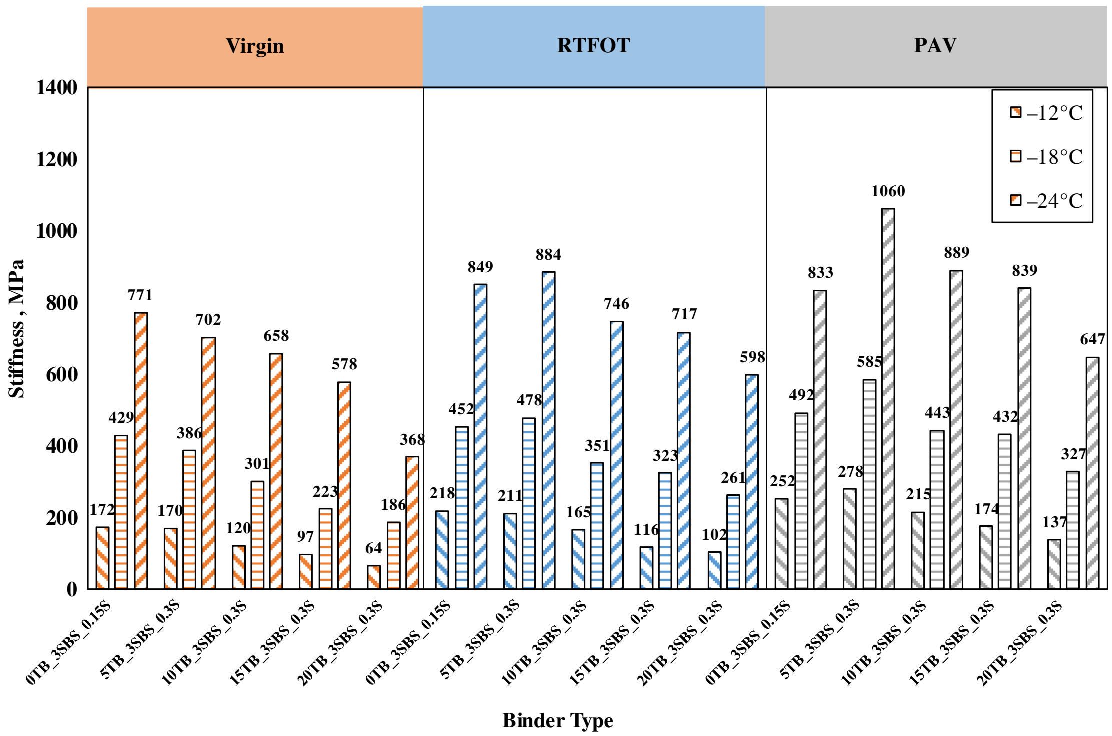

Fig. 4. TBHA stiffness before and after aging.

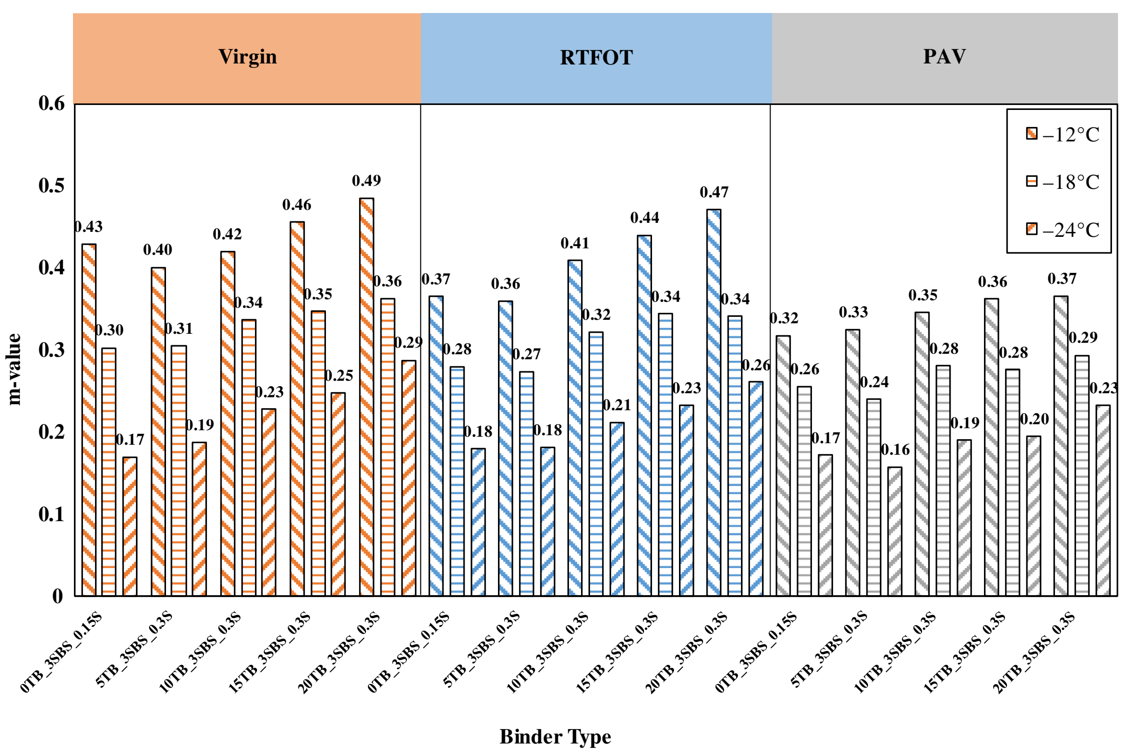

Fig. 5. TBHA *m*-value before and after aging.

black into the asphalt phase, improving TBRA's low-temperature properties (Wang et al. 2017). The more CR, the greater its degradation in, which led to the input of more materials beneficial to low-temperature cracking resistance and thus better low-temperature performance. Moreover, the order of S after aging was the same as that before aging at −12°C,−18°C, and −24°C, which indicated that TBRA's low-temperature cracking resistance after aging was still better than that of 0TB.

TBRA m–values before and after aging at −12°C, −18°C, and −24°C are presented in Fig. 3. For the same binder, decreasing temperature lowered the m-value. Unlike S, the m-value gradually increased before and after aging at −12°C, −18°C, and −24°C with the increase in CR content; its ranking was 20TB > 15 TB > 10 TB > 5 TB > 0 TB. This showed that, compared with that of neat asphalt, TBRA's S decreased greatly under different aging conditions while m-value increased. Moreover, the increase in CR content made the modification effect more obvious, so that the low-temperature cracking resistance of TBRA was better than that of the neat asphalt.

Figs. 4 and 5 show TBHA S and m-value under different aging conditions. Fig. 4 shows that the S values of 0TB_3SBS_0.15S, 5TB_3SBS_0.3S, 10TB_3SBS_0.3S, 15TB_3SBS_0.3S, and 20TB_3SBS_0.3S in the unaged state at −12°C were 172, 170, 120, 97, and 64, respectively. That is to say, the ranking of binder S in the unaged state was 0TB_3SBS_0.15S > 5TB_3SBS_0.3S > 10TB_3SBS_0.3S > 15TB_3SBS_0.3S > 20TB_3SBS_0.3S. Meanwhile, TBHA S at −18°C and −24°C before aging was the same as that at −12°C, indicating that TBHA had better low-temperature cracking resistance than SBSMA before aging. Moreover, all TBHA S values increased after aging, indicating that aging could make TBHA low-temperature cracking resistance of worse. Comparing S of the virgin sample and that of the PAV aging sample, it was found that at −24°C S of 5TB_3SBS_0.3S, 10TB_3SBS_0.3S, and 15TB_3SBS_0.3S in the PAV aging state was greater than that of 0TB_3SBS_0.15S. This was mainly because SBS had a strong thermal-oxidative aging reaction in the PAV aging process (Wang et al. 2020; Wang and Huang 2021), which may have reacted with the substances in the CR, resulting in declining low-temperature performance.

According to Fig. 5, the TBHA m-value gradually increased at −18°C and −24°C under unaged conditions with the increase in CR content; the ranking was 20TB_3SBS_0.3S > 15TB_3SBS_0.3S > 10TB_3SBS_0.3S > 5TB_3SBS_0.3S > 0TB_3SBS_0.15S. This trend was opposite that of S before aging. The TBHA change in

Table 2. PG low-temperature results

Binder type	Tsp (°C)	Temperature (°C)	PG low temperature (°C)	Rank
0TB	−23.1	−23.5	−23.1	2
5TB	−25.1	−25.9	−25.1	5
10TB	−26.1	−26.5	−26.1	7
15TB	−27.9	−26.5	−26.5	8
20TB	−29.8	−28.3	−28.3	10
0TB_3SBS_0.15S	−23.6	−23.7	−23.6	3
5TB_3SBS_0.3S	−22.6	−23.8	−22.6	1
10TB_3SBS_0.3S	−24.8	−26.2	−24.8	4
15TB_3SBS_0.3S	−25.6	−26.3	−25.6	6
20TB_3SBS_0.3S	−27.4	−27.5	−27.4	9

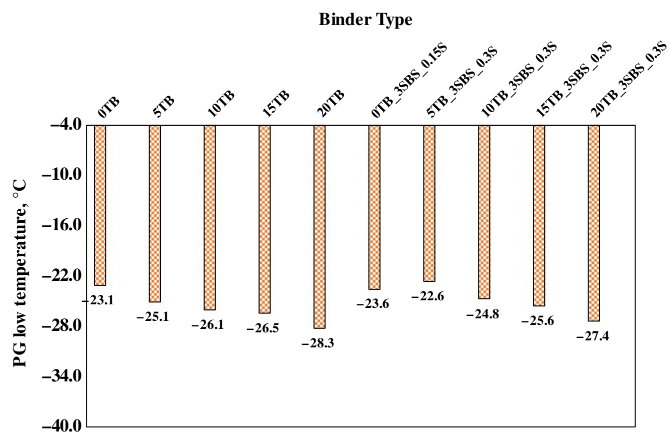

Fig. 7. Binder PG low-temperature grades.

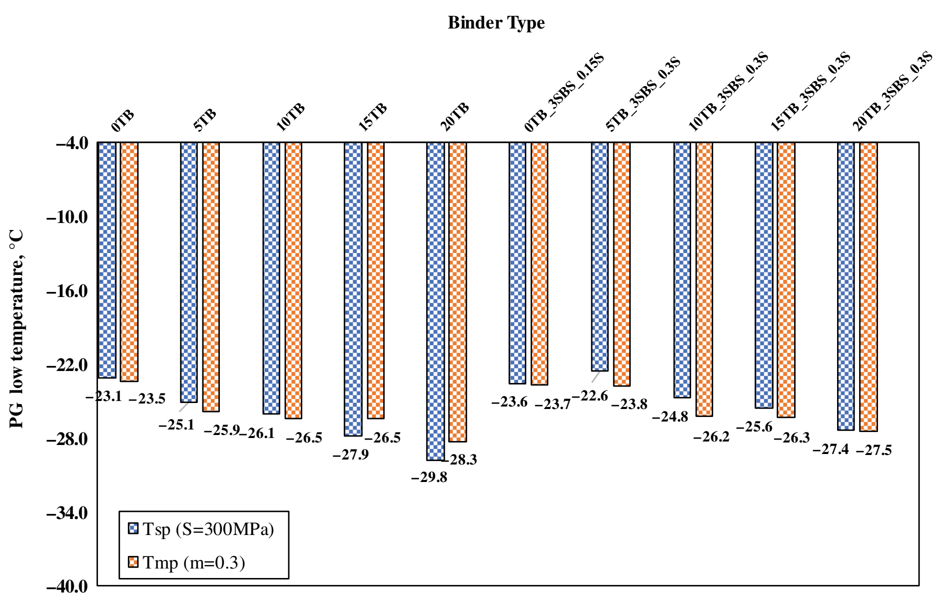

Fig. 6. Binder PG low temperature under different criteria.

m-value after aging was the same as that before aging. This showed that, compared with SBSMA, TBHA increased its m-value greatly under different aging conditions, indicating that its low-temperature cracking resistance was better than SBSMA's.

PG Low-Temperature Grade Analysis

Tsp, Tmp, and PG low-temperature TBRA and TBHA after PAV are summarized in Table 2 and shown in Figs. 6 and 7. Comparing PG low-temperature grades in the PAV aging state, it was found that SBSMA's PG low-temperature grade was lower than that of neat asphalt, and that TBRA's PG low-temperature grade was lower than that of TBHA at the same amount of CR, indicating that TBRA's low-temperature cracking resistance was better than TBHA's in the PAV aging state. The reason was that, on the one hand, TBRA had better aging resistance and so thermal-oxidative aging had little effect on its low-temperature performance (Wang and Huang 2021). On the other hand,, the cross-linking of SBS polymer and CR in asphalt could be destroyed due to the high-temperature and high-pressure effect of TBHA in PAV aging, making TBRA's low-temperature performance worse.

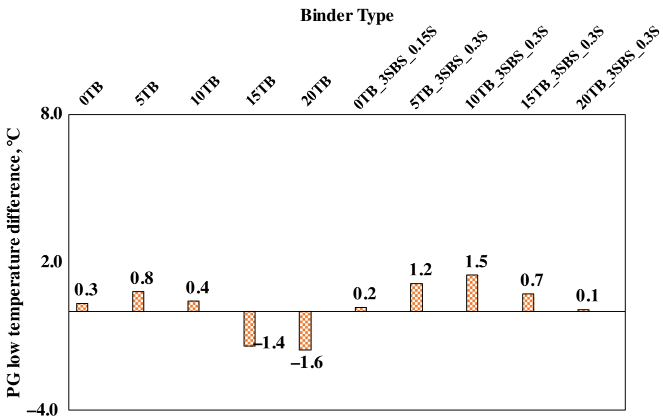

Fig. 8. PG low-temperature difference between all binders.

To further investigate DCRMB damage at low temperatures, PG low-temperature differences were calculated for Tsp and Tmp. A difference value greater than 0 indicated that the low-temperature cracking resistance of the bitumen was controlled by S; a difference value less than 0 indicated that this resistance was controlled by m-value (Lin et al. 2017). From Fig. 8, the PG low-temperature difference in DCRMB in the PAV aging state was greater than zero except for 15TB and 20TB, indicating that S controlled the low-temperature cracking resistance of these asphalts. Meanwhile, with the increase in CR, control of the low-temperature performance of TBRA gradually transferred from S to m-value, which showed that the CR increase led to the increase in m-value and the decrease in S, but the improvement in S was more obvious because the increase in CR allowed more of the lighter components in TBRA to be

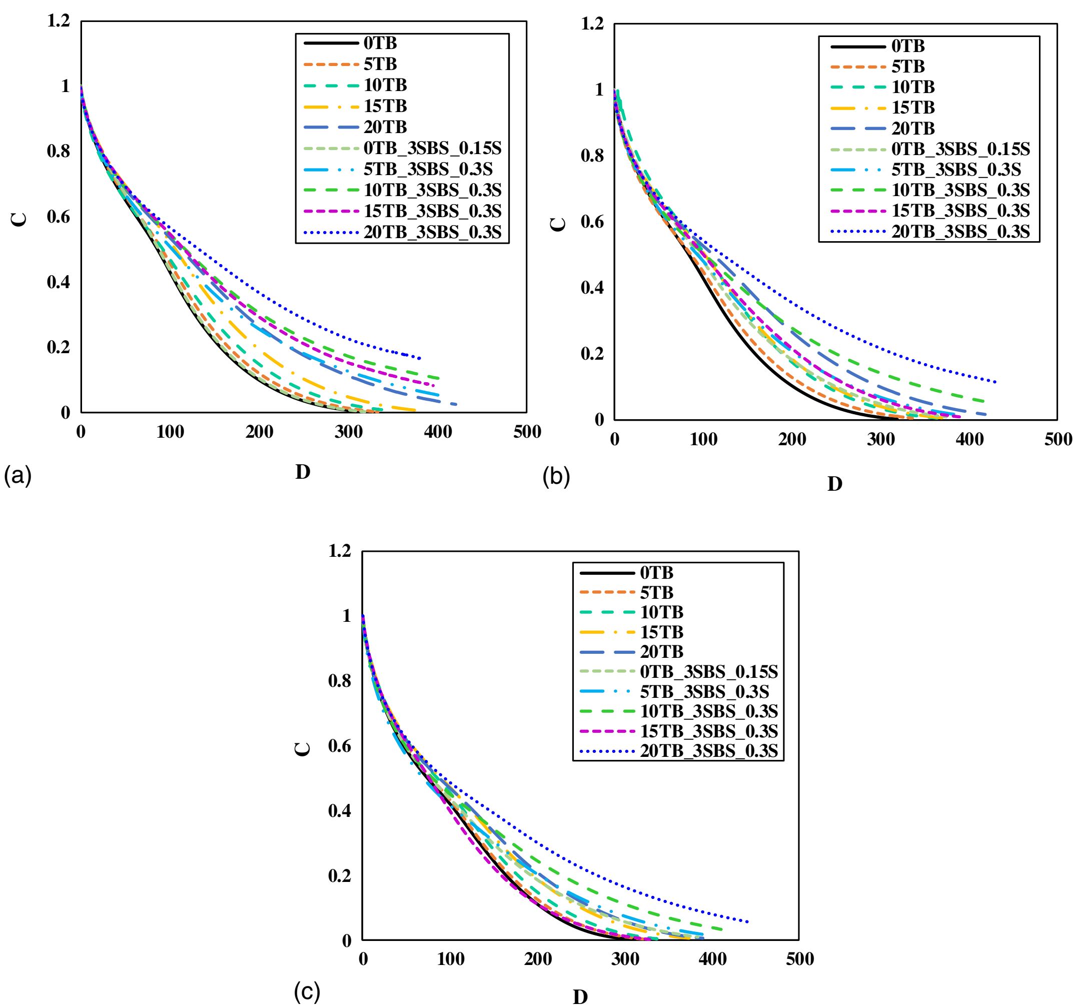

Fig. 9. Damage characteristic curves under different aging conditions (a) virgin; (b) RTFOT; and (c) PAV.

absorbed by the CR, which had a negative effect on the relaxation properties of the asphalt, reducing the m-value and producing low-temperature cracking due to insufficient creep rate.

Fatigue Performance

LAS Test Results

Based on the LAS test, the damage characteristic curves of DCRMB before and after aging are shown in Fig. 9, where the vertical coordinate C represents integrity of the asphalt sample and the horizontal coordinate D represents damage intensity. When C = 1, the sample was in an undamaged state of integrity; when C = 0, the sample was completely damaged. For a given D, as C increased, resistance to damage increased (Li et al. 2021). As described in Fig. 9, the TBRA and TBHA C values before and after aging were higher than the 0TB C value; the largest value was for 20TB_3SBS_0.3S. This meant that, after the LAS test, DCRMB binder integrity before and after aging was better than that of the neat asphalt, with the best integrity shown by 20TB_3SBS_0.3S.

DCRMB fatigue life curves under different aging conditions, predicted using VECD, are shown in Fig. 10. For the convenience of comparison, fatigue life at 2.5% low strain and 5% high strain is shown in Fig. 11, which indicates that the order of fatigue life under different aging conditions under 2.5% strain was the same as that under 5% strain. The N_f of TBRA and TBHA decreased with increasing aging. Moreover, the N_f of TBRA was higher than that of 0TB at 2.5% strain, ranking 20TB > 15 TB > 10 TB > 5 TB > 0 TB before and after RTFOT. This indicated that TBRA's fatigue resistance improved before and after aging compared with neat asphalt's fatigue resistance. The higher the of CR content, the greater the fatigue resistance improvement. Moreover, TBHA's N_f was higher than TBRA's N_f before and after aging, indicating the former's better fatigue resistance. The reason was that CR entered the asphalt after degradation and acted as a skeleton in the asphalt phase, which prevented further fatigue cracking and so avoided its further extension into the asphalt interior of and improved TBRA's overall fatigue deformation ability. After SBS was added to TBRA, a three-dimensional network structure was formed by cross-linking, thus adding to the improvement of fatigue resistance. In addition, the carbon black in the CR and asphalt phases represented incompatible two-phase systems, which were uniformly dispersed to improve asphalt aging resistance. Thus, TBRA and TBHA fatigue resistance after aging was still better than neat asphalt fatigue resistance.

Fatigue Factor

The fatigue factor represents the energy loss of asphalt in the process of deformation. The smaller the fatigue factor, the better the fatigue resistance (Yu et al. 2013). DCRMB fatigue factor values

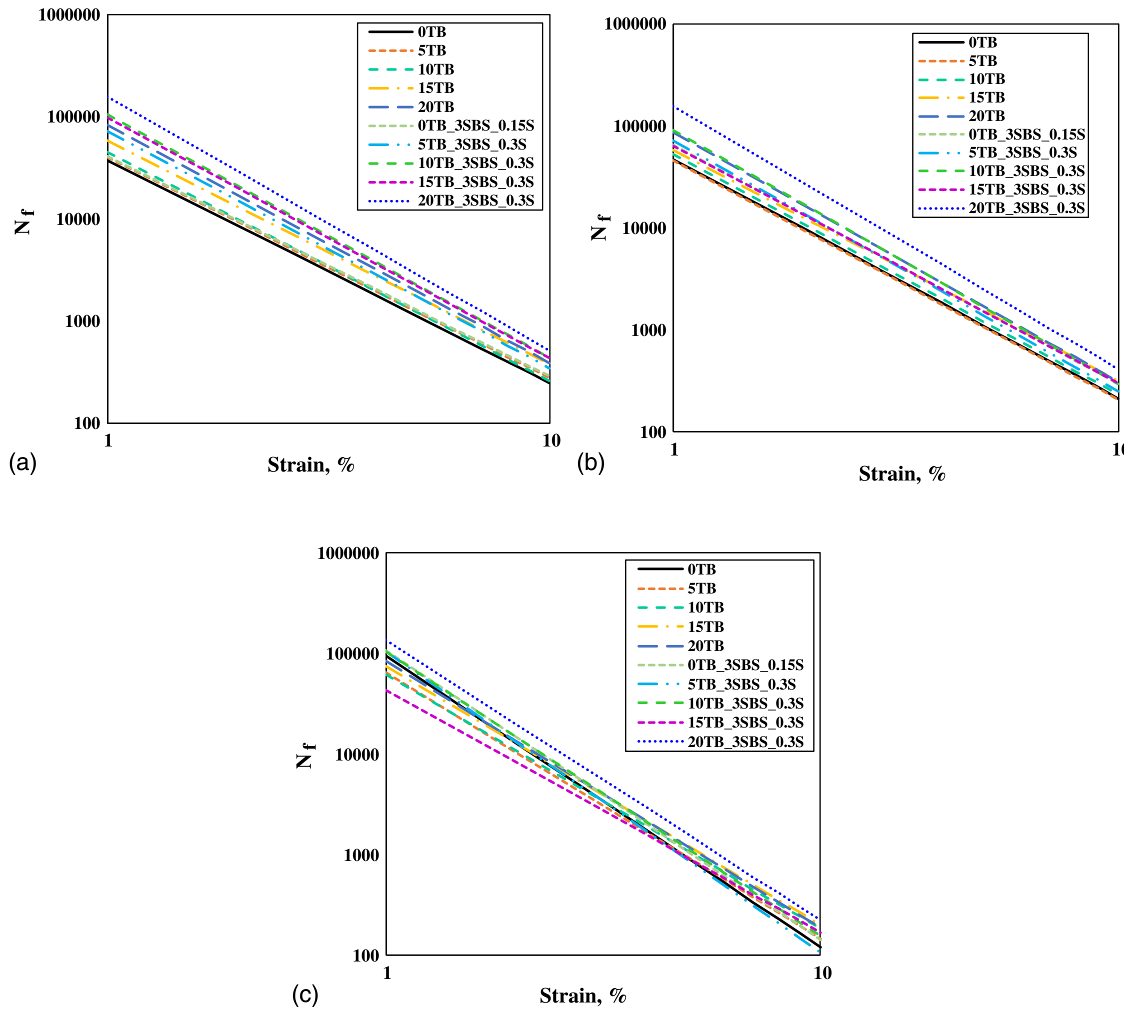

Fig. 10. Fatigue curves under different aging conditions (a) virgin; (b) RTFOT; and (c) PAV.

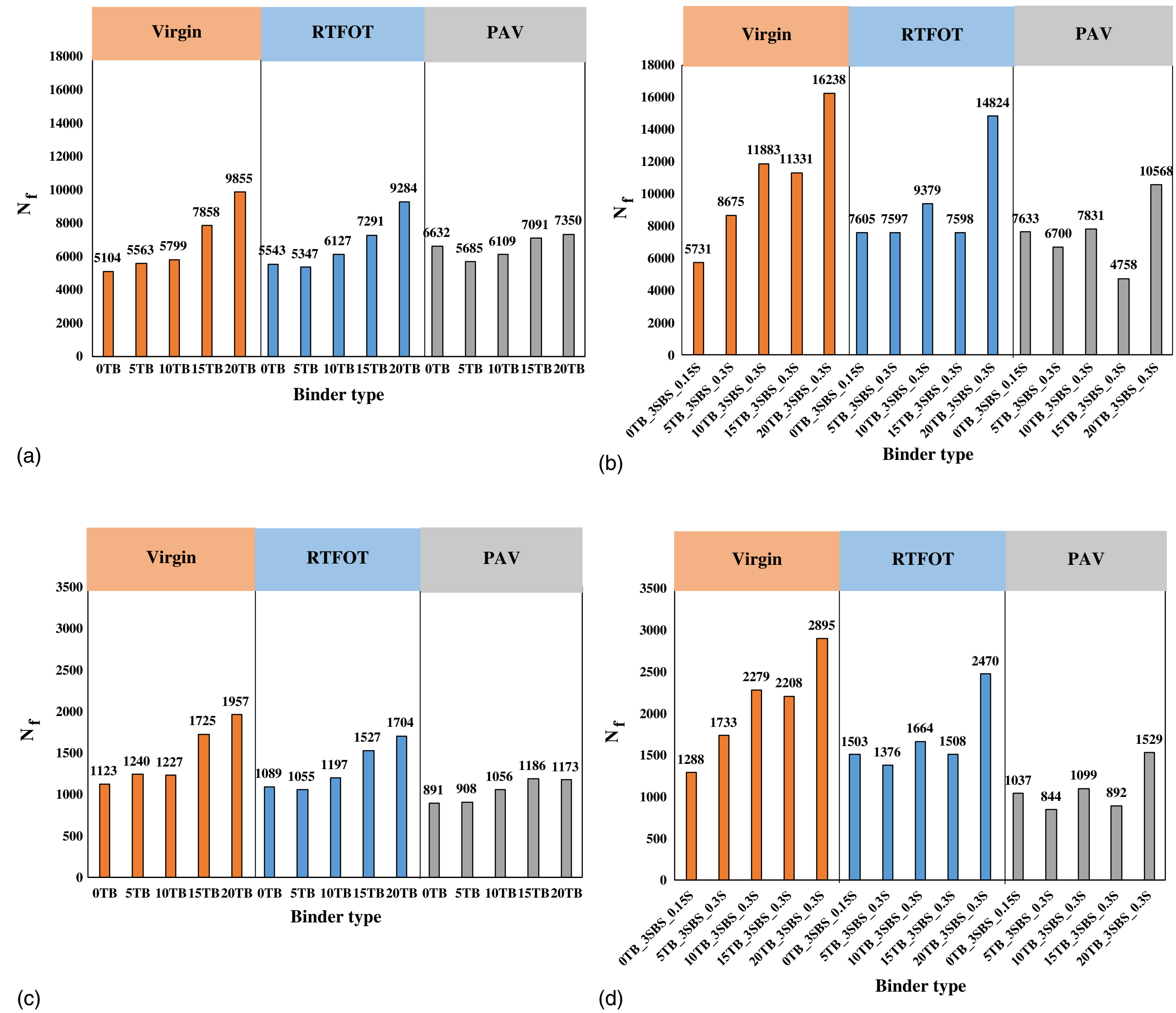

Fig. 11. Fatigue life before and after aging at different strain levels: (a) TBRA at 2.5% strain; (b) TBHA at 2.5% strain; (c) TBRA at 5% strain; and (d) TBHA at 5% strain.

before and after aging are presented in Fig. 12 and Table 3, which show that the fatigue factor of the same binder increased from RTFOT to PAV. The fatigue factor of both TBRA and TBHA before and after aging was lower than that of 0TB, indicating that the degraded CR and SBS improved the fatigue resistance of neat asphalt.

Correlation Analysis

To further investigate the relationship between DCRMB low-temperature cracking resistance indicators and fatigue resistance indicators, SPSS software was used to perform Pearson correlation analysis on the data. The correlation result is presented in Table 4. Here, $N_{f2.5\%}$ and $N_{f5\%}$ indicate asphalt N_f at 2.5% and 5% strain; $m_{-12°C}$, $m_{-18°C}$, and $m_{-24°C}$ indicate m-value at −12°C, − 18°C, and −24°C. The definitions of $S_{-12°C}$, $S_{-18°C}$, and $S_{-24°C}$ are the same as those of $m_{-12°C}$, $m_{-18°C}$, and $m_{-24°C}$. Table 4 shows that there was a good correlation between $S_{-12°C}$, $S_{-18°C}$, $S_{-24°C}$, $m_{-12°C}$, $m_{-18°C}$, and $m_{-24°C}$. However, the correlation between $G^*/\sin\delta$ and $N_{f2.5\%}$ and $N_{f5\%}$ was not high, perhaps because $G^*/\sin\delta$ is based on stiffness, which was only a characteristic value of the initial state of the fatigue test. The fatigue factor was measured using a dynamic shear rheometer at a smaller strain and a fixed number of frequency actions. This evaluation index distinguished varying bitumen resistance to fatigue damage in the online viscoelastic range, but for modified bitumen the fatigue factor was poorly correlated with the fatigue test results of its corresponding asphalt mixture (Ameri et al. 2020; Nuñez et al. 2014; Singh et al. 2017). Moreover, the fatigue factor, unlike complex fatigue phenomena with more loading cycles and damage characteristics, did not undergo cumulative damage development under repeated loading and could not indicate the degree of fatigue damage of asphalt (Norouzi et al. 2021). The LAS test is recommended for DCRMB fatigue resistance before and after aging.

Conclusion

In this research, the low-temperature and fatigue characteristics of degraded crumb rubber–modified bitumen (DCRMB) at different aging degrees were investigated with BBR and LAS tests.

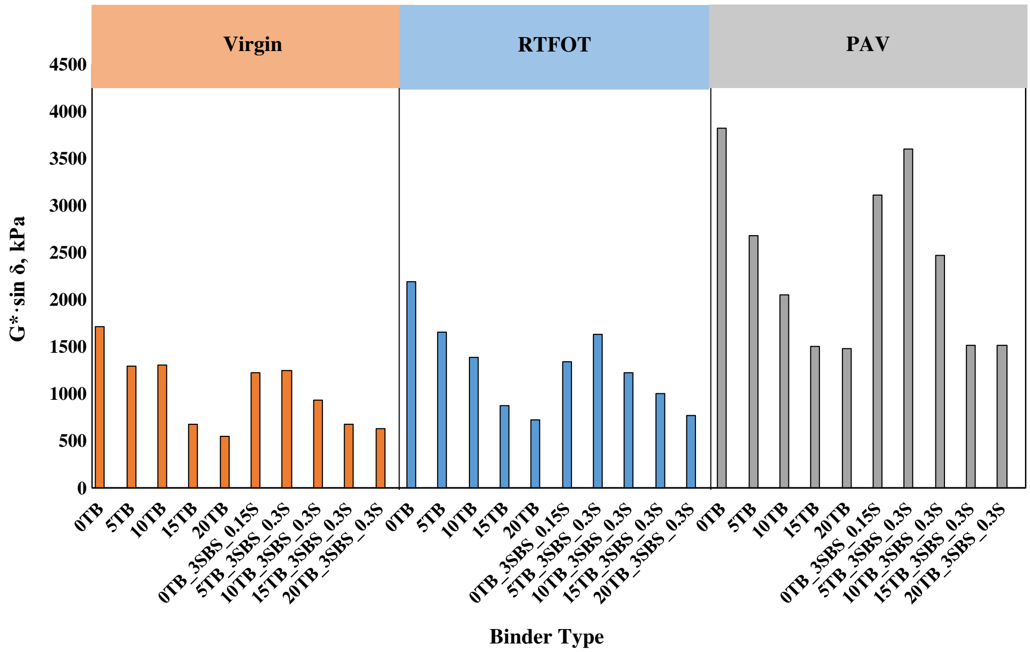

Fig. 12. Fatigue factor results before and after aging.

Table 3. Fatigue factor results

Binder type	Virgin Fatigue factor (kPa)	Virgin Rank	RTFOT Fatigue factor (kPa)	RTFOT Rank	PAV Fatigue factor (kPa)	PAV Rank
0TB	1,704	1	2,189	1	3,822	1
5TB	1,289	3	1,649	2	2,681	4
10TB	1,306	2	1,378	4	2,042	6
15TB	670	8	870	8	1,501	9
20TB	540	10	718	10	1,473	10
0TB_3SBS_0.15S	1,218	5	1,334	5	3,114	3
5TB_3SBS_0.3S	1,239	4	1,628	3	3,598	2
10TB_3SBS_0.3S	922	6	1,219	6	2,466	5
15TB_3SBS_0.3S	673	7	998	7	1,515	7
20TB_3SBS_0.3S	623	9	767	9	1,507	8

Table 4. Pearson correlation analysis results

Index type	Correlation index	$S_{-12°C}$	$m_{-12°C}$	$S_{-18°C}$	$m_{-18°C}$	$S_{-24°C}$	$m_{-24°C}$	Fatigue factor	$N_{f2.5\%}$	$N_{f5\%}$
$S_{-12°C}$	P	1	−0.896	0.970	−0.932	0.929	−0.930	0.845	−0.541	−0.691
	N	30	30	30	30	30	30	30	30	30
$m_{-12°C}$	P	−0.896	1	−0.851	0.936	−0.803	0.827	−0.842	0.546	0.752
	N	30	30	30	30	30	30	30	30	30
$S_{-18°C}$	P	0.970	−0.851	1	−0.936	0.963	−0.945	0.804	−0.615	−0.719
	N	30	30	30	30	30	30	30	30	30
$m_{-18°C}$	P	−0.932	0.936	−0.936	1	−0.865	0.924	−0.861	0.645	0.807
	N	30	30	30	30	30	30	30	30	30
$S_{-24°C}$	P	0.929	−0.803	0.963	−0.865	1	−0.884	0.752	−0.570	−0.661
	N	30	30	30	30	30	30	30	30	30
$m_{-24°C}$	P	−0.930	0.827	−0.945	0.924	−0.884	1	−0.755	0.719	0.790
	N	30	30	30	30	30	30	30	30	30
Fatigue factor	P	0.845	−0.842	0.804	−0.861	0.752	−0.755	1	−0.455	−0.713
	N	30	30	30	30	30	30	30	30	30
$N_{f2.5\%}$	P	−0.541	0.546	−0.615	0.645	−0.570	0.719	−0.455	1	0.920
	N	30	30	30	30	30	30	30	30	30
$N_{f5\%}$	P	−0.691	0.752	−0.719	0.807	−0.661	0.790	−0.713	0.920	1
	N	30	30	30	30	30	30	30	30	30

Given the results presented, the following summary and conclusions are provided:

- BBR test analysis indicated that aging caused a deterioration of the low-temperature properties of TBRA and TBHA. The increase in CR content led to an increase in m-value and a decrease in S value TBRA, but the improvement in S was more obvious. Moreover, DCRMB's low-temperature performance in PAV aging was superior to that of neat asphalt.
- After the LAS test, DCRMB binder integrity before and after aging was superior neat asphalt binder integrity, with 20TB_3SBS_0.3S having the best integrity. Aging made the fatigue resistance of DCRMB worse. Moreover, the test showed that TBHA had better low-temperature and fatigue properties than TBRA and neat asphalt, with 20TB_3SBS_0.3S showing the best properties.
- The correlation between $G^*/\sin\delta$ and N_f was low, meaning that the LAS test is recommended for evaluating DCRMB fatigue resistance before and after aging.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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