buildings

Article

Performance Evaluation of Soybean Oil/SBR Reclaimed Asphalt and Mixtures

Yu Chen [1], Xiao Li [1,*] and Xiaoge Tian [2]

[1] Faculty of Civil Engineering, Changsha University of Science and Technology, Changsha 410114, China; 202202110136@stu.csust.edu.cn
[2] School of Traffic and Transportation Engineering, Changsha University of Science and Technology, Changsha 410114, China; tianxiaoge@126.com
* Correspondence: lixiao@stu.csust.edu.cn

Abstract: This study evaluated the properties of soybean oil/SBR reclaimed asphalt (SSRA). The optimal preparation method for SSRA was determined. Additionally, the feasibility of the optimal SSRA scheme was verified through asphalt mixture performance tests. With the soybean oil dosage enhanced, the penetration and low-temperature rheological performance of SSRA were improved. The incorporation of soybean oil lowered the softening point, viscosity, and rutting index of aged asphalt. The softening points of SBR-4%+Oil-7.5% and SBR-6%+Oil-7.5% were 79.4 °C and 82.9 °C, respectively. The stiffness modulus of SBR-6%+oil-10% decreased by 35.37%. When the soybean oil dosage was 10% and the SBR dosage was 6% (SBR-6%+oil-10%), the properties of RTFOT+PAV aged asphalt were restored to those of its original state. The splitting tensile strength ratio of the SBR-6%+oil-10% mixture was 89%, with a decrease of 1.5% compared to the original asphalt mixture. The SBR-6%+oil-10% mixture exhibited improved high-temperature and low-temperature service properties. The total deformation of the SBR-6%+oil-10% mixture decreased by 8.43%, while its dynamic stability increased by 22.21%. This degree of improvement compared to the original asphalt mixture was not significant. The rejuvenation of the aged asphalt and mixture performance can mainly be attributed to the soybean oil supplementing the lost lightweight components of the aged asphalt, while SBR supplemented the degraded polymers. Utilizing soybean oil as a rejuvenating asphalt agent facilitates waste material recycling. Furthermore, this study provides a new idea for the recycling of polymer-modified asphalt and reclaimed asphalt pavement.

Keywords: soybean oil; SBR; rejuvenate aged asphalt; rheological properties; mixture

Citation: Chen, Y.; Li, X.; Tian, X. Performance Evaluation of Soybean Oil/SBR Reclaimed Asphalt and Mixtures. *Buildings* **2024**, *14*, 2085. https://doi.org/10.3390/buildings14072085

Academic Editor: Bjorn Birgisson

Received: 29 May 2024
Revised: 23 June 2024
Accepted: 4 July 2024
Published: 8 July 2024

1. Introduction

During its service life, asphalt pavement is exposed to ultraviolet radiation, thermal cycles, oxygen, and water, inducing both physical and chemical changes that lead to aging. Asphalt aging results in the hardening and embrittlement of the mixture. Over time, the volatilization of light fractions within the asphalt makes the material more rigid, reducing its elasticity and flexibility. This increased rigidity makes the pavement more prone to cracking, especially in low-temperature environments. Asphalt aging can severely impact the durability of pavements, significantly shortening their service life [1]. The increasing amount of recycled asphalt mixtures generated due to aging leads to the wastage of aggregates and petroleum and environmental pollution. Therefore, effectively recycling aged asphalt is essential.

1.1. Bio-Oil Recycled Asphalt and Recycled Asphalt Pavement

As a renewable material, bio-oil exhibits an excellent compatibility with asphalt [2]. Bio-oil has shown significant potential in the field of asphalt rejuvenation. Ji utilized waste cooking oil to restore UV-aged asphalt, which decreased the rutting factor of the asphalt [3]. However, bio-oil only replenishes the light fractions in aged asphalt and does not effectively restore its viscoelastic properties. Ye investigated the rejuvenating effect of bio-oil, revealing that the incorporation of 7% bio-oil could reduce the complex shear modulus by approximately 90% [4]. The temperature sensitivity of the rejuvenated asphalt binder was also reduced. Additionally, the feasibility of bio-oil-rejuvenated asphalt was confirmed through molecular dynamics simulations. Lv investigated the rejuvenation of asphalt at various degrees of aging using bio-oil [5]. Bio-oil increased the irrecoverable creep compliance and improved the low-temperature behavior of aged asphalt binder. Muhammad's research demonstrated that bio-oil reduced the carbonyl functional group area in asphalt, validating the rejuvenating effect of bio-oil [6]. Nizamuddin investigated the rejuvenation effect of plastic bio-oil on aged asphalt [7]. The bio-oil induced the softening of the aged asphalt, thereby enhancing its fatigue performance and reducing its stiffness [8].

Peng investigated the rejuvenation effects of different types of bio-oil [2], which indicated that bio-oil decreased the temperature sensitivity of asphalt. Additionally, the rejuvenated asphalt maintained good high-temperature behavior. The microstructure of the rejuvenated asphalt closely matched that of the original asphalt. Chen summarized the rejuvenation effects of vegetable oil on aged asphalt [9]. The good compatibility between the vegetable oil and asphalt ensured the feasibility of rejuvenation. The vegetable oil improved the thermal stability and service performance of the aged asphalt. Chen pointed out that the composite rejuvenation of asphalt with bio-oil and polymers could increase the properties of aged asphalt [10].

Bio-oil can be used not only for asphalt rejuvenation, but also for the rejuvenation of recycled asphalt mixtures, as explored by researchers. Saeed utilized rubber seed oil to regenerate RAP materials, and the results indicated that bio-oil exhibited a favorable viscosity reduction effect on aged asphalt [11]. With an increase in bio-oil dosage, the strength and stiffness of the recycled asphalt mixture gradually decreased. Costa chose cottonseed oil for the regeneration of RAP. The cottonseed oil tended to reduce the fatigue life of its mixture [12]. However, it exhibited significant improvements in resistance to brittle failure and stiffness reduction.

In summary, numerous researchers are currently focused on studying the performance of bio-oil in rejuvenating aged asphalt. Related studies have proven the feasibility of using bio-oil for asphalt rejuvenation. Similarly, bio-oil can also be used directly for the rejuvenation of RAP. By replenishing its light components, bio-oil can rejuvenate the service performance of aged asphalt. Moreover, bio-oil effectively increases aged asphalt's low-temperature performance and fatigue properties. However, the current lack of research on the properties of bio-oil-rejuvenated asphalt mixtures significantly limits their widespread application.

1.2. Polymer Recycled Asphalt and Recycled Asphalt Pavement

The superior performance and environmental advantages of polymers have led to their increasing emphasis regarding reclaimed asphalt and mixtures. Hu investigated the role of polymers in rejuvenated asphalt [13]. Polymers enhanced the toughness and anti-aging properties of the asphalt and reinforced the polymer network structure in aged asphalt. Li investigated the effects of Styrene Butadiene Rubber (SBR) on asphalt [14]. The results indicated that SBR can effectively enhance the low-temperature service properties and fatigue cracking performance of asphalt. Yi utilized epoxy resin polymers to rejuvenate aged asphalt [15]. The results demonstrated that the polymers formed a stable network structure within the aged asphalt, thereby improving its fatigue performance and low-temperature properties. Ren used SBS and rubber to rejuvenate aged asphalt [16]. The polymers significantly enhanced the viscoelastic properties and anti-aging behavior of the aged asphalt. Additionally, the polymer-rejuvenated asphalt mixtures exhibited an excellent road performance. Almusawi utilized polymers as rejuvenators for RAP, resulting in significant improvements in the moisture stability and strength of the rejuvenated asphalt mixtures [17]. Viscione employed the dry method to incorporate polymers into rejuvenated asphalt mixtures [18]. The polymers enhanced the moisture stability and crack resistance of the mixtures.

In summary, polymers enhance the low-temperature service behavior and fatigue resistance by forming new cross-linked network structures within aged asphalt. Moreover, aging reduces the adhesion between asphalt and aggregates, severely impacting moisture sensitivity. Polymers significantly increase the high-temperature properties of aged asphalt binder. In addition, polymers can enhance the adhesion between aged asphalt and aggregates, thereby protecting reclaimed asphalt mixtures from water damage.

1.3. Objective

The aging process of SBS-modified asphalt includes two parts: neat asphalt aging and polymer degradation. In this study, soybean oil and SBR were utilized to reclaim aged SBS-modified asphalt. On the one hand, soybean oil, as a waste product, has essentially the same composition as neat asphalt and contains sufficient lightweight components. Soybean oil can supplement the volatilized lightweight components. On the other hand, SBR can supplement the deteriorated polymers. The feasibility and effects of soybean oil and SBR on aged SBS-modified asphalt and its mixture are worth investigating.

This study evaluated the properties of reclaimed asphalt with different dosages of soybean oil and SBR. The reclaimed asphalt properties mainly include conventional and rheological properties, with indicators such as penetration, softening point, viscosity, rutting index, m-value, and stiffness modulus. The optimal preparation content for SSRA was determined. Additionally, the road properties of the SSRA mixture were tested.

2. Materials and Tests Design

2.1. Materials

The SBS-modified asphalt was purchased from Baoli Bitumen Co., Ltd. in Changsha, China. The dosage of the SBS modifier was 5%. The property indicators of the original asphalt are displayed in Table 1. SBS-modified asphalt was utilized to prepare the aged asphalt. The SBR was purchased from Shanghai Jinlang Rubber & Plastic Technology Co., Ltd., in Shanghai, China. The bio-oil was purchased from Shandong Fenghui New Energy Co., Ltd., in Jinan, China. Soybean oil and SBR were used as regenerating agents, and the performance indicators are described in Tables 2 and 3.

Table 1. Performance indicators of original asphalt.

Index	Results	Technical Requirements
Solubility (%)	99.8	≥99.5
Penetration (0.1 mm)	58.6	60~80
Ductility (cm)	126.4	≥100
Viscosity (60 °C) (Pa·s)	206.5	≥160
Softening point (°C)	79.6	≥46
Flashpoint (°C)	256.2	≥230
	After RTFOT aged	
Mass loss (%)	0.06	≤±0.8
Penetration ratio (%)	65	≥61
Ductility (5 cm/min, 10 °C)	7.9	≥6

Table 2. Performance indicators of soybean oil.

Index	Results
PH	2.76
Flashpoint (°C)	239
Ash dosage (%)	0.07
Aliphatic acid dosage (%)	65.8
Alcohol dosage (%)	5.62
Density (g/cm^3)	0.941

Table 3. Performance indexes of SBR.

Index	Results
Solid dosage (%)	58.4
Viscosity (MPa)	74.8
PH	7.2
Tensile strength (MPa)	24.5
Styrene dosage (%)	26.3

2.2. Preparation of Soybean Oil/SBR Reclaimed Asphalt

The asphalt was then heated at 163 °C for 85 min with a specified air flow rate, preparing rolling thin-film oven test (RTFOT) aged asphalt. Subsequently, the RTFOT aged asphalt was subjected to the PAV aging procedure. The test conditions for PAV were an air pressure of 2.1 MPa ± 0.1 MPa, a test temperature of 100 °C ± 0.5 °C, and an aging time of 20 h. Then, the RTFOT+PAV aged asphalt was prepared.

The soybean oil and RTFOT+PAV aged asphalt were blended first. The soybean oil dosages were 5%, 7.5%, 10%, and 12.5% (mass ratio of aged asphalt) [5]. During this process, the shear temperature was 150 °C. The shear rate was 1500 r/min for 30 min [19]. Soybean oil reduced the viscosity of the aged asphalt, facilitating a better blend of the SBR and aged asphalt. Next, the SBR was blended with the soybean oil reclaimed asphalt. The SBR dosages were 4% and 6% (mass ratio of aged asphalt) [19]. The shear temperature was 160 °C, and the shear rate was 3000 r/min for 30 min [5]. To ensure that the SBR and soybean oil reclaimed asphalt fully dispersed, the asphalt was developed at 160 °C for 60 min. The abbreviations for the soybean oil/SBR reclaimed asphalt (SSRA) are shown in Table 4.

Table 4. Abbreviations of soybean oil/SBR reclaimed asphalt.

SBR Dosage	Soybean Oil	Abbreviation
4%	5%	SBR-4%+Oil-5%
	7.5%	SBR-4%+Oil-7.5%
	10%	SBR-4%+Oil-10%
6%	7.5%	SBR-6%+Oil-7.5%
	10%	SBR-6%+Oil-10%
	12.5%	SBR-6%+Oil-12.5%

2.3. Test Methods

2.3.1. Conventional Properties Tests of Asphalt

Penetration, softening point, viscosity, and segregation tests were performed to assess the conventional performance of the recycled asphalt. The penetration tests were performed at 25 °C [20]. The softening point tests were conducted according to the specification requirements [21]. The viscosity tests were performed at 160 °C. The segregation test was performed to assess the storage stability of the reclaimed asphalt. The compatibility of the soybean oil, SBR, and aged asphalt was investigated. To ensure the accuracy of the test results, three parallel tests were conducted for each conventional properties test.

2.3.2. Rheological Behavior Tests of Asphalt

Temperature sweep and bending beam rheometer (BBR) tests were utilized to reveal the rheological properties of the reclaimed asphalt. The temperature sweep test was conducted at 46–82 °C. The temperature sweep test was conducted in strain-controlled mode. The gap distance and diameter of the specimens were 1 mm and 25 mm, respectively. The tests were performed at a constant loading frequency of 10 rad/s. The RTFOT+PAV aged asphalt samples were also subjected to BBR tests. The BBR tests were performed at −24 °C [22]. To ensure the accuracy of the test results, three parallel tests were conducted for each rheological behavior test.

2.3.3. Performance Tests of Asphalt Mixture

This study conducted road performance tests on the recycled asphalt mixtures. To ensure the accuracy of the test results, three parallel tests were conducted for each mixture test. The wheel tracking test (T 0719-2011) was utilized to verify the high-temperature stability of the mixtures [23,24]. In the laboratory, asphalt mixture specimens with dimensions of 300 mm × 300 mm × 50 mm were prepared. The specimens were kept at 60 °C for 8 h. The dynamic stability of the specimens was calculated using Equation (1).

$$Dynaamic\ stability = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2 \tag{1}$$

where: t_2 is 60 min, t_1 is 45 min, N represents the reciprocating rolling speed (42 times/min), C_1 is the equipment factor (C_1 is 1.0), C_2 is the asphalt mixture size factor (C_2 is 1.0), d_1 is the deformation of the specimen at 45 min, and d_2 is the deformation of the specimen at 60 min.

The freeze–thaw indirect tension test can simulate the process experienced by asphalt roads in freeze–thaw regions, accelerating the damage caused by water to the mixture. After subjecting the specimens to freeze–thaw treatment, the indirect tension strength was tested according to the specifications (T 0729-2011) [24].

The low-temperature service performance of the mixture was tested through the low-temperature bending test (T 0715-2011) [24]. The specimens were prismatic with dimensions of 250 mm × 30 mm × 35 mm. Before testing, the beams were conditioned at −10 °C for 3 h. The data were processed using Equation (2).

$$S_B = \frac{R_B}{\varepsilon_B} \tag{2}$$

where R_B represents the bending tensile strength of the specimen (MPa), ε_B represents the maximum strain of the specimen ($\mu\varepsilon$), and S_B represents the flexural modulus of the specimen (MPa).

2.4. Flow Chart

Figure 1 shows the test flow chart of this study.

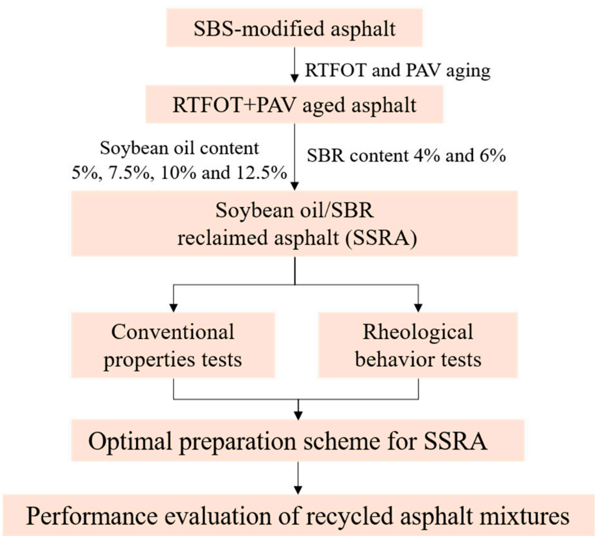


Figure 1. Test flow chart.

3. Soybean Oil/SBR Reclaimed Asphalt Performance Test Results

3.1. Penetration

Penetration is an indicator that reveals the consistency of asphalt. The penetration test results are described in Figure 2.

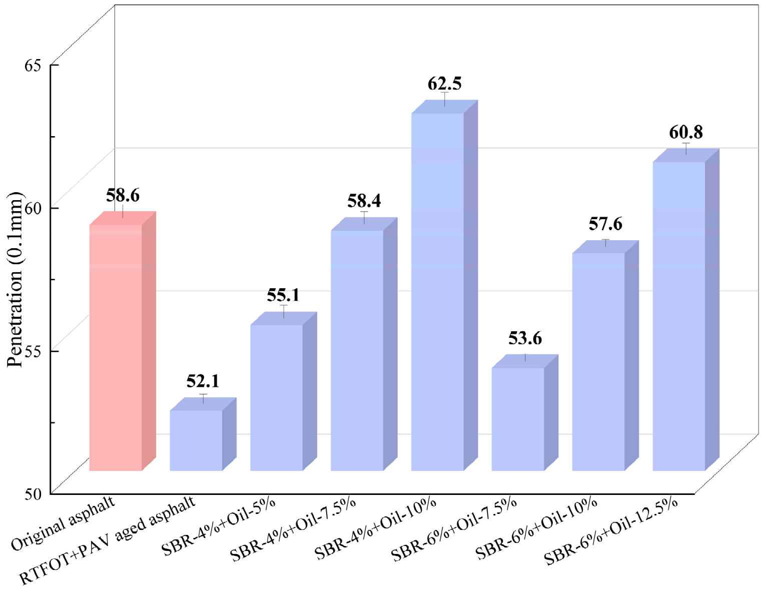


Figure 2. Penetration test results.

After thermo-oxidative aging, the penetration of the original asphalt was reduced from 58.6 to 52.1. Aging causes the lighter components to volatilize and increases the stiffness of the asphalt [25]. From the results of Figure 2, it can be seen that the addition of SBR and soybean oil enhanced its penetration.

When the SBR dosage was 4% and the soybean oil dosage was 5%, 7.5%, and 10%, the penetration of SSRA was 55.1, 58.4, and 62.5, respectively. There was an obvious increase in the penetration of SSRA with an increase in the bio-oil dosage. This was mainly due to the high content of light fractions in the soybean oil, which reduced the stiffness of aged asphalt. This indicated that soybean oil effectively restored the aged asphalt [19].

The penetration of SBR-4%+Oil-5% was still lower than that of the original asphalt. When the SBR dosage was 4% and the soybean oil dosage was 7.5%, the penetration of the RTFOT+PAV aged asphalt could be reclaimed to its original state. However, with the soybean oil dosage increased to 10%, the penetration of SBR-4%+Oil-10% increased by 6.66% compared to the original asphalt.

When the SBR dosage was 6% and the soybean oil dosage was 10%, the penetration of SSRA was 57.6. This showed that the consistency of SBR-6%+Oil-10% was the same as that of the original asphalt. Moreover, SBR-6%+Oil-10% and SBR-4%+Oil-7.5% provided the same degree of penetration recovery for the RTFOT+PAV aged asphalt. When the soybean oil dosage was 10%, the penetration of SBR-6%+Oil-10% and SBR-4%+Oil-10% was 57.6 and 62.5. This indicated that SBR had a reduction effect on the penetration of the reclaimed asphalt.

The analysis of the penetration indicator indicated that the penetration of SBR-4%+Oil-7.5% and SBR-6%+Oil-10% was basically the same as that of the original asphalt samples. As the soybean oil dosage continued to increase, the SSRA penetration would exceed that of the original asphalt. This is due to the fact that the lighter components of bio-oil would reduce the consistency of the aged asphalt [26].

3.2. Softening Point

The softening point, as one of the essential performance indicators of asphalt, can reflect the temperature sensitivity of asphalt, the results of which are illustrated in Figure 3.

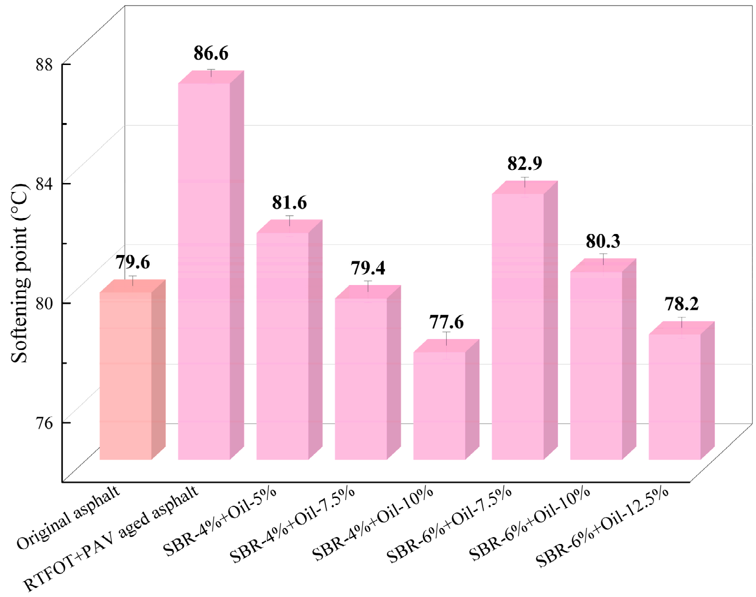


Figure 3. Softening point test results.

The softening point of the RTFOT+PAV aged asphalt increased by 7 °C compared to the original asphalt. The aging process led to the volatilization of lighter components and the degradation of polymers, resulting in an increase in the molecular weight of the asphalt and a higher softening point [27]. Figure 3 illustrates a gradual decrease in the softening point of SSRA with an increasing soybean oil dosage. Specifically, at an SBR dosage of 4%, the softening point of SSRA decreased by 5.8%, 8.31%, and 10.4% with soybean oil dosages of 5%, 7.5%, and 10%, respectively. Soybean oil supplementation replenished the lighter components of the aged asphalt, while bio-oil reduced the temperature sensitivity of the aged asphalt. Notably, at a soybean oil dosage of 7.5%, the softening points of SBR-4%+Oil-7.5% and SBR-6%+Oil-7.5% were 79.4 °C and 82.9 °C, respectively. SBR, acting as a polymer, contributed to enhancing the high-temperature behavior of the RTFOT+PAV aged asphalt [28].

The analysis of the softening point of SSRA demonstrated that the synergistic action of SBR and soybean oil partially restored the softening point. Specifically, when the SBR dosage was 4% and the soybean oil dosage ranged from 7.5% to 10% or when the SBR dosage was 6% and the soybean oil dosage ranged from 10% to 12.5%, the softening point of SSRA closely approximated that of the original asphalt.

3.3. Viscosity

Asphalt viscosity refers to the flowability or consistency of asphalt at a certain temperature. It plays a crucial role in determining the mixing and construction temperatures of asphalt mixtures. Figure 4 displays the viscosity results of the original asphalt, RTFOT+PAV aged asphalt, and various types of SSRA asphalt.

The viscosity of the RTFOT+PAV aged asphalt exhibited a significant increase compared to that of the original asphalt. Thermal oxidative aging resulted in a decrease in the dosage of light components and an increase in the dosage of heavy components in the asphalt [29]. Thermal oxidative aging caused the asphalt to become harder and resulted in an increase in its viscosity. The effect of SBR and soybean oil significantly decreased the viscosity of the RTFOT+PAV aged asphalt. With a continued enhancement in the bio-oil dosage, the soybean oil significantly reduced the viscosity of SSRA. This was consistent with the results of the softening point test. The viscosities of SBR-4%+Oil-10% and SBR-6%+Oil-12.5% were lower than that of the original asphalt.

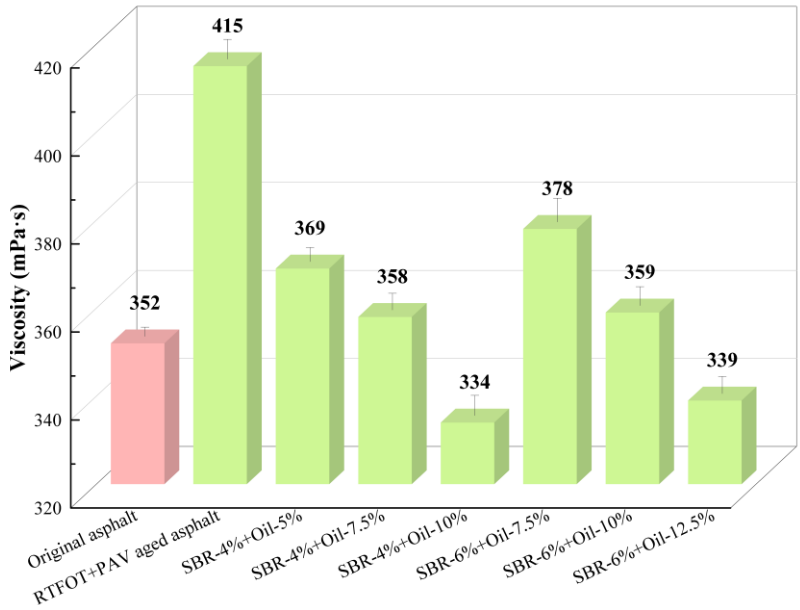


Figure 4. Viscosity test results at 160 °C.

The viscosities of the six types of SSRA prepared in this study did not differ significantly from that of the original asphalt. This finding also suggested that the selected combination of SBR and soybean oil dosage in this study was appropriate for restoring the viscosity of the RTFOT+PAV aged asphalt. The viscosities of SBR-4%+Oil-7.5% and SBR-6%+Oil-10% were essentially consistent with that of the original asphalt.

3.4. Storage Stability Tests

Compatibility reactions between bio-oil and asphalt may occur, resulting in changes in its chemical properties. Certain bio-oils may partially dissolve in asphalt, leading to modifications in its viscosity, flowability, and stability [30]. Therefore, storage stability tests on SSRA must be conducted, and the experimental results are shown in Table 5. Previous studies have indicated that asphalt maintains a good storage stability when the softening point difference is less than 2.5 °C [31].

Table 5. Softening point difference of soybean oil/SBR reclaimed asphalt.

Asphalt Types	Softening Point Difference (°C)	Standard Deviation
Original asphalt	1.3	0.16
PAV aged asphalt	1.8	0.15
SBR-4%+Oil-5%	1.5	0.09
SBR-4%+Oil-7.5%	1.9	0.13
SBR-4%+Oil-10%	2.4	0.18
SBR-6%+Oil-7.5%	1.5	0.13
SBR-6%+Oil-10%	2.1	0.19
SBR-6%+Oil-12.5%	2.9	0.18

The findings presented in Table 5 revealed that, as the soybean oil dosage increased in SSRA, so did the difference in the softening point [30]. Notably, when the soybean oil dosage exceeded 10%, the difference in the softening point of SSRA exceeded 2.5 °C. This suggested that an excessive soybean oil dosage degraded the storage stability of SSRA. However, with a constant soybean oil dosage, the difference in the softening point decreased with an increase in the SBR dosage. The softening point difference between SBR-6%+Oil-10% and SBR-4%+Oil-10% decreased by 0.5 °C. This occurred due to the formation of a cross-linked network structure between the SBR and asphalt, enhancing the storage stability of SSRA [32]. Based on the analysis of the softening point difference of SSRA, it is recommended that the soybean oil dosage should not exceed 10%, as it may otherwise affect the storage stability of the asphalt.

3.5. Temperature Sweep

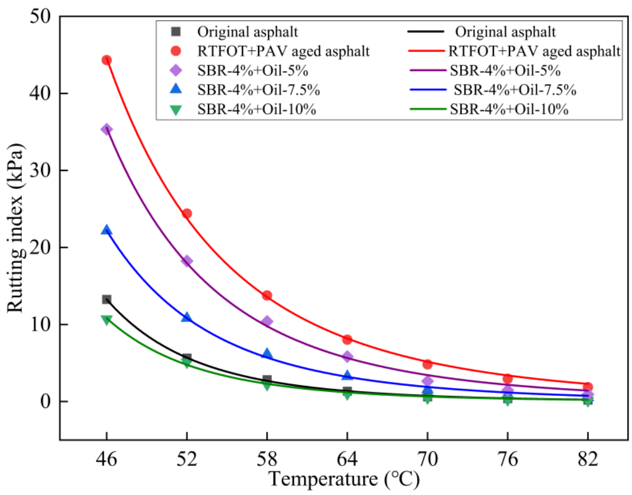
The rutting index of asphalt indicates its tendency to develop ruts under the load of vehicle traffic and heavy loads. The rutting index has frequently been employed to evaluate the properties of asphalt in resisting deformation. Figure 5 depicts the rutting indexes of the various asphalt binders.

Figure 5 illustrates that PAV aging increased the rutting index of the original asphalt. When the temperature was 64 °C, the RTFOT+PAV aged asphalt showed an increase of 6.693 kPa compared to the original asphalt. After aging, the asphalt's molecular chains may experience breaking, cross-linking, or increased rigidity, leading to an enhancement in the rutting factor [33].

The addition of SBR and soybean oil resulted in a reduction in the rutting index of SSRA. This suggested that the SBR and soybean oil contributed to partially restoring the aged asphalt. At a test temperature of 64 °C, with an SBR dosage at 4% and soybean oil dosage at 5%, 7.5%, and 10%, the rutting index of SSRA increased by 1.92 kPa, 4.5 kPa, and −0.33 kPa, respectively. Moreover, with an increase in the dosage of the soybean oil, there was a significant decrease in the rutting index of SSRA. This indicated that the soybean oil significantly restored the performance of the aged asphalt, bringing its high-temperature performance back to the level of the original asphalt [3].

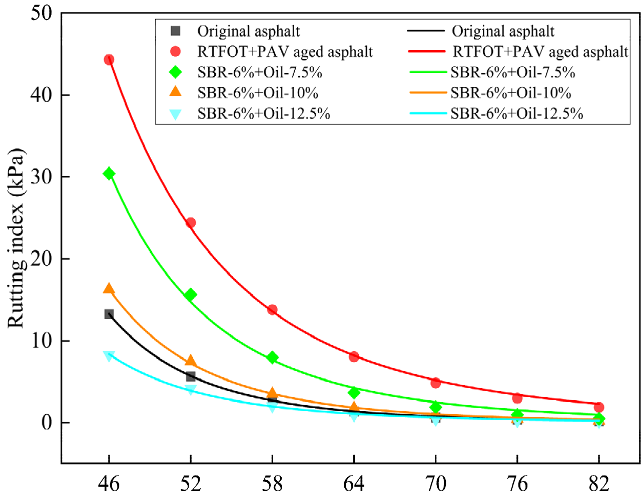
As illustrated in Figure 5a, when the SBR dosage was 4% and the soybean oil dosage was 10%, the rutting index of SSRA was lower than that of the original asphalt. Similarly, as depicted in Figure 5b, the rutting index of SBR-6%+oil-10% was slightly higher than that of the original asphalt, while the rutting index of SBR-6%+oil-12.5% was lower than that of the original asphalt. This observation indicates that a significant amount of soybean oil contributed to a marked reduction in the rutting index of SSRA.

Comparing the rutting indexes of the original asphalt and SSRA, it became apparent that the synergistic influence of soybean oil and SBR played a crucial part in restoring the rutting index of the RTFOT+PAV aged asphalt. The rutting indexes of SBR-4%+oil-10% and SBR-6%+oil-10% were largely consistent with those of the base asphalt.



(**a**) SBR dosage 4%

Figure 5. *Cont.*



(**b**) SBR dosage 6%

Figure 5. Temperature sweep test results.

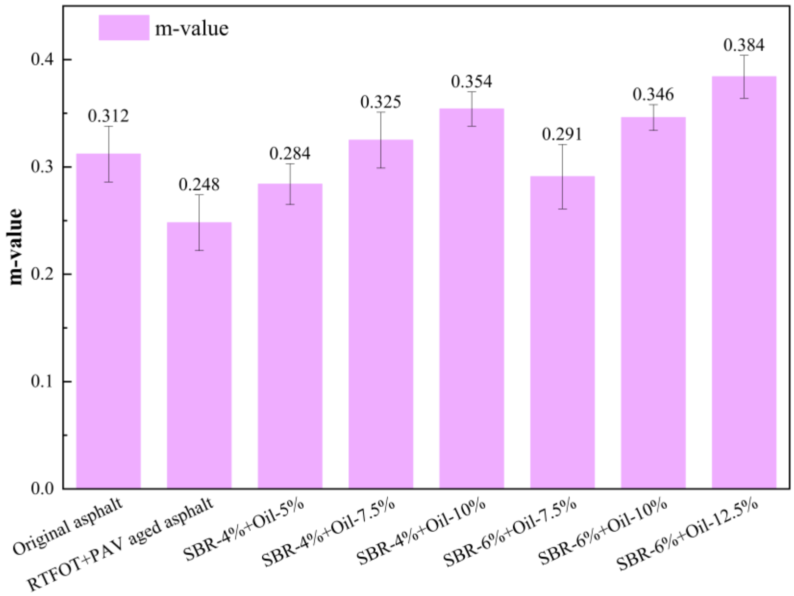
3.6. BBR Test

The BBR is a widely utilized test to assess the deformation performance of asphalt under low-temperature conditions [34]. This test has commonly been employed to assess the low-temperature embrittlement characteristics of asphalt binders in order to evaluate their performance in cold climates. The BBR tests were performed at −24°C, and the results are presented in Figure 6.

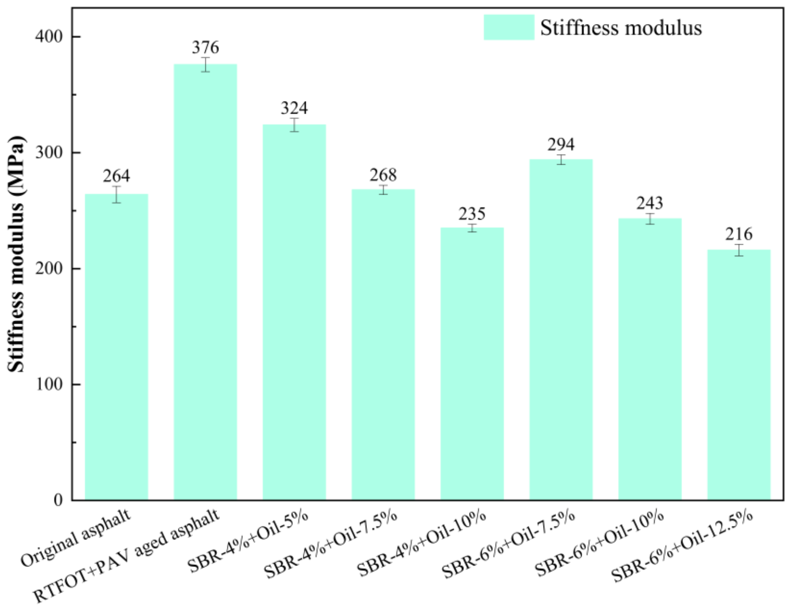
According to the specifications, when asphalt maintains good low-temperature rheological properties at a certain temperature, the m-value must be higher than 0.3 and the stiffness modulus must be lower than 300 MPa [22]. The findings in Figure 6 suggested that the original asphalt retained a better low-temperature performance at −24 °C. However, after PAV aging, the m-value reduced to 0.248, while the stiffness modulus increased to 376 MPa. Under the influence of oxidation, the asphalt experienced oxidation, hardening, and degradation, resulting in an increased brittleness and susceptibility to cracking [35]. PAV aging markedly deteriorated the low-temperature behavior [36].

The findings in Figure 6 describe that the SBR and soybean oil blended with the aged asphalt and enhanced its low-temperature performance. Moreover, with an increase in the soybean oil dosage, the m-value of SSRA gradually rose while the stiffness modulus declined. At an SBR dosage of 4% and soybean oil dosages of 5%, 7.5%, and 10%, the m-value of SSRA increased by 14.5%, 31%, and 42.74%, respectively, compared to the RTFOT+PAV aged asphalt. Likewise, the stiffness moduli of SBR-6%+oil-7.5%, SBR-6%+oil-10%, and SBR-6%+oil-12.5% decreased by 21.8%, 35.37%, and 42.55%, respectively, compared to the RTFOT+PAV aged asphalt. Soybean oil enhanced the low-temperature toughness of the aged asphalt, restoring its low-temperature performance.

Among the six types of SSRA, SBR-4%+oil-7.5%, SBR-4%+oil-10%, SBR-6%+oil-10%, and SBR-6%+oil-12.5% exhibited favorable resistance to low-temperature cracking at −24 °C. This indicated that, when the SBR dosage was 4% and the soybean oil dosage was 7.5% and 10% or when the SBR dosage was 6% and the soybean oil dosage was 10% and 12.5%, the low-temperature performance of the RTFOT+PAV aged asphalt could be restored to its original state.



(**a**) m-value



(**b**) Stiffness modulus

Figure 6. BBR test results.

4. Determining the Optimal Preparation Scheme for Soybean Oil/SBR Reclaimed Asphalt

The optimal preparation method of SSRA was determined by analyzing the conventional and rheological properties of various types of SSRA. Table 6 presents the optimal preparation scheme for SSRA, determined through different asphalt tests.

An analysis of various tests revealed that, when the SBR dosage was 6% and the soybean oil dosage was 10%, the PAV aged asphalt could be restored to a performance level equivalent to that of the original asphalt. Thus, the optimal preparation scheme for SSRA, SBR-6%+oil-10%, was determined.

Table 6. SSRA optimal preparation scheme.

Tests	SSRA Optimal Preparation Scheme
Penetration	SBR-4%+Oil-7.5% and SBR-6%+Oil-10%
Softening point	SBR-4%+Oil-7.5%, SBR-4%+Oil-10%, SBR-6%+Oil-10%, and SBR-6%+Oil-12.5%
Viscosity	SBR-4%+Oil-7.5% and SBR-6%+Oil-10%
Storage stability	SBR-4%+Oil-5%, SBR-4%+Oil-7.5%, SBR-4%+Oil-10%, SBR-6%+Oil-7.5%, and SBR-6%+Oil-10%
Temperature sweep	SBR-4%+oil-10% and SBR-6%+oil-10%
BBR	SBR-4%+Oil-7.5%, SBR-4%+Oil-10%, SBR-6%+Oil-10%, and SBR-6%+Oil-12.5%

5. Soybean Oil/SBR Reclaimed Asphalt Mixture Performance Test Results

5.1. Asphalt Mixture Gradation Design

To verify the rejuvenation effects of soybean oil and SBR, this study conducted asphalt mixture tests on both the original asphalt mixture and the SBR-6%+oil-10% mixture. Moreover, the feasibility of the SBR-6%+oil-10% scheme was further validated. The aggregate gradation type of the asphalt mixture was AC-16, as illustrated in Figure 7. Limestone was selected as the aggregate. The limestone originated from the Shengxing Stone Quarry in Guangxi Province, China. The properties of limestone are shown in Table 7. The asphalt–stone ratio for the different asphalt mixtures was established through the Marshall test [37]. The results regarding the mixing temperature, compaction temperature, and asphalt–stone ratio for the various asphalt mixtures are presented in Table 8.

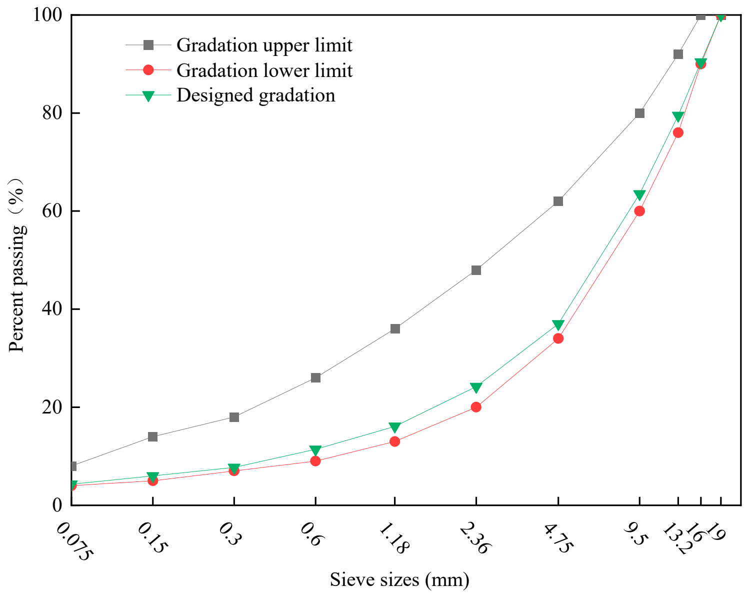


Figure 7. AC-16 mixture gradation.

Table 7. The properties of limestone.

Properties	Test Results	Requirements
Needle-flake particle dosage	3.2%	≤15
Abrasion value	16.3%	≤30
Polished value	59.6%	≥45
Crush value	17.6%	≤26

Table 8. The preparation conditions for different types of mixtures.

Asphalt Types of Mixture	Mixing Temperature	Compaction Temperature	Asphalt-Stone Ratio
Original asphalt	173 °C–175 °C	164 °C–168 °C	4.97
SBR-6%+oil-10%	174 °C–177 °C	165 °C–169 °C	4.93

5.2. Wheel Tracking Test

As traffic loads increase, asphalt pavement becomes more susceptible to plastic deformation, resulting in an increase in rut depth [38]. The rutting resistance of both the SBR-6%+oil-10% and original asphalt mixtures was tested, and the total deformation and dynamic stability are illustrated in Figure 8.

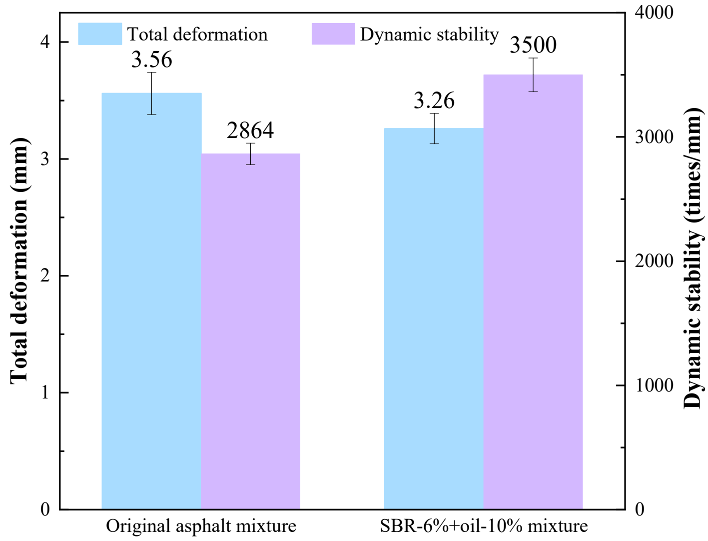


Figure 8. The total deformation and dynamic stability.

As illustrated in Figure 8, the original asphalt mixture exhibited a total deformation of 3.56 mm and a dynamic stability of 2864 times/mm. On the other hand, the SBR-6%+oil-10% mixture demonstrated a total deformation of 3.26 mm and dynamic stability of 3500 times/mm. In comparison, the total deformation decreased by 8.43%, while the dynamic stability increased by 22.21%.

The SBR-6%+oil-10% mixture exhibited improved high-temperature properties compared to the original asphalt mixture. The difference in the high-temperature performance between these two types of asphalt mixtures was minimal. The conclusions drawn from wheel tracking tests on the asphalt mixtures aligned with those obtained from the rheological tests on the asphalt. The synergistic effect of SBR and soybean oil led to an enhanced rejuvenation of the RTFOT+PAV aged asphalt [39,40]. Soybean oil increased the proportion of lighter components in the RTFOT+PAV aged asphalt, while SBR supplemented the polymers that underwent degradation due to the aging process [19].

5.3. Freeze–Thaw Indirect Tension Test

When water infiltrates into asphalt pavement, it can cause a decrease in the adhesion behavior of asphalt, leading to a reduced pavement strength and stiffness [41]. Furthermore, the aging process can also decrease the adhesion property of asphalt. Therefore, evaluating the water stability of recycled asphalt mixtures is of practical significance. Freeze–thaw splitting tests were utilized to assess the moisture sensitivity of the mixture, with the results depicted in Figure 9.

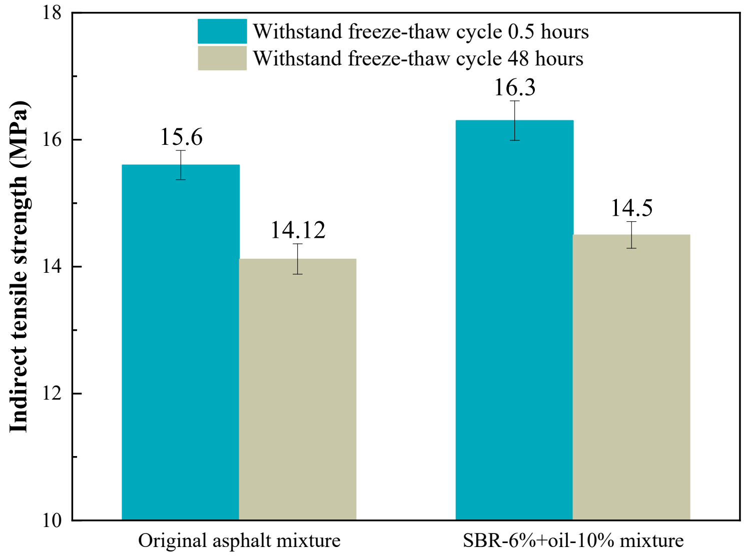


Figure 9. Freeze–thaw indirect tension test results.

After immersing the asphalt mixtures in water for 0.5 h, the indirect tension strength of the original asphalt mixture was 15.6 MPa. Meanwhile, the strength of the SBR-6%+oil-10% mixture was 16.3 MPa, reflecting an increase of 0.8 MPa compared to the original asphalt mixture. After 48 h of immersion in water, there was a notable decrease in the strength [42]. The strength of the original asphalt mixture was 14.12MPa, with a splitting tensile strength ratio of 90.5%. However, the splitting tensile strength ratio of the SBR-6%+oil-10% mixture was 89%. The splitting tensile strength ratios of these two asphalt mixtures were essentially the same. This suggested that the moisture sensitivity of the SBR-6%+oil-10% mixture was essentially equivalent to that of the original asphalt mixture.

5.4. Low-Temperature Bending Test

When there is a sudden drop in temperature, if the thermal stress generated within the asphalt surface layer does not relax promptly, exceeding the tensile strength of the asphalt layer, it may lead to fracture. Low-temperature bending tests were performed at −10 °C to assess the low-temperature performance of the mixtures, and the results are presented in Table 9.

Table 9. The bending test results.

Mixture Types	Parallel Specimens	R_B/MPa	Average Value /MPa	$\varepsilon_B/\mu\varepsilon$	Average Value /$\mu\varepsilon$	S_B/MPa	Average Value /MPa
Original asphalt mixture	1	7.16	7.23	2367	2423	3025	2984
	2	7.23		2446		2956	
	3	7.29		2456		2968	
SBR-6%+oil-10% mixture	1	8.19	8.25	2648	2724	3093	3028
	2	8.21		2759		2976	
	3	8.34		2765		3016	

The failure flexural tensile strength of the original asphalt mixture was 7.23 MPa, while that of the SBR-6%+oil-10% mixture was 8.25 MPa, representing an increase of 14.1% in contrast with the original asphalt mixture. The failure strains of the original asphalt mixture and the SBR-6%+oil-10% mixture were 2423 με and 2724 με, respectively. The flexural moduli of bending of the original asphalt mixture and the SBR-6%+oil-10% mixture were 2984 MPa and 3028 MPa, respectively. Both the failure flexural tensile strength and failure strain of the SBR-6%+oil-10% mixture were improved compared to the original asphalt mixture, indicating a significant increase in low-temperature behavior. This could be attributed to the soybean oil increasing the lighter components proportion in the recycled asphalt, thereby increasing the oil dosage ratio in the SBR-6%+oil-10% mixture [43]. Changes in the asphalt components enhanced the low-temperature service properties of the SBR-6%+oil-10% mixture [4,44].

6. Conclusions

This study explored the regeneration effects of soybean oil and SBR. The optimal rejuvenation method for RTFOT+PAV aged asphalt was determined based on performance test results. Moreover, mixture road properties tests were conducted to validate the feasibility of the optimal rejuvenation method for aged asphalt.

1. With an increase in the soybean oil dosage, the penetration of SSRA gradually increased, while high-temperature performance indicators such as the softening point, viscosity, and rutting index gradually decreased. The softening points of SBR-4%+Oil-7.5% and SBR-6%+Oil-7.5% were 79.4 °C and 82.9 °C, respectively. Soybean oil supplemented the aged asphalt with lighter components, significantly restoring its low-temperature performance. The stiffness modulus of SBR-6%+oil-10% decreased by 35.37%.
2. By comparing the performances of six different kinds of SSRA, it was found that when the soybean oil dosage was 10% and the SBR dosage was 6%, the PAV aged asphalt could be rejuvenated to its original state. Soybean oil supplemented the volatilized lightweight components. SBR supplemented the deteriorated polymers.
3. Mixture tests were conducted on SBR-6%+oil-10% and original asphalt. The results indicated that the SBR-6%+oil-10% mixture exhibited improved high-temperature and low-temperature service properties. In comparison, the total deformation of the SBR-6%+oil-10% mixture decreased by 8.43%, while its dynamic stability increased by 22.21%. However, this degree of improvement compared to the original asphalt mixture was not significant. The splitting tensile strength ratio of the SBR-6%+oil-10% mixture was 89%, which was reduced by 1.5% compared to the original asphalt mixture.
4. The utilization of soybean oil as a waste material in rejuvenating asphalt enables waste utilization. Moreover, this study will offer new ideas for polymer-aged asphalt regeneration.
5. The medium properties and fatigue behavior of SSRA will be revealed in future studies. The types of bio-oils are diverse, and their effects on the performance of asphalt are different. In the future, we will evaluate the rejuvenation effects of different types of bio-oils on aged asphalt to determine the optimal type and dosage of bio-oil for asphalt rejuvenation.

Author Contributions: Conceptualization, X.L.; Methodology, X.T.; Writing—original draft, Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The author declare no conflicts of interest.

References

1. Lv, S.; Tan, L.; Peng, X.; Hu, L.; Borges Cabrera, M. Experimental investigation on the performance of bone glue and crumb rubber compound modified asphalt. *Constr. Build. Mater.* **2021**, *305*, 124734. [CrossRef]
2. Peng, X.; Xie, N.; Xia, C.; Zhou, X.; Zhao, P.; Ma, S.; Zhang, C.; Lv, S. Laboratory evaluation of different bio-oil recycled aged asphalts: Conventional performances and microscopic characteristics. *J. Clean. Prod.* **2023**, *428*, 139442. [CrossRef]
3. Ji, H.; Li, B.; Li, X.; Han, J.; Liu, D.; Dou, H.; Fu, M.; Yao, T. Waste cooking oil as a sustainable solution for UV-aged asphalt binder: Rheological, chemical and molecular structure. *Constr. Build. Mater.* **2024**, *420*, 135149. [CrossRef]
4. Ye, Q.; Yang, Z.; Lv, S.; Jin, J.; Zhang, S. Study on components selection and performance of bio-oil based asphalt rejuvenator based on softening and asphaltene deagglomeration effect. *J. Clean. Prod.* **2023**, *419*, 138238. [CrossRef]

5. Lv, S.; Liu, J.; Peng, X.; Liu, H.; Hu, L.; Yuan, J.; Wang, J. Rheological and microscopic characteristics of bio-oil recycled asphalt. *J. Clean. Prod.* **2021**, *295*, 126449. [CrossRef]
6. Zahoor, M.; Nizamuddin, S.; Madapusi, S.; Giustozzi, F. Recycling asphalt using waste bio-oil: A review of the production processes, properties and future perspectives. *Process Saf. Environ. Prot.* **2021**, *147*, 1135–1159. [CrossRef]
7. Nizamuddin, S.; Baloch, H.A.; Jamal, M.; Madapusi, S.; Giustozzi, F. Performance of waste plastic bio-oil as a rejuvenator for asphalt binder. *Sci. Total Environ.* **2022**, *828*, 154489. [CrossRef] [PubMed]
8. Girimath, S.; Singh, D. Effects of bio-oil on performance characteristics of base and recycled asphalt pavement binders. *Constr. Build. Mater.* **2019**, *227*, 116684. [CrossRef]
9. Chen, C.; Lu, J.; Ma, T.; Zhang, Y.; Gu, L.; Chen, X. Applications of vegetable oils and their derivatives as Bio-Additives for use in asphalt binders: A review. *Constr. Build. Mater.* **2023**, *383*, 131312. [CrossRef]
10. Peng, X.; Yuan, J.; Wu, Z.; Lv, S.; Zhu, X.; Liu, J. Investigation on strength characteristics of bio-asphalt mixtures based on the time–temperature equivalence principle. *Constr. Build. Mater.* **2021**, *309*, 125132. [CrossRef]
11. Saeed, S.M.; Sutanto, M.H.; Napiah, M.; Usman, A.; Batari, A.; Aman, M.Y.; Aliyu Yaro, N.S. Optimization of rubber seed oil content as bio-oil rejuvenator and total water content for cold recycled asphalt mixtures using response surface methodology. *Case Stud. Constr. Mater.* **2021**, *15*, e00561. [CrossRef]
12. da Costa, L.F.; de Medeiros Melo Neto, O.; de Macêdo, A.L.F.; de Figueiredo Lopes Lucena, L.C.; de Figueiredo Lopes Lucena, L. Optimizing recycled asphalt mixtures with zeolite, cottonseed oil, and varied RAP content for enhanced performance and circular economy impact. *Case Stud. Constr. Mater.* **2024**, *20*, e02707. [CrossRef]
13. Hu, M.; Sun, D.; Hofko, B.; Sun, Y.; Mirwald, J.; Xu, L. Multiscale optimization on polymer-based rejuvenators for the efficient recycling of aged high-viscosity modified asphalt: Molecular dynamics simulation and experimental analysis. *J. Clean. Prod.* **2024**, *449*, 141736. [CrossRef]
14. Li, Q.; Zhang, H.; Chen, Z. Improvement of short-term aging resistance of styrene-butadiene rubber modified asphalt by Sasobit and epoxidized soybean oil. *Constr. Build. Mater.* **2021**, *271*, 121870. [CrossRef]
15. Yi, X.; Wong, Y.D.; Chen, H.; Fan, Y.; Yang, J.; Huang, W.; Wang, H. Influence of epoxy resin polymer on recycled asphalt binder properties. *Constr. Build. Mater.* **2023**, *398*, 132549. [CrossRef]
16. Ren, S.; Liu, X.; Wang, H.; Fan, W.; Erkens, S. Evaluation of rheological behaviors and anti-aging properties of recycled asphalts using low-viscosity asphalt and polymers. *J. Clean. Prod.* **2020**, *253*, 120048. [CrossRef]
17. Almusawi, A.; Shoman, S.; Lupanov, A.P. Assessment of the effectiveness and the initial cost efficiency of hot recycled asphalt using polymer modified bitumen. *Case Stud. Constr. Mater.* **2023**, *18*, e02145. [CrossRef]
18. Viscione, N.; Veropalumbo, R.; Oreto, C.; Biancardo, S.A.; Abbondati, F.; Russo, F. Additional procedures for characterizing the performance of recycled polymer modified asphalt mixtures. *Measurement* **2022**, *187*, 110238. [CrossRef]
19. Li, Y.; Ge, D.; Ju, Z.; Lv, S.; Xue, Y.; Xue, Y.; Peng, L. Study on Performance and Mechanism of SBR and Bio-Oil Recycled SBS Modified Asphalt. *Polymers* **2022**, *14*, 5096. [CrossRef]
20. *AASHTO T 49-15*; Standard Method of Test for Penetration of Bituminous Materials. American Association of State Highway and Transportation Officials: Washington, DC, USA, 2015.
21. *AASHTO T 53-09*; Standard Method of Test for Softening Point of Bitumen (Ring-and-Ball Apparatus). American Association of State Highway and Transportation Officials: Washington, DC, USA, 2013.
22. *AASHTO T 313-19*; Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR). American Association of State Highway and Transportation Officials: Washington, DC, USA, 2019.
23. Eisa, M.S.; Mohamady, A.; Basiouny, M.E.; Abdulhamid, A.; Kim, J.R. Mechanical properties of asphalt concrete modified with carbon nanotubes (CNTs). *Case Stud. Constr. Mater.* **2022**, *16*, e00930. [CrossRef]
24. *JTG E20—2011*; Standard Test Methods of Bitumen and Bituminous Mixture. China Communications Press: Beijing, China, 2011.
25. Zhang, R.; You, Z.; Wang, H.; Chen, X.; Si, C.; Peng, C. Using bio-based rejuvenator derived from waste wood to recycle old asphalt. *Constr. Build. Mater.* **2018**, *189*, 568–575. [CrossRef]
26. Wang, L.; Si, B.; Han, X.; Yi, W.; Li, Z.; Zhang, A. Study on the effect of red mud and its component oxides on the composition of bio-oil derived from corn stover catalytic pyrolysis. *Ind. Crops Prod.* **2022**, *184*, 114973. [CrossRef]
27. Hu, M.; Ling, S.; Sun, D.; Lu, T.; Ma, J.; Sun, Y. A sustainable high-viscosity modified asphalt modified with multiple anti-aging agents: Micro-chemical analysis and macro-rheological characterization. *Constr. Build. Mater.* **2022**, *339*, 127701. [CrossRef]
28. Lu, C.; Zheng, M.; Gao, Y.; Ding, X.; Zhang, W.; Chen, W. Study of long-term skid and wear resistance of waterborne epoxy resin-SBR compound modified emulsified asphalt microsurfacing. *J. Appl. Polym. Sci.* **2023**, *141*, e54937. [CrossRef]
29. Wang, Q.; Li, S.; Wu, X.; Wang, S.; Ouyang, C. Weather aging resistance of different rubber modified asphalts. *Constr. Build. Mater.* **2016**, *106*, 443–448. [CrossRef]
30. Sun, G.; Li, B.; Sun, D.; Zhang, J.; Wang, C.; Zhu, X. Roles of aging and bio-oil regeneration on self-healing evolution behavior of asphalts within wide temperature range. *J. Clean. Prod.* **2021**, *329*, 129712. [CrossRef]
31. Kong, P.; Xu, G.; Fu, L.; Feng, H.; Chen, X. Chemical structure of rubber powder on the compatibility of rubber powder asphalt. *Constr. Build. Mater.* **2023**, *392*, 131769. [CrossRef]
32. Dong, D.; Huang, X.; Li, X.; Zhang, L. Swelling process of rubber in asphalt and its effect on the structure and properties of rubber and asphalt. *Constr. Build. Mater.* **2012**, *29*, 316–322. [CrossRef]

33. Xiao, M.M.; Fan, L. Ultraviolet aging mechanism of asphalt molecular based on microscopic simulation. *Constr. Build. Mater.* **2022**, *319*, 126157. [CrossRef]
34. Li, S.; Xu, W.; Zhang, F.; Wu, H. A study on the rheological properties and modification mechanism of graphene oxide/polyurethane/SBS-modified asphalt. *PLoS ONE* **2022**, *17*, e0262467. [CrossRef]
35. Chaihad, N.; Karnjanakom, S.; Abudula, A.; Guan, G. Zeolite-based cracking catalysts for bio-oil upgrading: A critical review. *Resour. Chem. Mater.* **2022**, *1*, 167–183. [CrossRef]
36. Daryaee, D.; Ameri, M.; Mansourkhaki, A. Utilizing of waste polymer modified bitumen in combination with rejuvenator in high reclaimed asphalt pavement mixtures. *Constr. Build. Mater.* **2020**, *235*, 117516. [CrossRef]
37. Xu, J.; Luo, X.; Qiu, X.; Hu, G. Wavelet and fractal analysis of acoustic emission characteristic of fatigue damage of asphalt mixtures. *Constr. Build. Mater.* **2022**, *349*, 128643. [CrossRef]
38. Zhang, C.; Yu, H.; Zhu, X.; Yao, D.; Peng, X.; Fan, X. Unified Characterization of Rubber Asphalt Mixture Strength under Different Stress Loading Paths. *J. Mater. Civ. Eng.* **2024**, *36*, 04023498. [CrossRef]
39. Vamegh, M.; Ameri, M.; Chavoshian Naeni, S.F. Experimental investigation of effect of PP/SBR polymer blends on the moisture resistance and rutting performance of asphalt mixtures. *Constr. Build. Mater.* **2020**, *253*, 119197. [CrossRef]
40. Zeng, M.; Tian, W.; Zhu, Y. Study on performance of castor oil bio asphalt blended asphalt mixture. *J. Hunan Univ.* **2017**, *44*, 177–182.
41. Asadi Azadgoleh, M.; Modarres, A.; Ayar, P. Effect of polymer modified bitumen emulsion production method on the durability of recycled asphalt mixture in the presence of deicing agents. *Constr. Build. Mater.* **2021**, *307*, 124958. [CrossRef]
42. Chen, S.; Gong, F.; Ge, D.; You, Z.; Sousa, J.B. Use of reacted and activated rubber in ultra-thin hot mixture asphalt overlay for wet-freeze climates. *J. Clean. Prod.* **2019**, *232*, 369–378. [CrossRef]
43. Kabir, S.F.; Mousavi, M.; Fini, E.H. Selective adsorption of bio-oils' molecules onto rubber surface and its effects on stability of rubberized asphalt. *J. Clean. Prod.* **2020**, *252*, 119856. [CrossRef]
44. Liao, M.; Liu, Z.; Gao, Y.; Liu, L.; Xiang, S. Study on UV aging resistance of nano-TiO_2/montmorillonite/styrene-butadiene rubber composite modified asphalt based on rheological and microscopic properties. *Constr. Build. Mater.* **2021**, *301*, 124108. [CrossRef]