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Laboratory Evaluation on Performance of Recycled Asphalt Binder and Mixtures under Short-Term Aging Conditions

Yuefeng Zhu [1,2,3], Jiawei Zhang [1,2,3], Chundi Si [1,2,3,*], Tao Yan [4,5] and Yanwei Li [4,5]

1 State Key Laboratory of Mechanical Behavior and System Safety of Traffic Engineering Structures, Shijiazhuang Tiedao University, Shijiazhuang 050043, China; yuefengzhu@stdu.edu.cn (Y.Z.); valentinajwzhang@gmail.com (J.Z.)
2 Key Laboratory of Traffic Safety and Control of Hebei Province, Shijiazhuang 050043, China
3 School of Traffic and Transportation, Shijiazhuang Tiedao University, Shijiazhuang 050043, China
4 Hebei Provincial Communications Planning and Design Institute, Shijiazhuang 050043, China; yichuyan@126.com (T.Y.); liyanwei69@vip.sina.com (Y.L.)
5 Research and Development Center of Transport Industry of Technologies, Materials and Equipments of Highway Construction and Maintenance, Shijiazhuang 050043, China
* Correspondence: sichundi@stdu.edu.cn; Tel.: +86-159-3266-1937

Abstract: As asphalt materials are exposed to very high temperatures before construction, such as in the transportation stage or the storage stage, short-term aging of asphalt material occurs. At these stages, diffusion or blending between RAP (reclaimed asphalt pavement) binder and virgin binder may occur. In this study, recycled blends, incorporating SBS modified binder, RAP binder and recycling agents, were prepared with incremental RAP binders of up to 40%, and RTFO (Rolling Thin-Film Oven) tests in condition times of 300 and 600 min were conducted on the recycled blends. Characterization tests included ΔT_{cr}, complex modulus master curve, a G-R (Glover-Rowe) parameter on recycled blends, and dynamic modulus, fracture test, and midpoint bending fatigue tests on mixtures. The ΔT_{cr} and the G-R parameter results showed that aging time significantly affected the cracking resistance of the recycled blends. Compared to the virgin SBS modified asphalt binder, the recycled blends tended to be more sensitive to the aging process. The complex modulus master curve of binders and the dynamic modulus and phase angle results of mixtures show that the binder/mixtures appear to be stiffer with an increase in the RAP binder dosage. Generally, the low temperature cracking and fatigue cracking resistance of virgin mixtures is better than that of RAP mixtures, especially for high RAP binder dosage mixtures, and longer aging times have a negative impact on the cracking resistance of mixture. However, when we extend RTFO aging time, the higher dosage of RAP mixtures show better cracking resistance than the lower dosage of RAP mixtures. The reason for this could be that the chemical process may occur between the virgin SBS modified asphalt binder and the RAP binder at high temperatures.

Keywords: reclaimed asphalt pavement; RTFO aging; cracking; stiffness; Glover-Rowe parameter; master curve

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1. Introduction

With the increasing price of asphalt and pressing social attention on environmental protection, the application of reclaimed asphalt pavement (RAP) in new asphalt pavement is becoming more and more common [1]. However, the asphalt binder in RAP has undergone an oxidative aging process, where the mechanical behavior of RAP binder changes [2,3]. At present, the RAP content in new asphalt pavement construction is controlled to 15~30% by total mass, but the actual content is only 20% or less. Studies have shown that the impact of RAP on the performance of pavement mainly focuses on the cracking and durability of pavement, including low-temperature cracking, fatigue cracking and water stability, etc. The lack of crack resistance of recycled asphalt mixture restricts the possibility of increasing RAP content [4].

In recent years, various types of rejuvenators have been used to improve the performance of high RAP content mixtures. Daryaee et al. [5] found that compared with the traditional HMA mixture, the combination of rejuvenator and waste polymer can improve the fatigue resistance and moisture sensitivity of high RAP content asphalt mixtures. High percentages of RAP can worsen pavement properties due to low asphalt content, low asphalt quality, and degradation of the mixture. Some transportation agencies are reluctant to use RAP in large-scale pavement constructions. To address this problem, waste engine oil (WEO) was used as a rejuvenating agent to reduce the viscosity and soften the RAP binder. It was found that the addition of WEO makes up for the loss of aromatic and resin content during the service life, and makes the RAP binder regenerated [6]. Woszuk et al. [7] explored the possibility of using WEO in asphalts foamed with water-soaked zeolites. The results showed that the addition of WEO reduced the viscosity and softening point of asphalt, but increased the penetration. The addition of zeolite had little effect on these parameters. The chemical analysis of the asphalt with WEO was carried out by an X-ray fluorescence method. The results showed that no obvious heavy metal content was found, which would increase the possibility of cracking at lower temperatures.

What is more, because of the environmental and economic benefits, the use of RAP materials has been widely discussed by researchers and asphalt manufacturers. At present, the focus is to increase the percentage of RAP in asphalt mixtures to maximize the benefits of RAP. There have been several attempts to demonstrate that even mixtures containing 100% RAP material can achieve or outperform the traditional HAM mixtures [8,9]. But as Hoon Moon et al. [10] mentioned, RAP binder is susceptible to cracking at low temperatures because when it is aged. Therefore, low temperature performance is an important characteristic of RAP mixtures, especially in low temperature countries. Nevertheless, Daniel et al. [11] and Tarbox et al. [12] found that the stiffening effect of RAP mixtures after long-term oven aging was less than that of the original mixture, which was probably due to the slow hardening speed of the aged binder. Previous research has been focused on the low temperature properties and fatigue properties of RAP mixtures, because of the stiffened properties of RAP. What is more, during the mixing and the construction stage, the asphalt materials need to be heated to very high temperatures, and additional aging of the binder is likely to happen. Aging makes the asphalt binder more brittle and stiffer, which affects its performance. It is very important to better understand the influence of aging on the field performance of the RAP mixture [13].

At high temperatures, the chemical process may occur between the virgin binder and the RAP binder and several studies have tried to describe this interaction. Kriz et al. [14] carried out DSR testing simulations to investigate the diffusion process and the blending degree in thin and thick binder layers. It was found that for the thinner binder layer, the diffusion process was finished just a few minutes after mixing. But for the thicker binder layer, after the typical production stage, only 90% of the mixing process was finished. Therefore, the high temperature may affect the mixing of virgin binder and RAP binder or/and the short-term aging of the RAP mixture. Zhao et al. [15] studied the interaction of the virgin and RAP binder, and questioned the hypothesis of full mobilization. It was found that the binder mobilization rate of 10% to 20% RAP mixtures was close to 100%, and that of 25%, the RAP mixture was about 75% mobilization, which indicated that 25% RAP binder may be further mobilized in high temperature aging conditions. In this study, it was also found that the mixtures containing higher RAPs may affect the crack resistance, not only because of the increased stiffness due to the RAP, but also due to the lower mobilization rate. Some production parameters, like the transportation stage or the silo storage stage, may cause short-term aging. Howard et al. [16] conducted research into the transportation time on the properties of HMA, and explored the method of using warm mixing technology to promote long-distance transportation.

The current literature shows that various types of rejuvenators have been used for increasing the mechanical properties of the high RAP content of mixtures and the effects of aging are also considered. However, at different aging times, the interactions, such as the blending or diffusion processes, may happen between the aged binder and the virgin binder. The purpose of this paper is to better understand the influence of different short-term aging times on the performance of RAP binder and RAP mixtures.

2. Materials and Methods

2.1. Materials

2.1.1. Recycled Blends

The RAP was milled from the surface layer of the expressway in Shaanxi Province. The rotary evaporator method was used to collect the aged binder in RAP. The recycling agent (RA), Evoflex 3G, light yellow low viscosity liquid at room temperature, was used to soften the RAP binder. The physical properties of Evoflex 3G are shown in Table 1. The virgin binder was SBS-modified asphalt, in which the SBS modifier was a commercial grade linear SBS block co-polymer (D1101). The performance grading (PG) results of the virgin binder and the RAP binder are shown in Table 2.

Table 1. Physical properties of Evoflex 3G.

Test Properties	Results
Viscosity (60 °C)/cSt	320
Flash point/°C	>220
Saturation content/%	14.7
Aromatic content/%	56.4
Surface tension (25 °C)/10 cm^{-3} Nm^{-1}	52.2
Viscosity ratio before and after RTFO	1.8
Mass change before and after RTFO/%	2.1
Density (15 °C)/(g·cm^{-3})	0.935

Table 2. Performance grading results for virgin binder and RAP binder.

Binder Type	High Temp.		Inter. Temp.	Low Temp. PAV (20 h)		PG Grade
	Origin	RTFO		S/MPa	m-Slope	
SBS modified asphalt	78.5	72.6	20.6	−26.9	−28.6	70–22
RAP	85.2	–	22.8	−21.2	−15.8	82–16

The optimal dosage of RA in the RAP binder was determined by meeting the PG grading of virgin binder. The results showed that when the dosage (mass fraction) of RA was 3.91%~5.59%, the RAP binder could meet the PG grading of the virgin binder. Considering application economy, the dosage of RA was selected at 4%. It should be noted that all the dosage in this paper refer to mass fraction. The recycled blends with different dosage of RAP binder were prepared as follows. Firstly, the RAP binder was heated to flow at 130 °C, 4% of RA was added to the RAP binder and stirred until well combined. Next, different contents (80%, 70% and 60%) of the virgin binder were added to the smooth mixture, and after 20 min of high speed shearing, the recycled blends were obtained. The PG grading results of different recycled blends are shown in Table 3. It can be seen that all the recycled blends reached the PG grading of the virgin binder. For simplicity, SBS-modified asphalt is denoted as the virgin binder, 20% RAP binder + 4% recycling agent + SBS modified asphalt is denoted as 20% RAP binder, and the other recycle blends use the same naming method.

Table 3. PG grading results for recycled asphalt binder.

Binder Type	High Temp.		Inter. Temp.	Low Temp.		PG Grade
				PAV (20 h)		
	Origin	RTFO		S/MPa	m-Slope	
SBS modified asphalt	78.5	72.6	20.6	−26.9	−28.6	70–22
20% RAP binder + 4% recycling agent + SBS modified asphalt	77.6	74	20.7	−27.9	−26.2	70–22
30% RAP binder + 4% recycling agent + SBS modified asphalt	77.8	74.5	21.3	−26.9	−24.6	70–22
40% RAP binder + 4% recycling agent + SBS modified asphalt	76.6	74.3	24.3	−25.3	−22.0	70–22

2.1.2. Mixture Gradation and Optimal Asphalt Content

The coarse and fine aggregates were basalts, and lime stone, respectively, and the limestone powder was used as the mineral filler. The physical properties of coarse and fine aggregates and mineral filler are presented in Table 4.

Table 4. Physical properties of aggregate and filler.

Test Properties		Results	Requirement
Coarse aggregate	Crushed value/%	11.8	≤26
	Los Angeles wear value/%	10.6	≤28
	Polished stone value/PSV	43	≥42
Fine aggregate	Apparent relative density	2.679	≥2.50
	Angularity/s	42.7	≥30
Filler	Apparent density/(g·cm^{-3})	2.761	≥2.50
	Water content/%	0.4	≤1

The mixture design follows the Technical Specification for Construction of Highway Asphalt Pavement (JTGF40-2004) [17]. The mixture gradation was determined according to the dense gradation, as shown in Figure 1. All mixture samples were compacted with 4% air void.

The optimal asphalt content was determined by the Marshall method. According to the change law of volume parameters of the Marshall specimen, the optimum asphalt content was determined. The Marshall test results of different kinds of mixtures are shown in Table 5. The mixture preparation was also based on the JTG F40-2004 specification [17]. It should be noted that during the mixing and the compaction procedure, the aging of asphalt materials may happen again, the temperature should be strictly controlled.

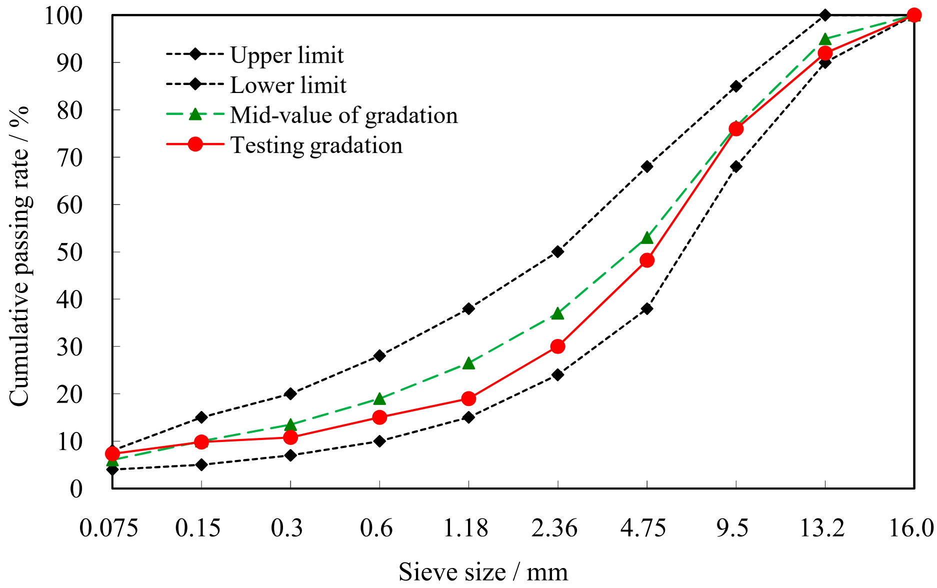

Figure 1. Gradation curve of AC-13 mixture.

Table 5. Volume parameters of different mixtures.

Binder Type	Asphalt-Aggregate Ratio/%	Air Void/%	VFA/%	VMA/%	Stability/kN	Flow/0.1 mm
Virgin binder	4.46	4.0	70.3	13.70	11.75	34.5
20% RAP binder	4.68	4.0	71.3	13.45	12.11	32.6
30% RAP binder	4.63	4.0	70.4	13.68	12.03	31.2
40% RAP binder	4.60	4.0	71.5	13.53	12.25	33.7

2.2. Testing method

2.2.1. Binder Testing and Analysis

The virgin binder and three kinds of recycled blends were all treated with an RTFO (Rolling Thin Film Oven) test for 300 min and 600 min at 163 °C to evaluate the short-term aging conditions of asphalt. DSR testing and BBR testing were conducted to evaluate the high temperature, low temperature and anti-cracking properties of different asphalt.

1. ΔT_{cr}

Anderson et al. [18] proposed a parameter, defined as ΔT_{cr}, to assess non-load-related cracking property of the asphalt binder, which was shown in Equation (1). In this equation, with ΔT_{cr} increases, the asphalt is considered to have a better anti-cracking property. Anderson et al. [18] considered that when $\Delta T_{cr} \leq -2.5$ °C, the cracking risk should be considered, and Rowe [19] set a limit of $\Delta T_{cr} \leq -5$ °C for immediate repair action should be applied.

$$\Delta T_{cr} = T_{cr(stiffness)} - T_{cr(m-slope)} \tag{1}$$

where $T_{cr(stiffness)}$ is critical low temperature grade predicted using the BBR Stiffness (S), $T_{cr(m\text{-}slope)}$ is critical low temperature grade predicted using the BBR m-slope.

2. Complex modulus master curve

DSR test was conducted at different temperatures (5, 15, 25, 35, 45 °C) and different loading frequencies (0.005 to 0.02 strain range), and the test specimen was 25 mm diameter and 1.5 mm thick. By using the Christensen–Anderson–Marasteanu Model (CAM), the complex modulus (G*) master curves of different asphalt were generated at 25 °C reference temperature.

3. G-R parameter

Glover et al. [20] and Rowe [19] proposed the Glover-Rowe (G-R) parameter to evaluate the field anti-cracking ability of asphalt pavement. The calculation of the G-R parameter, shown in Equation (2), was based on the construction of master curve at 15 °C and 0.005 rad/s. Higher G-R parameter values indicate an increase in the brittleness of asphalt binder. According to Anderson et al. [18], who studied the relationship between binder ductility and in-situ block cracking and surface spalling, it is proposed that a G-R value of 180 kPa corresponds to the onset of damage, while a G-R value of more than 600 kPa corresponds to significant cracking. The G-R parameters were determined by using the test results produced during the analysis of master curve analysis.

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

where, G* is the shear modulus, δ is the phase angle, the value of G* and δ are tested at 15 °C, 0.005 rad/s.

2.2.2. Mixture Testing and Analysis

Binder characterization was not adequate to fully represent the properties of mixture and this section discusses the method of mixture evaluation as a supplement to the test of binder properties. In order to investigate the performance of different asphalt mixtures, three test methods were adopted, including a complex modulus test, a disc-shaped compact tension (DCT) test and a fatigue test. The details of each test are as follows.

1. Complex modulus

Complex modulus test is used to evaluate viscoelasticity of asphalt mixture according to AASHTO TP-79 [21]. Two important viscoelastic properties of asphalt mixture, dynamic modulus (E*) and phase angle (δ), were measured by using Asphalt Mixture Performance Tester (AMPT). Each mixture had three replicates. Standard specimens with 150 mm in height and 100 mm in diameter were tested at 4.4 °C, 21.1 °C, 37.8 °C and 0.1, 0.5, 1, 5, 10 and 25 Hz. According to the principle of time temperature superposition, the master curve of the average dynamic modulus isotherm at reference temperature of 21.1 °C is established by using a generalized logistic function (Equation (3)).

$$\log|E^*| = \delta + \frac{\alpha}{\left[1+\lambda(\exp^{\beta+r(\log\omega_r)})\right]^{1/\lambda}} \tag{3}$$

where $|E^*|$ is dynamic modulus (MPa); α, β, γ, δ, and λ are the fitting parameters; and ω_r is reduced frequency (Hz), which can be calculated by multiplying the frequency by the shift factor, a_T, as shown in Equation (4).

$$\log a_T = a_1T^2 + a_2T + a_3 \tag{4}$$

where a_1, a_2, and a_3 are shift factors, and T is temperature.

2. DCT test

DCT test, a new fracture test method that can consider the influence of traffic loads and the crack growth over time, was conducted to evaluate the low temperature property of asphalt mixture [22]. The DCT test was performed following the ASTM D7313-07 [23] test procedure. During the test, the constant crack opening displacement (CMOD) was controlled as 1 mm/min and the test temperature as −12 °C. The load-displacement curve was obtained during the test. The fracture energy (G_F) can be calculated from the area under the load-displacement curve, as shown in Equation (5).

$$G_f = \frac{\int_0^{\Delta \text{Final}} F \cdot du}{t \times a} \quad (5)$$

where, G_f is the fracture energy, F is the test load during the test, u is the displacement during the test, ΔFinal is the displacement at the end of the test, t is the thickness of test specimen, a is the crack ligament length.

3. Fatigue test

The midpoint bending test was applied to study the fatigue property of different mixtures. Based on the method T0739-2011 in JTG E20-2011 [24], the sinusoidal load was applied at a frequency of 10 Hz and the stress ratio was determined as 0.2, 0.3 and 0.4. The testing temperature was 15 °C. Before starting the fatigue test, the initial stiffness modulus of each specimen was obtained at the 50th cycle of loading. Next, the number of cycles or the fatigue life was defined as the number of cycles when the stiffness modulus drops to 50% of the initial stiffness modulus [25].

3. Results and Discussion

3.1. Binder Testing

3.1.1. Performance Grading and ΔT_{cr}

The high temperature and low temperature PG grading results of different binders are shown in Figures 2 and 3. The overall trend of the PG grade results showed that the high temperature PG grade and the low temperature PG grade both increased as extending RTFO times and increasing RAP binder contents. The warmer temperatures of high, medium and low PG grades indicate the stiffening of binders. When the binder becomes stiffer, it can resist a higher shear stress and meet warmer PG grades. It can be concluded that the longer RTFO times cause age-hardening of binders (e.g., oxidation, volatilization).

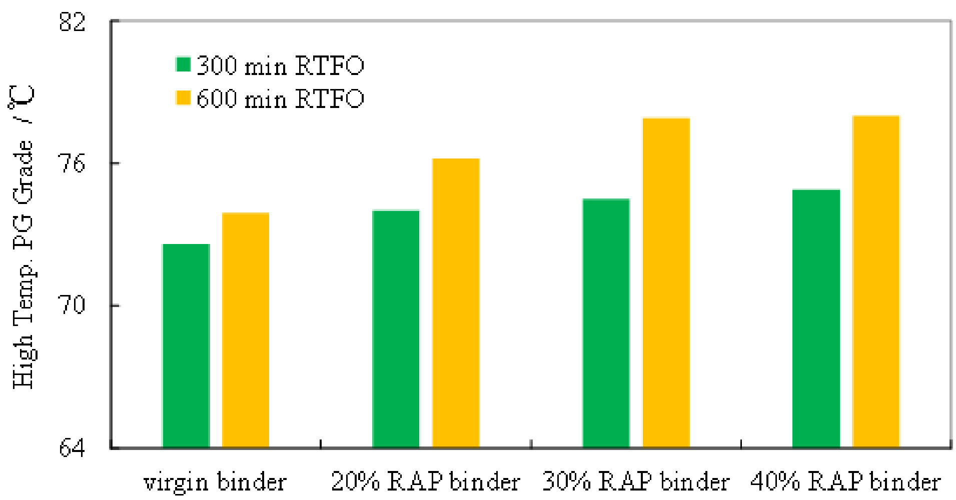

Figure 2. Binder high temperature PG grades of different RTFO times.

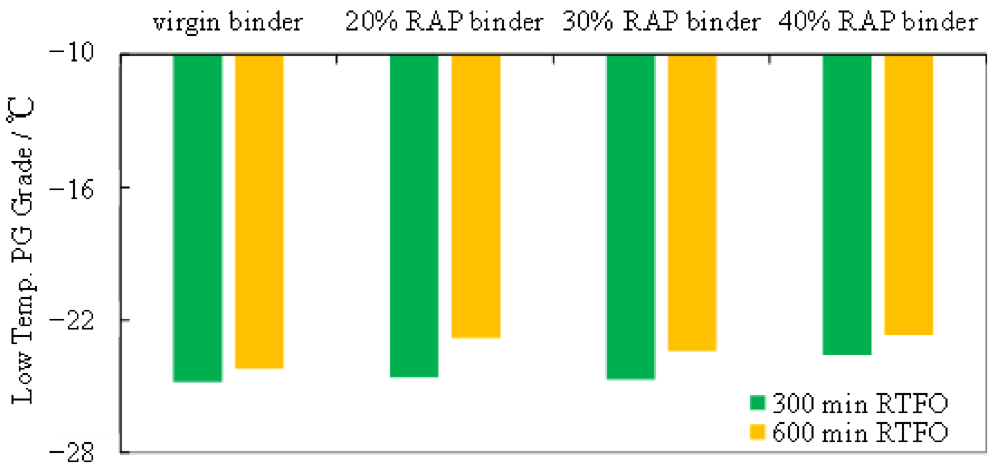

Figure 3. Binder low temperature PG grades of different RTFO times.

As previously explained, ΔT_{cr} has been used to determine the cracking susceptibility of different asphalt binders. The ΔT_{cr} results of different binders are shown in Figure 4. For each binder, there is one replicate sample. As can be seen in Figure 4, all the binders are m-slope controlled under RTFO short-term aging. And as previously described, all the recycled blends have reached the PG grading of virgin binder after softening by using a recycling agent. However, as can be seen in Figure 4, the ΔT_{cr} values have significantly decreased after RFTO short-term aging for recycled blends. Basically, when the dosage of RAP binder is less than 30%, the crack risk of asphalt binders are still under control. What is more, it can be seen in Figure 4 that the ΔT_{cr} values are gradually towards to the cracking warning with the increasing of RAP binder dosage. The virgin binder shows the pretty good low temperature cracking resistance compared with recycled blends. Generally, with the extension of aging time, the ΔT_{cr} values show negative increasing. It is very interesting that the ΔT_{cr} results of 600 min RTFO aging has a greater value than 300 min RTFO aging for 40% RAP recycled blends. This might be the reason that the interaction between binder and virgin binder occurred with longer aging times. However, it should be noted that 40% RAP recycled blends have crossed the crack warning risk line.

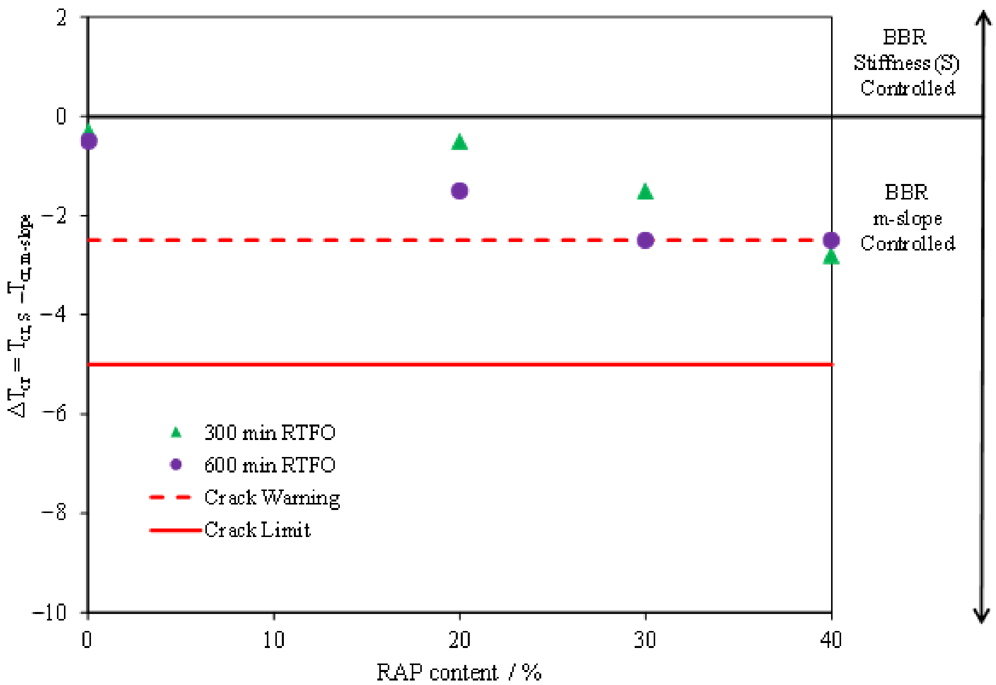

Figure 4. Binder ΔTcr results of different RTFO times.

Overall, the above results can be explained, as the aging process of SBS-modified asphalt includes a matrix asphalt component that removes, and a modifier that decomposes, to failure. Recycling agents have high aromatics and low saturated phenols, which could dissolve and disperse asphaltene, but cannot restore the SBS network structure. The addition of new asphalt helps to form the cross-linking network structure, which trends to a continuous phase. Various studies have shown that the SBS co-polymer swells in the maltene phase of the binder and creates an elastic network that enhances the viscoelastic properties of the binders [26,27]. At the appropriate polymer content, the polymer gets well dispersed in the binder and creates a three-dimensional polymer-rich phase. The formation of the interconnected polymer-rich phases significantly improves the properties of the base binder and provides strength and elasticity for the binder at higher and lower temperatures [28]. Although the PG grade of three recycled blends are the same, the interior asphalt aging state and the cross-linking state of the SBS modifier are different. The cracking resistance and aging resistance of recycled blends could be guaranteed only if the two states achieve balance.

3.1.2. Complex Modulus

The impact of the RTFO aging time and the RAP binder dosage on the complex shear modulus master curves are shown in Figures 5 and 6. The stiffness of all the binders show an increase with the higher RAP binder dosage, and the increases are more clear at intermediate frequencies. This indicates that the RAP binder dosage has a great influence on the intermediate stiffness of recycled blends. The intermediate stiffness is also related to the G-R parameters of binders. Therefore, the RAP binder dosage will affect the cracking resistance of binders. For both 300 min and 600 min RTFO aging mixtures, the 40% RAP binder mixtures are stiffest and the virgin binder mixtures are softest. However, it should be noted that the consecutive mixtures are not much stiffer than each other.

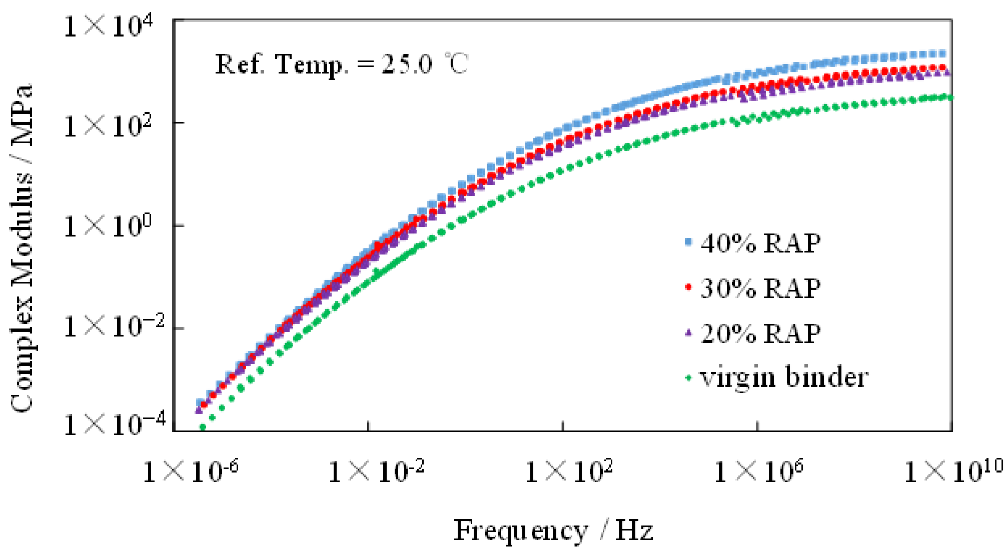

Figure 5. Complex modulus master curves of different binders (300 min RTFO).

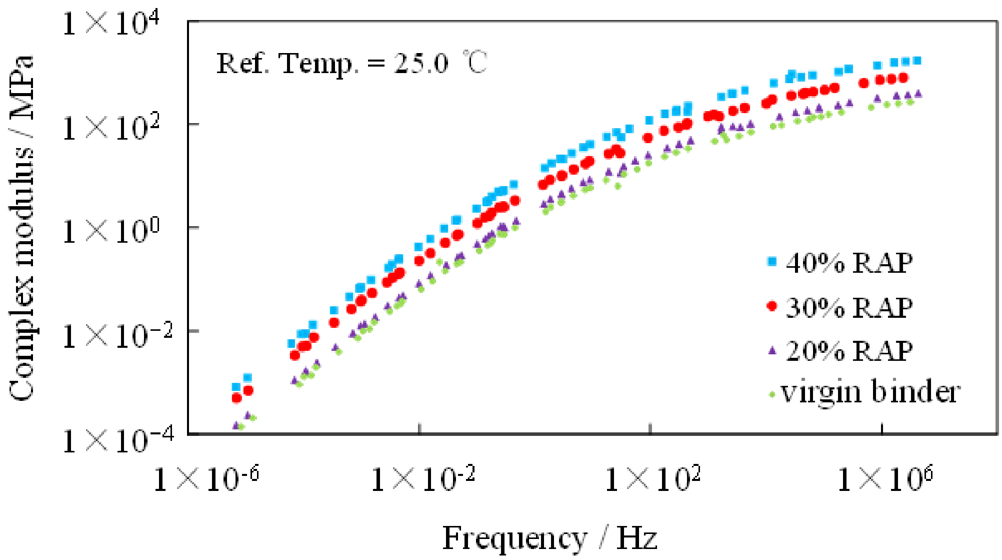

Figure 6. Complex modulus master curves of different binders (600 min RTFO).

3.1.3. G-R Parameter and Rheological Indices

Figure 7 shows the G-R parameter values of different binders under a Black Space diagram. The black dotted line means damage onset, and the black solid line means significant cracking. The figure shows that as the RAP binder dosage increases, the recycled blends become more aged and migrates to potential non-load-related cracking areas. The results also show that for the same type of binder, aging time is an important factor affecting the non-load-related cracking property of asphalt binder. As can be seen in Figure 7, as the aging time increases, the binder becomes more prone to cracking. The results also show that the P-G parameter of 40% RAP recycled blends are very close to the threshold value. Another phenomenon which should be realized is that the original RAP binder dosage is more important than the short-term lab aging test in terms of affecting the non-load-related cracking property of binders.

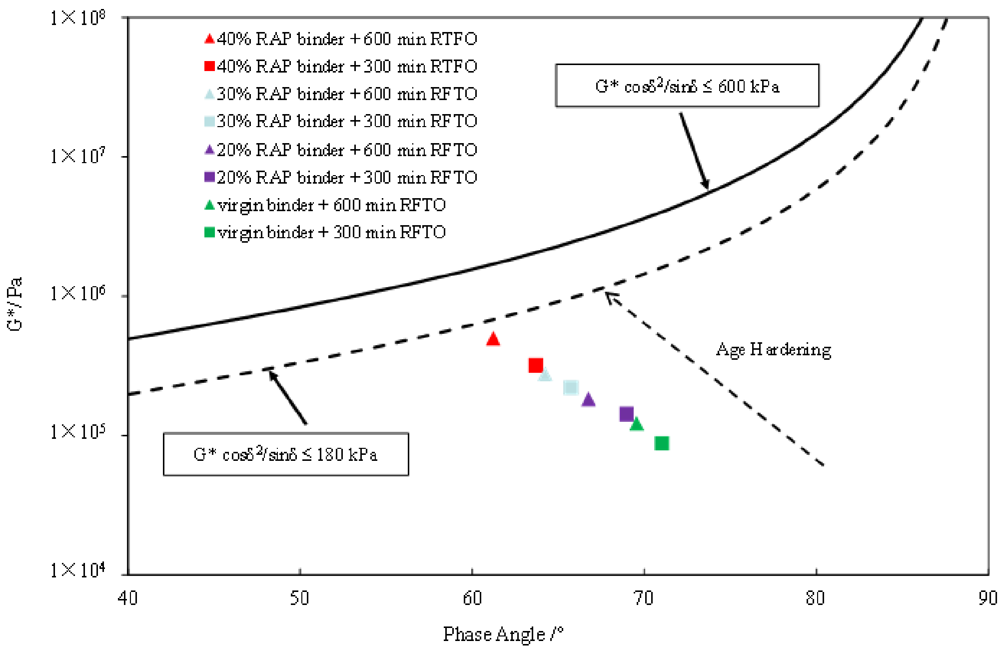

Figure 7. G-R parameter results of different binders.

The results of the R-value and the measured crossover frequency is shown in Figure 8. The lower crossover frequency is achieved by the phase angle of 45° at the lower frequency, which indicates that the binder has a greater elastic behavior. The higher the R-value, the smoother the master curve, which is another sign of aging. The figure clearly shows that the rheological index of CAM has changed due to the RAP binder dosage and RTFO aging times, which indicates that binders turn more brittle. The recycled blends with 40% RAP binder, which are very closed to the bottom right, shows greater changes than virgin binder.

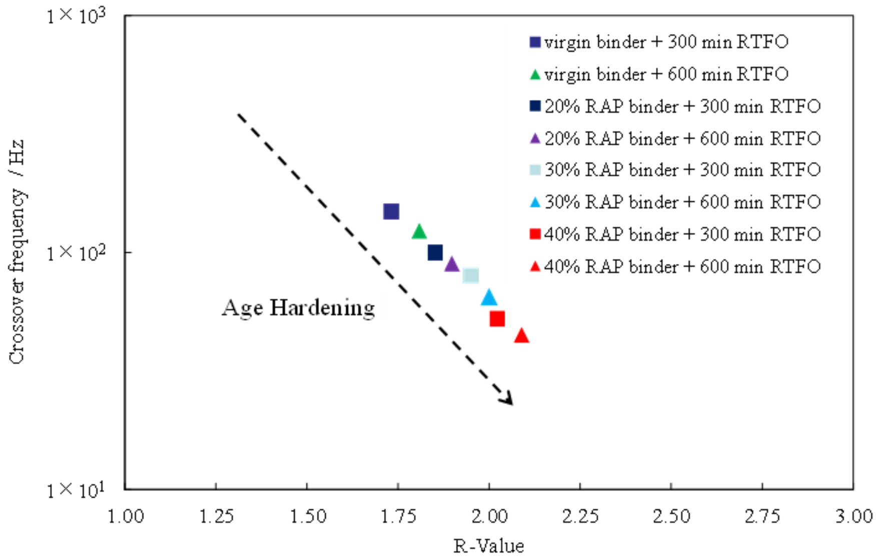

Figure 8. Rheological indices analysis of different binders.

3.2. Mixture Testing

3.2.1. Dynamic Modulus and Phase Angle

Dynamic modulus master curves were generated for different RAP binder dosages as shown in Figures 9 and 10 for the 300 min RTFO aging and 600 min RTFO aging mixtures, respectively. Each master curve shows the average of three replicate samples. As can be seen in Figures 9 and 10, both the 300 min RTFO aging and 600 min RTFO aging mixtures represent the increase in dynamic modulus with the RAP binder dosage increase. The 600 min RTFO aging mixtures show a greater increase with the RAP binder dosage than that of 300 min RTFO aging mixtures.

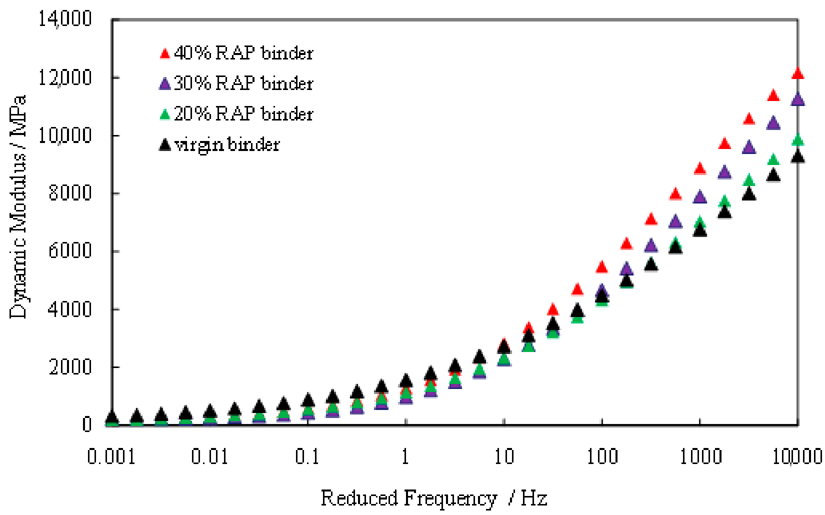

Figure 9. Dynamic modulus master curve for different mixtures (300 min RTFO aging).

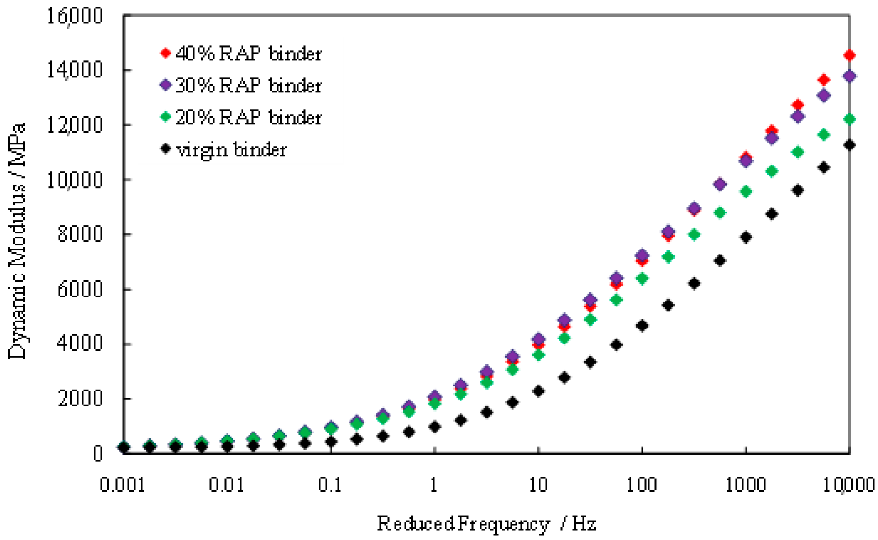

Figure 10. Dynamic modulus master curve for different mixtures (600 min RTFO aging).

Figures 11 and 12 represent phase angle curves for all mixtures. In phase angle curves, the lower phase angles at the same frequency mean that the mixture may have a greater potential to crack. At a lower frequency, the RAP binder dosage has little effect on the phase angle for both 300 min RTFO aging and 600 min RTFO aging mixtures. At higher frequencies and inflection points, with the RAP binder dosage increase, the phase angle decreases. The 600 min RTFO aging mixtures show a little difference near the inflection point, and the 300 min RTFO aging mixtures show little difference at higher frequencies.

An independent sample t-test was used to analyze the original data, and the confidence interval was 95%. Statistically, the 20% RAP binder and 30% RAP binder mixtures are similar to the virgin binder mixture. The 40% RAP binder mixture is significantly different to the other three mixtures. Phase angle results generally show little statistical significance.

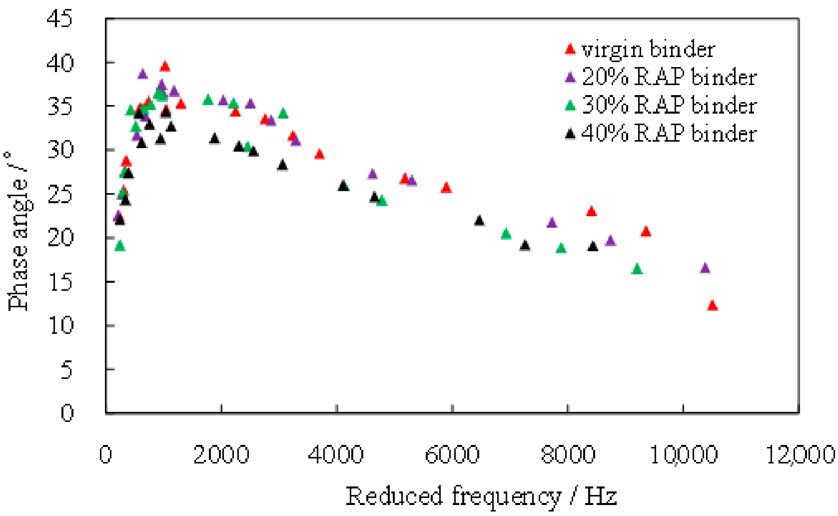

Figure 11. Phase angle of different mixtures (300 min RTFO aging).

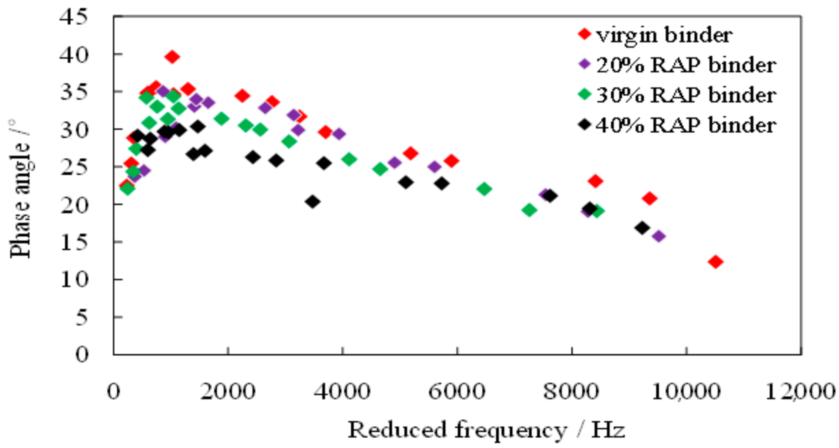

Figure 12. Phase angle of different mixtures (600 min RTFO aging).

A Sigmoid fit the master curve was used to calculate the dynamic modulus ratio, to compare each mixture with its respective virgin binder mixture at 300 min RFTO aging value. Figure 13 shows the average ratio of dynamic modulus values with respect to the virgin binder mixture at 300 min RFTO aging value. It can be seen that stiffness of 40% RAP binder mixtures under 600 min RTFO aging is 1.5 times stiffer approximately than the virgin binder mixture under 300 min RTFO aging. At the same RTFO conditioning, it is obvious that the stiffness change of the RAP binder mixture is greater than that of the virgin binder mixture.

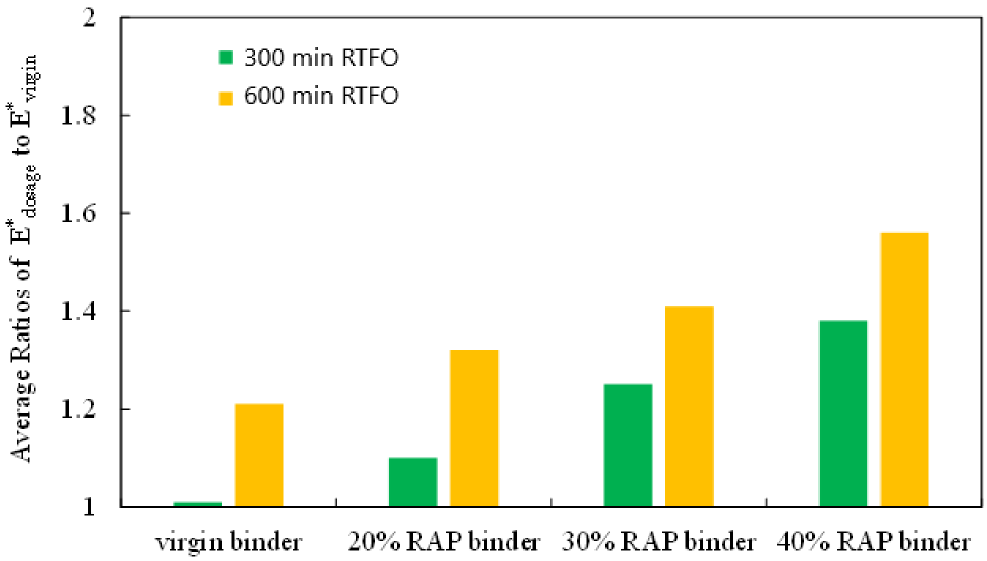

Figure 13. Dynamic modulus ratios for overall average.

3.2.2. Low Temperature Cracking

The results from DCT test are shown in Figure 14. The error bars indicate one standard deviation of three replicates. Generally, as can be seen in Figure 14, with the increase in the RAP binder, the fracture energy decreases. However, it is very interesting to notice that as the RTFO aging times extend, there have been different degrees of growth in fracture energy for 20%, 30%, and 40% RAP binder mixtures. The reason for this could be that diffusion or blending between binders prolongs the RTFO aging time, and this phenomenon may have an effect on the low temperature properties of the mixture. In future research, the diffusion mechanism or microscope images should be applied to explain this phenomenon.

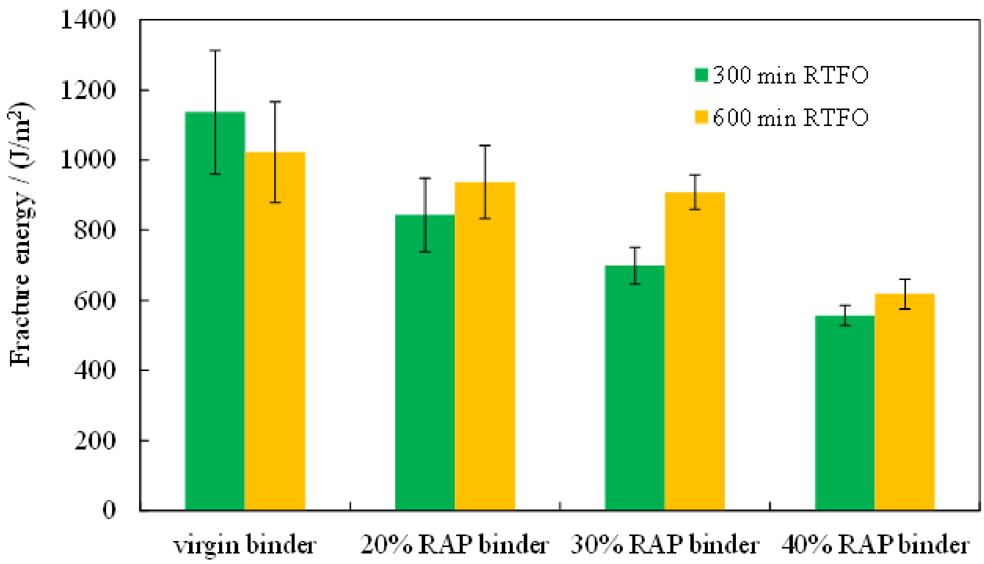

Figure 14. Fracture strain tolerance (disk-shaped compact tension (DCT)) of different asphalt.

3.2.3. Fatigue Behavior

The fatigue life results of the midpoint bending fatigue test for different mixtures are shown in Tables 6 and 7. The results show that with the increase in the stress ratio, the fatigue life for all kind of mixtures decrease. It also can be seen from Tables 6 and 7 that the ranking of four kinds of mixtures is virgin binder mixture > 20% RAP binder mixture > 30% RAP binder mixture > 40% RAP binder mixture under same aging conditions and stress ratio. This could be the reason for virgin SBS being a modified binder, the SBS co-polymer swells in the maltene phase of the binder and creates an elastic network that enhances the viscoelastic properties of the binders. While for recycled blends, the recycling agents have high aromatics and low saturated phenol, which could dissolve and disperse asphaltene, but cannot restore the SBS network structure. Therefore, as with increasing the RAP binder content, the fatigue life decreases. However, at 600 min short-term aging conditions, the fatigue life of 40% RAP binder mixture is greater than 30% RAP binder mixture.

Table 6. The midpoint bending fatigue results of different mixtures (300 min aging).

Binder Type	Stress Ratio		
	0.2	0.3	0.4
virgin binder	38,019	13,680	5248
20% RAP binder	32,810	12,023	4285
30% RAP binder	23,442	10,214	3540
40% RAP binder	19,953	8810	3589

Table 7. The midpoint bending fatigue results of different mixtures (600 min aging).

Binder Type	Stress Ratio		
	0.2	0.3	0.4
virgin binder	30,200	12,071	4387
20% RAP binder	25,119	10,256	3790
30% RAP binder	14,125	6026	2584
40% RAP binder	19,498	7586	3080

Studies have shown that the fatigue life in logarithmic coordinates and stress ratios maintain a linear relationship, which can be expressed by Equation (6). In Equation (6), k

and n are the fitting parameters. The greater values of k and n, the better fatigue cracking resistance.

$$\lg N_{\mathrm{f}} = k - n\sigma_{\mathrm{r}} \tag{6}$$

where, N_{f} is the fatigue life, σ_{r} is the stress ratio.

Table 8 shows the regression equation results of all the mixtures. Basically, with the increased RAP binder dosage, the parameters k and n both decrease, except for the 30% RAP binder mixture and 40% RAP binder mixture. This is because the virgin SBS modified binder have better polymer rich phases, which provide the better strength and elasticity for the binder. Although the PG grade of different recycled blends are equal to the virgin SBS modified binder, the interior cross-linking state is different. Therefore, the fatigue property cannot be guaranteed. Interestingly, under 300 min aging condition, the fatigue behavior of virgin binder mixture and 20% RAP binder mixture is at the same level. However, in general, the fatigue behavior of the virgin mixture is better than that of RAP mixtures, especially for high RAP binder dosage mixtures, and longer aging time has a negative impact on the fatigue property of the mixture.

Table 8. Regression equation results of different mixtures.

Binder Type	Regression Equation	Aging Time/Minutes
virgin binder	$\lg N_{\mathrm{f}} = 5.4354 - 4.300\ \sigma_{\mathrm{r}}$	300
20% RAP binder	$\lg N_{\mathrm{f}} = 5.4020 - 4.420\ \sigma_{\mathrm{r}}$	
30% RAP binder	$\lg N_{\mathrm{f}} = 5.2078 - 4.105\ \sigma_{\mathrm{r}}$	
40% RAP binder	$\lg N_{\mathrm{f}} = 5.0508 - 3.725\ \sigma_{\mathrm{r}}$	
virgin binder	$\lg N_{\mathrm{f}} = 5.3241 - 4.1892\ \sigma_{\mathrm{r}}$	600
20% RAP binder	$\lg N_{\mathrm{f}} = 5.2283 - 4.1068\ \sigma_{\mathrm{r}}$	
30% RAP binder	$\lg N_{\mathrm{f}} = 4.8873 - 3.6885\ \sigma_{\mathrm{r}}$	
40% RAP binder	$\lg N_{\mathrm{f}} = 5.0884 - 4.0072\ \sigma_{\mathrm{r}}$	

4. Summary and Conclusions

In this paper, the influence of RTFO short-term aging on recycled blends and RAP mixtures was studied. Binders were assessed by using ΔT_{cr}, G-R parameter, rheological indices, and master curve. Testing was conducted on four kinds of binders at two different RTFO aging time conditions. Mixtures were assessed by using complex modulus, a fracture test, and a midpoint bending fatigue test. The following conclusions were obtained according to the results:

The ΔT_{cr} and G-R parameters showed that the aging condition had a significant effect on the cracking resistance of recycled blends. Compared to the virgin binder, the recycled blends were more sensitive to the aging process. What is more, the RAP contents had a detrimental effect on the anti-cracking property of recycled blends and the higher dosage of RAP binder, the greater the anti-cracking attenuation of recycled blends with aging. Therefore, the recycling agent could help the RAP binder achieve a similar performance to the virgin binder, but the long-term anti-cracking property of recycled blends could not be guaranteed.

DSR modulus master curve on binders and dynamic modulus testing on mixtures showed that the increase of RAP binder dosage leads to an increase in the stiffness for binders and mixtures. By extending the RTFO aging time, the stiffness of RAP binders and RAP mixtures was significantly greater than that of 300 RTFO aging times.

Fracture test of mixtures showed that with the increase of the RAP binder, the fracture energy decrease. However, as the RTFO aging times extend, there have been different degrees of growth in fracture energy for 20%, 30%, and 40% RAP binder mixtures. The reason for this could be that a diffusion or blending between binders as prolongs the RTFO aging time.

Midpoint bending fatigue test of mixtures showed that with the increase in the RAP binder dosage and the RTFO aging time, the fatigue life of mixtures decreases. Analysis in regression equation showed that at 600 min RTFO conditioning, the fatigue behavior of 40% RAP binder mixture was better than that of 30% RAP binder mixture, probably because the longer aging time leads to a greater diffusion and blending between the virgin binder and RAP binder.

Future work is needed to gain more tests related to the binder absorption that supplies this research, such as Differential Scanning Calorimetry (DSC) test. The DSC test is recommended to show the thermal and chemical stability of different binders. We also recommend that the production parameters should be included in the future study, such as the haul time, and the silo storage time.

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