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Viscoelasticity of Recycled Asphalt Mixtures with High Content Reclaimed SBS Modified Asphalt Pavement

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Abstract: For the concerns of investigating the viscoelastic properties of recycled asphalt mixtures incorporating high content reclaimed styrene-butadiene-styrene (SBS) modified asphalt pavement (RAP-SBS), asphalt mixture performance tester (AMPT) was applied to analyze the dynamic modulus and phase angle of recycled mixtures by the influence of RAP-SBS content, temperature, loading frequency, long-term aging (LOTA), and the incorporation of a rejuvenating agent. Master curves of recycled asphalt mixture regarding dynamic modulus and phase angle are developed, and the viscoelastic properties of recycled mixtures within a wide frequency range are characterized with the Christensen–Anderson–Marastean (CAM) model. Eventually, the one-way analysis of variance (ANOVA) was applied to investigate the role of factors on the viscoelasticity of recycled mixtures. The research indicates that (1) the elastic component of recycled mixtures elevates with the increasing of RAP-SBS content and loading frequency; as a result, the high-temperature stability of it enhances, while it is prone to cracking at low temperatures; (2) RAP-SBS content should be selected according to specific characteristics of pavement. For most cases, a content of 50% is recommended; (3) the recycled mixtures incorporating high-content RAP-SBS mixed with a rejuvenating agent has outstanding aging resistance performance; (4) RAP-SBS content is observed to have a significant influence on the viscoelasticity of recycled mixtures.

Keywords: road engineering; viscoelastic properties; reclaimed SBS modified asphalt pavement; dynamic modulus; phase angle; CAM model

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1. Introduction

As a polymer modifier with excellent performance, styrene-butadiene-styrene (SBS) has been extensively utilized in asphalt pavement of high-grade highways in China [1–3]. No matter under high or low temperatures, it has the advantages of sufficient durability and satisfactory elastic resilience. However, enormous SBS-modified pavements have drawn near to or have entered into the overhaul period in China, especially being subject to the excessive and overloaded vehicles. The disposal of reclaimed SBS-modified pavements (RAP-SBS) is a protruding complication during the maintenance of SBS modified pavements, given the vast amount of pavements built in the past decades. According to the relative standard in China, the recommended percentages of reclaimed asphalt pavements (RAP) in the hot mix plant recycling are 15–30%, while the percentages in practical engineering are mostly controlled at about 25%. Consequently, the properties and applicability of recycled asphalt mixtures incorporating high-content (more than 30%) RAP-SBS have become a crucial study to promote the sustainability of asphalt pavements.

For a recycled mixture, the performance degradation of aged asphalt is the principle obstruction to incorporating high-content RAP into new asphalt pavement. As RAP content increases, the blended asphalt is observed to be harder, increases in elasticity, and decreases in viscosity, which may cause premature distress such as fatigue failure and low temperature cracking [4]. To resolve this problem, a rejuvenating agent (RA) is widely adopted to restore the performance of aged asphalt in RAP and improve the state of intermingling of aged and virgin asphalt binder [5,6]. For recycled asphalt mixtures with different RAP content and type of recycling, the appropriate type of RA and the corresponding dosage should be carefully determined. There have been a considerable number of studies focused on the RA applied in HMA [7,8], and many studies have been conducted toward rejuvenating SBS modified asphalt binders [9,10]. Previous studies indicated that a compound RA with appropriate ingredients and proportion is able to entirely renovate the long-term aged SBS modified asphalt to its virgin state in terms of penetration, ductility, and softening point, as well as improving the performance at both low and high temperature [11–15]. However, the suitable type and corresponding dosage of RA to incorporate into the recycled asphalt mixture and its influence on the viscoelasticity remains further exploration, especially when RAP-SBS content extends beyond 50%.

Because of the presence of SBS, there are many dissimilarities between RAP and RAP-SBS, which contribute to the uncertainties in recycling RAP-SBS [16–18]. As a result of it, the incorporation of high-content RAP-SBS remarkably converts the properties of recycled mixtures. Performances including crack resistance [19], rutting resistance [20,21], and moisture susceptibility [3,19] of recycled mixtures with RAP-SBS have been investigated systematically. In general, recycled mixtures with a high content of RAP-SBS exhibit poor moisture susceptibility and low-temperature cracking resistance, which can be improved by adding RA with appropriate content, while the investigation towards its material nature, i.e., viscoelasticity, remains extending. Compared with hot mixture asphalt, the phase angle peak of recycled asphalt mixtures incorporating RAP-SBS decreases and can be reached earlier, which is more conspicuous when loading frequency and the dosage of RAP-SBS increases [22]. On the other hand, it has been explored that the dynamic modulus of recycled mixtures increases with the reduction of RA content and the increase in RAP-SBS content [3].

However, in the previous studies, the range of RAP-SBS content variation was not set sufficiently, and there is a lack of investigation towards the change of recommended RAP-SBS content under the effect of long-term aging (LOTA) and incorporating RA. Additionally, the model adopted to evaluate the viscoelasticity of it is required to be innovated.

In this paper, two indicators, dynamic modulus and phase angle, were selected to characterize the viscoelasticity of asphalt mixtures. A mass of investigations has been conducted adopting various models to develop master curves, including the Christensen–Anderson (CA) model [23,24], the Sigmoidal model [25–27], the Havriliak–Negami (HN) model [28–30], etc. Modifying on the basis of the CA model, the Christensen–Anderson–Marasteanu (CAM) model was proposed by Marasteanu and Anderson, which was originally used to develop master curve for asphalt binder [31]. Compared with the above models, the CAM model provides a superior fit of the complex modulus master curve with a wide frequency range, especially for the polymer-modified asphalt binder [32,33]. Apart from it, the CAM model is also utilized to develop master curves of asphalt mixtures in terms of dynamic modulus widely [34–36]. However, there is still a lack of investigation towards the feasibility and effectiveness of fitting a master curve of recycled mixtures with the CAM model, especially with high RAP-SBS content.

In summary, previous studies focused on recycled mixtures with less than 30% RAP-SBS, and even though there have been a number of studies on the performance of recycled asphalt with high RAP-SBS content recently, further research is still needed, especially with 70% RAP-SBS content. Applicable RA for recycled mixtures with high RAP-SBS content has been investigated, while previous studies have not reached a consensus on the suitable type and the corresponding dosage of RA, and there is a lack of investigation towards the variation of viscoelasticity of recycled mixtures with high RAP-SBS content under the combined action of RA and LOTA. The CAM model has been widely adopted to develop master curve for asphalt mixture because of its reliability, while there is no study to prove its applicability for a recycled mixture with high RAP-SBS content. For the concerns of promoting service life of hot-mix recycled asphalt mixture, the content of RAP-SBS should be carefully selected according to specific pavement characteristics (including temperature, designed speed, and construction cost). To this end, this paper aims to explore the suitable RAP-SBS content for pavements with different characteristics according to its viscoelasticity, which is urgently needed from a practical level, and it is also the main embodiment of innovation in this paper.

2. Goals and Objective

Given the material essence of asphalt mixtures and the increasing amount of RAP-SBS generated every year, the viscoelasticity of recycled mixtures incorporating high-content RAP-SBS is an urgent issue to be evaluated effectively to optimize the technology of asphalt pavement recycling. To this end, this paper constructs intensive research regarding the viscoelasticity of recycled asphalt mixtures with high RAP-SBS content. AMPT was selected to analyze the dynamic modulus and phase angle of recycled mixtures with high RAP-SBS content compared with the control mixture with 0% RAP-SBS under the effect of different factors, including temperatures, frequencies, and with or without RA and LOTA. Based on the results, the CAM model was adopted to develop the master curves and evaluate the viscoelasticity of recycled mixtures, providing a reference for selecting an appropriate RAP-SBS content according to the specific characteristic of pavement. Eventually, the one-way analysis of variance (ANOVA) [37,38] was conducted to investigate the sensitivity of RAP-SBS content, LOTA, and the incorporation of RA on dynamic modulus and phase angle.

3. Materials and Methods

3.1. Materials

RAP-SBS used in this study was acquired in Beijing, and Abson method (ASTM D 1856) was conducted to reclaim asphalt from RAP-SBS. The aging of SBS modified asphalt was simulated with thin film oven test (TFOT). The aged asphalt content of RAP-SBS by mass was tested to be 3.6% with Abson Method according to ASTM D1856.

To enhance the performance of aged asphalt, a kind of rejuvenating agent (RA) was selected and procured from Sobute Ltd. in China, which was developed with an aim to increase RAP content in recycled mixtures. RA adopted in this paper is reddish-brown in color, whose main performance indexes were tested according to ASTM D4552 (TFOT was conducted according to ASTM D2872).

For the purpose of excluding the influence of aggregate gradation on the performance of mixtures with different dosages of RAP-SBS (0%, 30%, 50%, 70%), separate calculations were made for each mixture to ensure the consistency and coherence of the gradation. In this paper, the RAP-SBS content refers to the ratio of RAP-SBS to recycled mixture by mass. According to ASTM D1559, the Marshall methodology is adopted, and the aggregate gradation of each mixture is set separately.

This paper investigated the effect of RA on recycled asphalt mixtures incorporating high-content RAP-SBS, which affects the optimum asphalt content (OAC) for each mixture. The OAC of each mixture, including aged asphalt and virgin asphalt, was determined according to the Marshall methodology, considering volume of asphalt (VA), voids in mineral aggregates (VMA), voids filled with asphalt (VFA), Marshall stability (MS), and flow value (FV).

3.2. Dynamic Modulus Test

Dynamic modulus test (DM) was processed with an AMPT according to AASHTO T342, which was conducted at frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz at 4 °C, 20 °C, and 40 °C.

According to the current Chinese standard (JTG/T 5521), recycled mixtures were mixed with the following steps: 1. add RAP-SBS into a preheated mixing pot and incorporate RA; 2. add virgin fine aggregate and coarse aggregate; 3. add virgin asphalt; 4. add virgin filler. The material should be mixed evenly in each step, and the total mixing time is about 3 min. In this research, the Superpave gyratory compactor (SGC) method was adopted to fabricate specimens 17 cm in height and 15 cm in diameter at 7 ± 0.5% air voids;

by coring, the specimens were trimmed to 15 cm in height and 10 cm in diameter to fit the mold of AMPT. Three replicate specimens were tested for each type of mixture.

3.3. Long-Term Aging Test

Chinese current standard (JTG E20) adopts the long-term aging methods for asphalt mixtures proposed by SHRP, which is regarded as a reliable method to simulate the performance of asphalt pavement after 5–7 years and it has been conducted extensively in previous studies [39,40]. It was adopted in this study to investigate the long-term aged properties of recycled mixtures with a thin film oven. The specific steps are as follows: (1) after mixing, place recycled mixtures in an oven with trays at 135 °C for 4 h, and stir the recycled mixtures with a shovel once an hour; (2) fabricate specimens for DM test with recycled mixtures as the same method in Section 3.2; (3) heat the specimens in the oven at 85 °C for 120 h; (4) place the specimens at room temperature for 24 h and conduct DM test.

3.4. Statistical Analysis

One-way ANOVA is applied to evaluate the sensitivities of dynamic modulus and phase angle on RAP-SBS content, the incorporation of RA, and LOTA. The significance level α is set as 0.05, and the p-value of each factor is calculated and compared with α to investigate whether it has a significant impact on the test results.

As a viscoelasticity material, asphalt mixture exhibits different performances at different loading frequencies and temperatures. As a result of it, the ANOVA was conducted at 10 Hz and 20 °C according to the most common applying situation for pavements in China.

4. Results and Discussion

4.1. Material Performance

The main performance indexes of the aged asphalt and virgin asphalt used are presented in Table 1, as well as the standard limit for SBS modified asphalt.

Table 1. Main performance indexes of modified asphalt.

Indexes		Aged Modified Asphalt	Virgin Modified Asphalt	Standard Limit
Penetration (25 °C/0.1 mm)		31.3	48.1	40~60
Softening point (°C)		70.0	69.3	≥60
Ductility (5 °C/cm)		0.1	30.7	≥20
Viscosity (135 °C/Pa·s)		2.36	1.05	≤3
Residue after TFOT	Mass loss (%)	-	0.52	≤±1.0
	Penetration ratio (25 °C/%)	-	72.0	≥65
	Ductility (5 °C/cm)	-	16.1	≥15

The result of saturates, aromatics, resins, and asphaltenes (SARA) fractions analysis is presented in Table 2, and the main performance indexes of RA are presented in Table 3. Blended with RA, the penetration, ductility, viscosity, and tenacity of aged modified asphalt were improved, as shown in Table 3. Table 4 represents the effect of RA on aged modified asphalt, after considering the efficiency of regenerating and the economy of RA simultaneously, the content of RA was set to 6%.

Table 2. SARA fraction analysis results of RA.

Fraction	Saturates	Aromatics	Resins	Asphaltenes
Mass fraction (%)	51.9	40.6	6.5	0.8

Table 3. Main performance indexes of rejuvenating agent.

Indexes	Value
Viscosity (60 °C/10^{-3} Pa·s)	1202
Flash point (°C)	267
Saturates content (%)	26.04
Aromatic content (%)	42.27
Density (g·cm^{-3})	1.013
Residue from TFOT	
Viscosity ratio	1.80
Weight change (%)	−2.62

Table 4. Effect of RA on aged modified asphalt.

Indexes	Value	Dosage of RA/%		
		3	6	9
Penetration (25 °C/0.1 mm)	31.3	39.6	51.2	64.9
Softening point (°C)	70.0	67.5	65.1	62.8
Ductility (5 °C/cm)	0.1	13.8	22.2	30.3
Viscosity (135 °C/Pa·s)	2.36	1.360	1.111	0.841
Toughness (25 °C/N·m)	16.90	14.21	11.21	7.53
Tenacity (25 °C/N·m)	4.21	5.78	5.45	4.43

Table 5 presents the aggregation for mixtures with different RAP-SBS contents, and Table 6 presents the OAV and volumetric properties for different mixtures.

Table 5. Aggregate gradation for mixtures with different RAP-SBS contents.

Sieve Size (mm)	Gradation Passing by Mass (%)			
	0%	30%	50%	70%
16	100.0	100.0	100.0	100.0
13.2	97.3	97.2	97.0	96.9
9.5	75.1	75.0	73.4	72.6
4.75	41.9	41.9	40.4	40.7
2.36	28.1	29.1	28.2	28.4
1.18	18.2	18.7	18.4	18.6
0.6	13.6	13.8	13.7	14.0
0.3	10.2	10.3	10.3	10.6
0.15	8.0	7.9	8.0	8.4
0.075	6.3	6.2	6.4	6.7

Table 6. OAC and volumetric properties for different mixtures.

Properties		RAP-SBS Content (%)						
		0	30 #	30 *	50 #	50 *	70 #	70 *
OAC	Virgin asphalt (%)	4.60	3.52	3.46	2.90	2.79	2.28	2.13
	Total asphalt (%)	4.60	4.60	4.60	4.70	4.70	4.80	4.80
Volumetric properties	VA (%)	4.1	4.3	4.3	4.3	4.3	4.6	4.6
	VMA (%)	14.2	15.0	14.9	15.3	15.3	16.1	16.0
	VFA (%)	70.9	71.5	71.4	71.6	71.4	71.4	71.3
	MS (kN)	11.1	8.8	12.3	9.7	13.3	11.3	16.2
	FV (mm)	3.2	4.5	3.8	4.1	3.4	4.9	4.3

#: addition of rejuvenating agent; *: no addition of rejuvenating agent.

4.2. Dynamic Modulus

Dynamic modulus is a significant index to evaluate the viscoelasticity of the mixture, which characterizes the ability to resist deformation when subjected to load. Figure 1 presents the variation of the dynamic modulus with temperatures and frequencies for mixtures with different RAP-SBS content. Firstly, as shown in Figure 1, the dynamic modulus of mixtures presented an identical pattern of variation due to temperature and frequency, i.e., the dynamic modulus values increased with decreasing temperature and increasing frequency, regardless of the dosages of RAP-SBS. Apparently, the addition of RAP-SBS in recycled mixtures is incapable of converting its temperature and frequency dependence. At high temperature (40 °C) and low frequencies (less than 10 Hz), recycled mixtures were observed to have higher dynamic modulus than control mixtures, which is more protruding for mixtures with higher RAP-SBS content. In comparison, at low temperature (4 °C) and high frequencies (higher than 10 Hz), only the recycled mixtures with 50% RAP-SBS exhibited higher dynamic modulus values than the control mixture. This result demonstrates that, when the dosage of RAP-SBS is 50%, the ability of recycled mixtures to resist deformation both at low and high temperatures could be effectively improved. In addition, the dynamic modulus of mixtures with 50% RAP-SBS and 70% RAP-SBS are similar at low frequencies, although there is a considerable difference in engineering economy between them. As a result, for pavements with slower design speed, the RAP-SBS dosage can be considered to be increased from 50% to 70% after verifying that other properties meet the specification requirements.

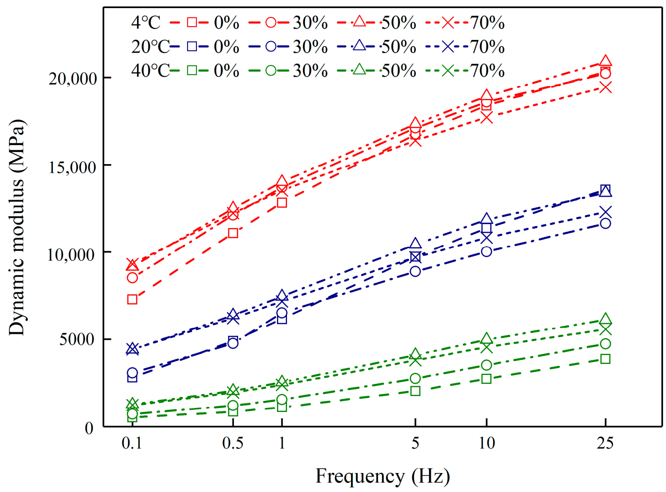

Figure 1. Dynamic modulus of recycled mixtures with different RAP-SBS content.

4.3. Phase Angle

Determined from dynamic modulus test, phase angle is the angle between peak strain and peak stress, which directly demonstrates the viscoelasticity of asphalt mixtures. Figure 2 presents the phase angle variation with temperatures and frequencies for the mixtures with different RAP-SBS content. As shown in Figure 2, at 4 °C and 20 °C, the phase angle of mixtures with different RAP-SBS contents presented an identical pattern of variation due to temperature and frequency, i.e., the phase angle of recycled mixtures decreased with the increasing RAP-SBS content, characterizing the reduction of the viscous component, which is not conducive to the resistance of permanent deformation at low temperatures. However, at 40 °C, the phase angle of the control mixtures increased with frequency below 10 Hz, and decreased with it slightly above 10 Hz; as for recycled mixture, the inflection point of the phase angle was advanced from 10 Hz, which is more evident for mixtures with higher RAP-SBS content, indicating that recycled mixtures with RAP-SBS exhibited more elastic components at high temperatures and low frequencies, demonstrating the great capability of resistance to rutting.

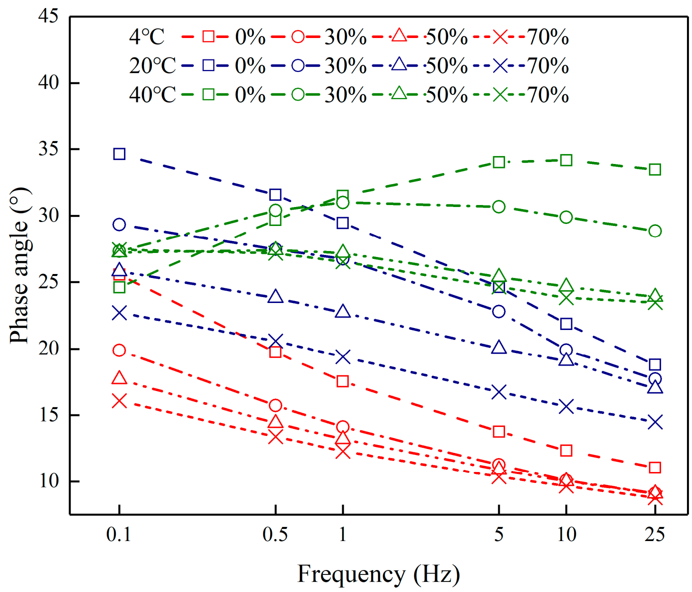

Figure 2. Phase angle of recycled mixtures with different RAP-SBS content.

4.4. Master Curve

As introduced above, the CAM model is able to fit the behavior of a mixture as a viscoelastic solid in a universal form within a wide range of temperatures and frequencies; therefore, it was adopted in this study to develop the dynamic modulus and phase angle master curve of mixtures, as Equations (1) and (2) represent.

$$G^* = G_e^* + \frac{G_g^* - G_e^*}{\left[1 + (f_c/f\prime)^k\right]^{m_e/k}} \quad (1)$$

where G_g^* and G_e^* are the glassy modulus and equilibrium modulus, respectively; f_c is the crossover frequency; f is the frequency related to temperature and strain; m_e and k are non-dimensional factors.

$$\delta = \delta_m \left[1 + \left(\frac{\lg(f_d/f\prime)}{R_d}\right)^2\right]^{-m_d/2} \quad (2)$$

where δ_m is the peak value of phase angle; f_d is the frequency to the highest point of the phase angle; m_d and R_d are shape parameters.

In this study, 20 °C was chosen as a reference temperature, and the CAM model was adopted to construct the dynamic modulus master curves of mixtures with different RAP-SBS dosages, before and after incorporating RA and LOTA. Obtaining temperature shift factors, as shown in Table 7, dynamic modulus of mixtures under different temperatures is converted according to the time–temperature superposition principle with Arrhenius method. Developed from different mixtures, the dynamic modulus master curve model parameters are presented in Table 8. The correlation coefficient shown in Table 8 indicates that the CAM model adopted for constructing the master curves of dynamic modulus are highly related.

The master curve being a semi-log plot of G^* versus log reduced frequency, plots of dynamic modulus master curves of different mixtures are presented in Figures 3 and 4. As Figures 3 and 4 represent, for mixtures without RA, the difference in RAP-SBS contents contributed little to effecting G^* in the high-frequency section with a frequency greater than 10 Hz, while in the low-frequency section under 10^{-2} Hz, the general pattern of increasing the G^* of recycled mixtures with increasing RAP-SBS content is observed. Since low frequency corresponds to high temperature according to time-temperature shift, this result indicates that manipulating the RAP-SBS content of recycled mixtures has a more pronounced effect on the resistance to deformation at high temperatures. For recycled mixtures incorporating RA and being subject to LOTA, the G^* of recycled mixtures with 30% and 50% RAP-SBS decreased in the low-frequency section, while in other cases, the addition of RA improved the G^* of recycled mixtures after LOTA significantly, indicating that the incorporation of RA effectively enhanced the aging-resistance of recycled mixtures. In addition, recycled mixtures with 50% RAP-SBS exhibited the greatest G^* in both the high-frequency section and low-frequency section, while recycled mixtures with 70% RAP-SBS exhibited the greatest G^* in the medium-frequency section, which fully demonstrates the feasibility of increasing RAP-SBS content in practical engineering.

Table 7. Temperature shift factors.

Temperature (°C)	Mixtures										
	0%	**0%**	**30%**	**30%**	**30%**	**50%**	**50%**	**50%**	**70%**	**70%**	**70%**
4	1.68	1.62	1.65	1.43	1.90	1.57	1.59	1.34	1.72	1.62	1.91
20	0	0	0	0	0	0	0	0	0	0	0
40	−1.86	−1.79	−1.82	−1.58	−2.10	−1.73	−1.76	−1.48	−1.90	−1.79	−2.12

Table 8. Dynamic modulus master curve model parameters of recycled mixtures.

Mixtures	**G^* Master Curve Parameters**						**Correlation Coefficient**
	G_g^*	G_e^*	f_c	m_e	k	R	R^2
0% #	35,302	124.3	7.29×10^{-5}	1.844	0.1748	2.378193	0.99
30% #	34,322	136.6	0.503	0.5808	0.206	0.838381	0.99
50% #	44,682	141.8	1.46×10^{-4}	0.9578	0.1374	1.953896	0.99
70% #	41,557	72.01	1.66×10^{-4}	0.8075	0.1286	1.836046	0.99
30% *	40,562	251	0.4874	0.6373	0.1883	0.99417	0.99
50% *	36,702	355.5	0.01099	0.8002	0.174	1.296245	0.99
70% *	39,237	61.6	1.80×10^{-4}	0.819	0.125	1.913262	0.99
0% L	38,462	84.26	0.00103	1.244	0.1761	2.015608	0.99
30% L	37,412	21.55	1.95×10^{-6}	1.537	0.1385	2.986263	0.99
50% L	43,416	367	0.01489	0.7095	0.1658	1.225345	0.99
70% L	38,957	32.54	1.99×10^{-6}	0.7848	0.1181	1.965873	0.99

#: incorporating RA; *: no incorporating RA; L: incorporating RA and being subject to LOTA.

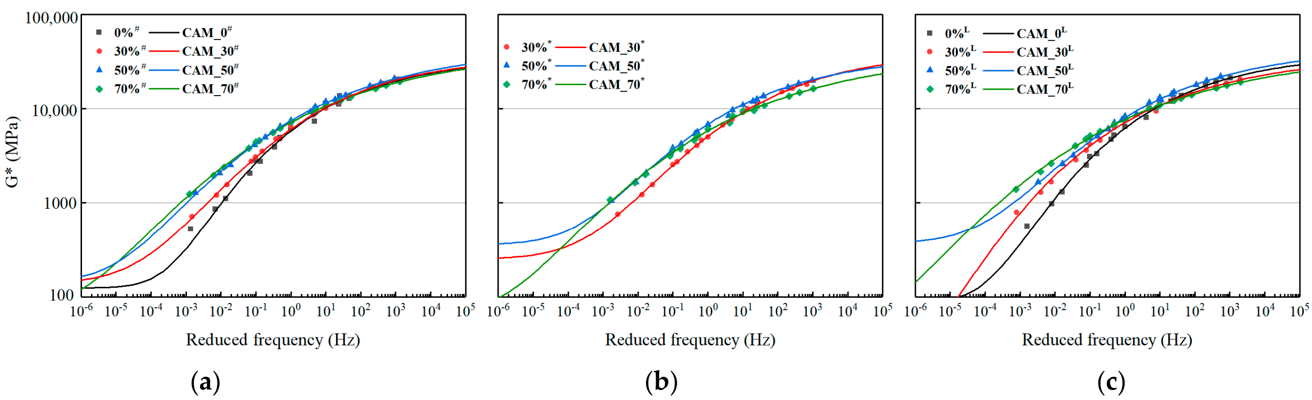

Figure 3. (**a**) Dynamic modulus master curves of recycled mixtures without RA; (**b**) Dynamic modulus master curves of recycled mixtures with RA; (**c**) Dynamic modulus master curves of recycled mixtures after LOTA with RA.

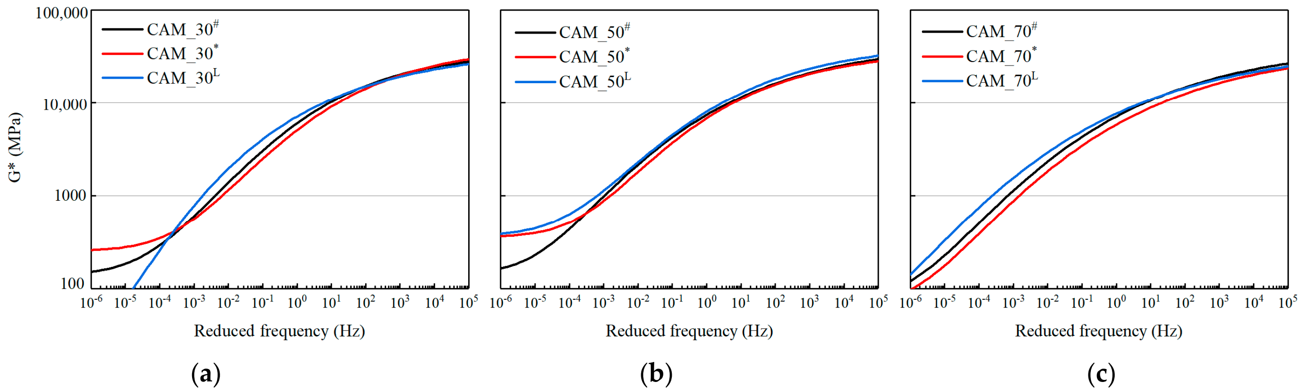

Figure 4. (**a**) Dynamic modulus master curves of recycled mixtures with 30% RAP-SBS; (**b**) Dynamic modulus master curves of recycled mixtures with 50% RAP-SBS; (**c**) Dynamic modulus master curves of recycled mixtures with 70% RAP-SBS.

Apart from dynamic modulus, phase angle master curves were developed according to the CAM model as well, the model parameters of which are presented in Table 9. The correlation coefficient shown in Table 9 indicates that the CAM model used for developing the master curves of phase angle are highly related.

Table 9. Phase angle master curve model parameters of recycled mixtures.

Mixtures	δ Master Curve Parameters				Correlation Coefficient
	δ_m	f_d	m_d	R_d	R^2
0% #	34.33	0.0858	1.908	6.259	0.99
30% #	30.94	0.0306	11.310	20.67	0.99
50% #	27.61	0.009	5.272	15.37	0.99
70% #	27.5	0.0019	2.860	12.07	0.99
30% *	28.04	0.019	4.393	12.66	0.99
50% *	27.89	0.0125	5.840	16.42	0.99
70% *	26.55	0.0095	1.421	7.39	0.99
0% L	34.3	0.0455	1.587	5.475	0.99
30% L	30.55	0.0062	1.638	6.73	0.99
50% L	27.89	0.0096	2.465	9.622	0.99
70% L	26.24	0.0029	1.551	6.869	0.99

#: incorporating RA; *: no incorporating RA; L: incorporating RA and being subject to LOTA.

The master curve being a semi-log plot of δ versus log reduced frequency, plots of phase angle master curves of different recycled mixtures were presented in Figures 5 and 6. As can be seen in Figures 5 and 6, for recycled mixtures without RA, the peak of δ decreased and appeared in advance with the increasing RAP-SBS content, which indicates that recycled mixtures with high-content RAP-SBS exhibited less viscous components. Incorporating RA, recycled mixtures with 30% and 70% RAP-SBS presented a delay in the peak of δ and a decrease in the peak value, while recycled mixtures with 50% RAP-SBS presented little change. In addition, for recycled mixtures incorporating 50% and 70% RAP-SBS with RA, the δ exhibited a slight increase in the high-frequency section and medium-frequency section after LOTA, with no significant change in low-frequency section, which indicates that the incorporation of RA enhanced the aging resistance of recycled asphalt mixtures with high-content RAP-SBS effectively, and the viscoelasticity of it is less affected by aging.

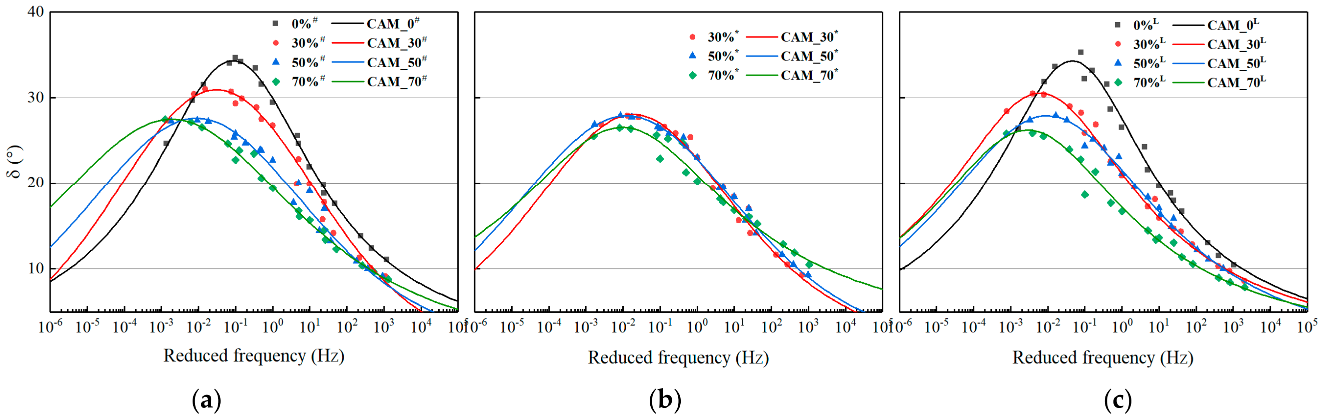

Figure 5. (**a**) Phase angle master curves of recycled mixtures without RA; (**b**) Phase angle master curves of recycled mixtures with RA; (**c**) Phase angle master curves of recycled mixtures after LOTA with RA.

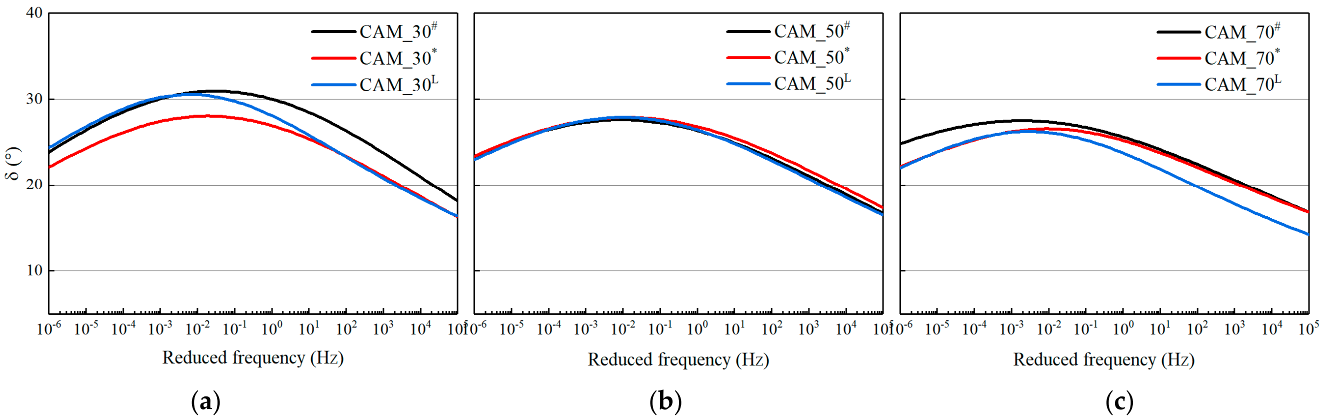

Figure 6. (**a**) Phase angle master curves of recycled mixtures with 30% RAPSBS; (**b**) Phase angle master curves of recycled mixtures with 50% RAP-SBS; (**c**) Phase angle master curves of recycled mixtures with 70% RAP-SBS.

4.5. Sensitivities of Dynamic Modulus and Phase Angle

From the above analysis, it is obvious that many factors including RAP-SBS content, LOTA, and the incorporation of RA will influence the viscoelasticity of recycled mixtures to some extent, and to balance the significance of each factor, the *p*-values are calculated and shown in Tables 10 and 11.

Table 10. ANOVA results of dynamic modulus.

Source	Sum of Square	Degree of Freedom	Mean of Squares	F-Value	*p*-Value	$F_{0.05}$
RAP-SBS Content	6,781,440	2	3,390,720	5.36	0.046	5.14
Incorporation of RA	149,152	1	149,152	0.09	0.772	7.70
LOTA	502,282	1	502,282	1.38	0.304	

Table 11. ANOVA results of phase angle.

Source	Sum of Square	Degree of Freedom	Mean of Squares	F-Value	*p*-Value	$F_{0.05}$
RAP-SBS Content	23.77	2	11.88	10.16	0.011	5.14
Incorporation of RA	0.49	1	0.49	0.18	0.688	7.70
LOTA	6.55	1	6.55	5.53	0.078	

Table 10 represents the ANOVA result of dynamic modulus in terms of RAP-SBS content, LOTA, and the incorporation of RA. According to the *p*-value of the three factors, it is obvious that RAP-SBS content has a significant impact on dynamic modulus, while LOTA and the incorporation of RA do not.

Table 11 represents the ANOVA result of phase angle in terms of RAP-SBS content, LOTA, and the incorporation of RA. It is similar to the ANOVA result of dynamic modulus that RAP-SBS content has a significant influence on the phase angle, while LOTA and the incorporation of RA do not. Comparing the F-value of adding RA (0.09 and 0.18) and LOTA (1.38 and 5.53), it is evident that the RA plays a more and more significant role in the viscoelasticity of recycled mixture with the aging of mixture.

As mentioned above, recycled mixtures with 50% RAP-SBS content exhibit satisfactory performance at both low temperature and high temperature, so 50% was set as reference content when analyzing the effect of LOTA and the incorporation of RA. What is more, adding RA in recycled mixtures without LOTA was set as the reference treatment method.

Combined with the above CAM model fitting results, it is proved that RAP-SBS content has an extremely significant effect on the viscoelasticity of recycled mixtures, and the RAP-SBS content of recycled mixtures can directly reflect the viscoelasticity of it to a certain extent. As a result, RAP-SBS content should be one of the first parameters to be determined in practice. The unassailable effects of LOTA and the incorporation of RA on the viscoelasticity of recycled mixtures are also analyzed. If conditions permit, it is better to evaluate the performance of recycled mixture after aging and add RA into recycled mixtures to improve the viscoelasticity.

5. Conclusions

In this study, the viscoelasticity of recycled mixtures with high-content (more than 30%) RAP-SBS was investigated in terms of dynamic modulus and phase angle with AMPT. The effect of different factors on the viscoelasticity was evaluated with CAM model and ANOVA, including RAP-SBS content, temperatures, and loading frequencies, with or without RA and LOTA. The results can be drawn as follow:

According to the results of dynamic modulus test, the elastic component of recycled asphalt mixture elevated with the increasing of RAP-SBS content and loading frequency; as a result of it, the high-temperature stability of it enhances but it is prone to cracking at low temperatures; while when the dosage of RAP-SBS is set to 50%, the recycled mixtures exhibited satisfactory resistance to deformation in both cases.

CAM model is not only applicable to fit the dynamic modulus and phase angle master curves of conventional asphalt mixtures but is also able to develop master curves of recycled asphalt mixtures with high RAP-SBS content. For recycled asphalt mixtures with high RAP-SBS content, the incorporation of RA improved the resistance to deformation and reduced the loss of viscous components of it, reflecting protruding anti-aging properties. Besides, compared with LOTA and the incorporation of RA, RAP-SBS content of recycled mixtures is observed to have a more significant influence on the viscoelasticity and it should be one of the first parameters to be determined.

In conclusion, the recycled asphalt mixtures with high-content RAP-SBS exhibited greater viscoelasticity than control mixtures. For the general situation, 50% RAP-SBS is recommended to incorporate in recycled mixtures to ensure the satisfactory performance of asphalt pavements from the aspect of viscoelasticity. As for pavements with slower design speed, the dosage of RAP-SBS can be considered to increase from 50% to 70% after verifying that other performances meet the specification requirements.

Further investigation into recycled mixtures with hig-content RAP-SBS remains to be explored, including aged performance, low-temperature resistance, and fatigue performance. What is more, the study about the type and dosage of RA embraced in it is of great engineering value.

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