Hindawi
Advances in Materials Science and Engineering
Volume 2022, Article ID 8287460, 11 pages
https://doi.org/10.1155/2022/8287460

Research Article

Research on Rejuvenation of Styrene-Butadiene-Styrene Block Copolymer Modified Asphalt with Rejuvenating Agent Based on Pre-Mixing Method

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Received 23 May 2022; Revised 26 June 2022; Accepted 11 July 2022; Published 11 August 2022

Academic Editor: Yu Chen

The traditional addition method of rejuvenating agent used in the laboratory is inconsistent with the actual situation of the project, which reduces the reliability of the test results. In this paper, the way of premixing rejuvenating agent and Reclaimed Asphalt Pavement (RAP) and extracting asphalt binder is selected, and the modification effect, mechanism, and optimal content of rejuvenating agent on Styrene-Butadiene-Styrene Block Copolymer (SBS) modified asphalt are studied. In this paper, the asphalt in RAP is recycled and restored with different content of regenerant, and the conventional technical performance and Performance Graded (PG) grade of regenerated asphalt was tested. The composite equation of regenerated viscosity of SBS-modified asphalt was analyzed, and the pavement performance of regenerated SBS-modified asphalt mixture with different content of rejuvenating agent and RAP was tested, such as high-temperature stability, low-temperature crack resistance, and water stability. Finally, the determination method of the optimal content of rejuvenating agent was discussed. The results show that it is reliable to predict the viscosity, penetration, and softening point of regenerated asphalt by viscosity logarithmic composite equation. The content of rejuvenating agent has a certain influence on the PG classification of SBS-modified asphalt, which is mainly reflected in the low-temperature critical temperature. There is a certain content of rejuvenating agent to make the high-temperature stability of regenerated SBS-modified asphalt mixture reach the maximum. When the content of rejuvenating agent reaches a certain value, the low-temperature crack resistance and water stability of regenerated SBS-modified asphalt mixture no longer increase significantly with the increase of the content of regenerant. Using the three-level determination method of the optimal content of rejuvenating agent proposed in this paper, the optimal content and reasonable content range of rejuvenating agent can be obtained, which makes the technical performance of regenerated asphalt, PG grade, and the pavement performance of regenerated SBS-modified asphalt mixture meet the specification requirements.

1. Introduction

The resource utilization of waste asphalt pavement materials has become an irresistible trend, which is determined by China's low-carbon environmental protection concept and relevant policies [1–3]. China has started the research work related to RAP since the 1990s and carried out the central plant hot rejuvenation technology on the Guangfo free-way in 2003. After 2010, the plant mixing hot rejuvenation technology began to be popularized and applied on a large scale, and the mixing rate of RAP generally remained at 20%–30% [4, 5], which was similar to the current 20% mixing amount of RAP in the United States, but far from the average 45% RAP utilization rate in Japan [1, 6].

There are two main methods of RAP rejuvenation. One is to mix new asphalt with RAP to regenerate and restore the old asphalt. The second is to use a rejuvenating agent to regenerate and recover the old asphalt in RAP. However, no matter which method is used, the recovery of SBS-modified asphalt is more difficult than that of matrix asphalt due to the complex material composition and spatial network structure. Researchers have done a lot of work in the field of

SBS-modified asphalt rejuvenation and recovery. For example, Zhang et al. [7] used polysulfide regenerator SBS-modified asphalt for performance recovery and found that polysulfide can effectively enhance its rheological properties. In addition, a variety of asphalt regenerants have been applied to the performance recovery of SBS-modified asphalt, which have achieved good results. For example, mixed rejuvenating agent material composed of new asphalt and rejuvenating agent [8], composite rejuvenating agent composed of multiple regenerants with complementary properties [9], biological regenerants such as tung oil and soybean oil [10–12]. In terms of performance recovery evaluation methods of SBS-modified asphalt, generally, the asphalt in RAP is extracted and recovered, and then the performance is recovered with regenerant. Finally, a variety of methods are used to evaluate the performance recovery effect, such as component change analysis [13], fluorescence differential analysis [14, 15], dynamic rheological properties [16–18] attached total reflection imaging in the mid-infrared [19], morphologies and chemical components analysis [20], and interfacial adhesion between aggregate and regenerated SBS-modified asphalt [21]. In addition, many scholars prepare asphalt mixture from regenerated SBS-modified asphalt and then evaluate the rejuvenation effect by testing the technical performance of the mixture [22–25]. These performances include rutting resistance and fatigue cracking performance [26, 27], stress creep recovery [28], compaction performance [29], durability [30], and viscoelasticity [31].

However, there are still many problems in the domestic research on the rejuvenation of waste asphalt by regenerants, mainly in the following aspects:

(1) There is lack of relevant technical standards for regenerants

(2) The rationality of the evaluation of the recovery degree of asphalt performance is in doubt

(3) The research on the relationship between asphalt mixture pavement performance and asphalt rejuvenation effect is not thorough enough

(4) The addition method of the rejuvenating agent in the laboratory is inconsistent with the construction site

The above problems, especially the disconnection between the use of rejuvenating agent and the actual situation, led to some defects in the previous research.

Based on the background, this paper abandons the traditional addition method of rejuvenating agent in the laboratory, adopts the addition method consistent with the construction site, studies the composite equation of regenerated viscosity of SBS-modified asphalt, tests the PG grade of regenerated SBS-modified asphalt, detects the pavement performance and influence law of regenerated SBS-modified asphalt mixture, and puts forward the determination method of the optimal content of regenerant. The purpose is to provide a reference for the performance recovery of waste SBS-modified asphalt mixture with regenerant.

2. Materials and Methods

2.1. Raw Materials. The high-performance asphalt rejuvenating agent used in this paper is produced by Sobute New Materials Co., Ltd. (Nanjing, China). This high-performance asphalt rejuvenating agent can restore the penetration and softening point of the aged asphalt to the original asphalt level, and the low-temperature ductility can be restored by more than 70%. The measured values of its technical indexes are shown in Table 1. The RAP used in this paper is the milling material of AC-16 (Asphalt concrete, Nominal maximum size of aggregate is 16 mm) on the upper layer of a freeway in Gansu. The original asphalt is SBS I-C and the milling speed is 5 m/min. The milled RAP is extracted and screened, and the asphalt content is 4.45%. The grading and coefficient of variation are shown in Table 2. The technical performance of asphalt recovered from RAP is tested, and the test results are given in Table 3. The technical properties of coarse aggregate and fine aggregate in RAP are tested, respectively, and the test results are given in Tables 4 and 5, respectively. The new coarse aggregate used in this paper is basalt, and its technical indexes are shown in Table 4. The new fine aggregate is limestone, and its technical indexes are shown in Table 5. The mineral powder is ground from limestone, the hydrophilic coefficient is less than 1, and the passing rate of 0.075 mm is 92.1%.

Because the coarse aggregate in RAP is limestone, the water absorption is higher than that of basalt. In addition, the basalt aggregate used in this paper has water absorption of 1.7%, which belongs to basalt with high water absorption.

2.2. Experimental Design. In view of the inconsistency between the asphalt rejuvenation method after RAP extraction and the actual situation of the project, this paper uses RAP and asphalt rejuvenating agent to regenerate the mixture, and then tests the performance of the extracted asphalt. The specific method is as follows: preheat the RAP to 110°C, add 0%, 4%, 8%, 12%, and 16% rejuvenating agent (asphalt mass percentage in RAP), mix at 175°C for 180s, and then store it at 150°C for 60 min. The regenerated RAP is extracted, and the obtained regenerated asphalt is tested, including 135°C viscosity, 163°C viscosity, softening point, 5°C ductility, 15°C penetration, 25°C penetration, and 30°C penetration. In addition, the Dynamic Shear Rheometer (DSR) test is carried out on regenerated asphalt, and the test temperatures are 52°C, 58°C, 64°C, 70°C, 76°C, and 82°C, respectively, and Bending Beam Rheometer (BBR) test was carried out for regenerated asphalt at the test temperatures of −16°C, −22°C, and −28°C, to determine its PG grade. AC-16 mix proportion design is carried out by using new aggregate, mineral powder, and the mineral mixture of RAP. The mixing ratio of RAP is 0%, 20%, 40%, and 60% (the percentage of the total mass of mineral mixture and mineral mixture of RAP), and the mixing amount of rejuvenating agent (the percentage of asphalt in rap) is 0%, 4%, 8%, 12%, and 16%. Ensure that the

Table 1: Technical indicators of high-performance asphalt regenerant.

Technical indicators	Measured values
Viscosity at 60°C, Pa·s	5836
Relative density	0.998
Viscosity ratio after RTFOT[1]	0.2
Chemical properties	It has the basic structure of a benzene ring and is soluble in organic solvents, such as ether, carbon tetrachloride, petroleum ether, and other nonpolar solvents.
Flash point, °C	240
Mass loss after RTFOT[1], %	1.28
Appearance description	Black viscous liquid

[1]RTFOT: Rolling Thin Film Oven Test.

Table 2: Gradation and coefficient of variation of RAP.

Mesh size, mm		19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.015
RAP coarse aggregate	Sample 1%	100.0	84.6	80.6	72.1	55.1	29.9	22.3	16.5	12.2	9.4	6.5
		100.0	80.9	79.7	72.2	58.0	30.4	21.5	16.1	11.3	7.9	6.4
	Sample 2%	100.0	96.6	85.4	79.4	62.8	39.9	29.1	20.8	16.8	13.7	10.2
		100.0	91.9	92.4	84.6	68.0	42.8	28.2	23.1	15.1	12.3	9.5
	Sample 3%	100.0	97.8	89.5	78.0	62.0	38.1	24.4	18.7	13.5	11.1	8.3
		100.0	92.1	86.4	77.2	64.6	39.7	26.8	21.7	17.1	12.6	9.2
	Sample 4%	100.0	94.3	92.3	81.2	67.6	45.1	30.1	23.2	15.8	12.0	10.2
		100.0	97.1	93.0	85.2	73.4	46.0	35.1	25.4	19.3	14.5	9.3
	Sample 5	100.0	92.4	92.2	77.4	64.2	43.3	27.2	20.3	15.6	11.9	8.5
		100.0	97.5	89.3	78.0	62.1	40.7	28.9	20.6	13.8	10.6	8.4
	CV%	0.0	6.2	5.6	5.6	8.1	14.0	14.5	14.3	16.0	17.9	16.3
RAP fine aggregate	Sample 6%	100.0	100.0	100.0	96.6	89.5	64.7	38.3	28.8	19.0	14.9	10.8
		100.0	100.0	100.0	97.5	89.9	59.3	43.6	33.5	21.8	16.1	12.8
	Sample 7%	100.0	100.0	100.0	94.8	89.8	48.0	32.0	24.1	18.8	14.6	10.2
		100.0	100.0	100.0	100.0	80.3	49.7	33.6	26.7	18.6	13.9	9.9
	Sample 8%	100.0	100.0	100.0	95.8	86.3	59.6	42.0	29.9	21.8	16.9	12.8
		100.0	100.0	100.0	96.3	82.5	60.5	42.0	32.7	22.4	16.4	13.8
	Sample 9%	100.0	100.0	100.0	99.1	92.2	69.9	50.2	39.1	27.3	17.4	12.9
		100.0	100.0	100.0	99.1	92.2	69.9	50.2	39.1	27.3	17.4	12.9
	Sample 10%	100.0	100.0	100.0	97.0	97.4	68.2	48.1	40.4	25.7	20.4	14.2
		100.0	100.0	100.0	95.6	85.7	56.1	38.8	29.0	20.3	15.8	11.3
	CV%	100.0	100.0	100.0	95.4	87.6	60.4	43.3	29.5	22.2	15.5	11.2

Table 3: Technical indicators of recycled SBS I-C modified asphalt.

Technical indicators	Recycled SBS I-C modified asphalt	Technical indicators	Recycled SBS I-C modified asphalt
Penetration at 25°C, 0.1 mm	39.5	Softening point, °C	72.6
Ductility at 5°C, cm	4.6	Rotational viscosity at 135°C, Pa·s	3.457

Table 4: Technical indicators of coarse aggregate.

Technical indicators	Coarse aggregate in RAP	New coarse aggregate
Crushing value, %	25.6	18.9
Los Angeles abrasion value, %	28.4	22.8
Needle flake, %	11.3	4.2
Adhesion to asphalt	5	5
Water absorption, %	2.9	1.7

gradation of each mixture is the same, and determine the best asphalt aggregate ratio. Dynamic stability (DS), maximum bending tensile strain (ε_B), residual stability (MS$'$), and percentage of residual strength ratio of the freeze-thaw splitting test (TSR) are tested.

3. Compound Equation of Regenerated Viscosity of SBS-Modified Asphalt

3.1. Compound Equation of Regenerated Viscosity. The traditional method of the content selection and rejuvenation

Table 5: Technical indicators of fine aggregate.

Technical indicators	Fine aggregate in RAP	New fine aggregate
Angularity, s	31	45
Sand equivalent, %	—	73.1
Mud content, %	—	0.4

effect evaluation of asphalt rejuvenating agent is generally determined by penetration, ductility, and softening point, and its rationality is still controversial. In recent years, scholars have generally shifted their research focus to the recovery effect of viscosity and conducted a more in-depth study on the viscosity compound equation of regenerated asphalt. It is difficult to establish a general viscosity compound equation of regenerated asphalt because the properties of rejuvenating agent and asphalt are quite different. At present, there are mainly five viscosity compound equations of rejuvenating agent and regenerated asphalt.

Arrhenius compound equation. Based on the material compound theory, regenerated asphalt can be regarded as the compound composition of aged asphalt and regenerant. The viscosity of the compound solution can be expressed by the compound theoretical model proposed by Arrhenius, as shown in (1) [32].

$$lg\eta_m = wlg\eta_s + (1-w)lg\eta_0, \tag{1}$$

where η_m is the viscosity of regenerated asphalt, PA·s; η_s is the viscosity of regenerant, PA·s; η_o is the viscosity of old asphalt, and PA·s; w is the mixing proportion of regenerant, %.

Technical Specification of Construction of Highway Asphalt Pavement (JTG F40-2004. 2004) adopts the compound quadratic logarithm equation of viscosity of regenerated asphalt, as shown in (2) [33].

$$lglg\eta_m = wlglg\eta_s + (1-w)lglg\eta_o, \tag{2}$$

where all symbols have the same meaning as (1).

According to the experimental results, scholars put forward the modified logarithmic viscosity compound formula of regenerated asphalt, as shown in (3) [34].

$$lg\eta_m = w^a lg\eta_s + (1-w)^a lg\eta_o, \tag{3}$$

where a is the viscosity deviation index; other symbols have the same meaning as (1).

According to the different viscosity deviation indexes corresponding to the viscosity differences between old asphalt with different aging degrees and different regenerants, Ding et al. [35] proposed the viscosity compound model of regenerated asphalt with a modified viscosity deviation index as shown in (4) [35].

$$lg\eta_m = w^{lg\eta_0/\eta_s} lg\eta_s + (1-w)^{lg\eta_0/\eta_s} lg\eta_0, \tag{4}$$

where $lg\eta_0/\eta_s$ is the modified viscosity deviation index; other symbols have the same meaning as (1).

Considering the large difference between the viscosity of rejuvenating agent and aging asphalt, Gu et al. [36] proposed the Grunberg Nissan equation to compound the viscosity of regenerated asphalt. The model equation is shown in equation (5) [36].

$$lg\eta_m = wlg\eta_1 + (1-w)lg\eta_2 + w(1-w)G_{12}, \tag{5}$$

where G_{12} is the modified coefficient, which is a function of the viscosity difference between the two liquids; other symbols have the same meaning as (1).

3.2. Comparison and Selection of Compound Equation of Regenerated Viscosity of SBS-Modified Asphalt. The test results of rotation viscosity at 135°C of regenerated asphalt SBS I-C with different content of rejuvenating agents are shown in Table 6. The shear rate is 20 r/min.

Based on the test data and the different models, the viscosity compound equation and the correlation coefficient of regenerated asphalt with rejuvenating agent are calculated. The equations are shown in Table 7.

From the related coefficients of these equations, it can be seen that the order of related coefficients from large to small is: logarithmic compound equation of viscosity, Grunberg–Nissan viscosity compound equation, quadratic logarithmic compound equation of viscosity, Arrhenius compound equation, and modified viscosity deviation index equation. The logarithmic compound equation of viscosity and Grunberg–Nissan viscosity compound model are better than the quadratic logarithmic compound equation of viscosity proposed by the specification. The fitting effect of the quadratic logarithm compound equation of viscosity proposed in the specification is in the middle, which is better than the Arrhenius composite equation. The modified viscosity deviation index equation has the worst effect, which violates the test law. The reason is that the calculated viscosity deviation index is less than 1.0. Only when the viscosity of old asphalt/rejuvenating agent is more than 100 and its viscosity deviation index is more than 1.0, the law that the viscosity of regenerated asphalt decreases with the increase of rejuvenating agent dose can be obtained. Therefore, this compound model has great limitations. The fitting degree of the quadratic logarithm compound equation of viscosity is general, which is attributed to the viscosity of 60°C instead of 135°C.

Therefore, the Logarithmic compound equation of viscosity is recommended to estimate the viscosity, penetration and softening point of regenerated asphalt in this project. The viscosity deviation index a is 0.169. As shown in equations (6) to (8).

$$lg\eta_m = w^{0.169} lg\eta_s + (1-w)^{0.169} lg\eta_o, \tag{6}$$

$$lgP_m = w^{0.169} lgP_s + (1-w)^{0.169} lgP_0, \tag{7}$$

$$T_m = w^{0.169} T_s + (1-w)^{0.169} T_0, \tag{8}$$

where P_m, P_s, and P_0 refer to the penetration of regenerated asphalt, rejuvenating agent, and old asphalt, respectively; T_m,T_s, and T_0 are the softening point of regenerated asphalt, rejuvenating agent and old asphalt, respectively.

Table 6: Test data of rotation viscosity at 135°C of regenerated asphalt with regenerant.

Rejuvenating agent content, %	Rotation viscosity at 135°C, Pa·s					
	0	4	8	12	16	100
Group 1	3.457	2.752	2.006	1.515	1.208	0.722
Group 2	3.426	2.765	2.033	1.556	1.219	0.721
Group 3	3.457	2.814	1.995	1.515	1.225	0.720
Group 4	3.464	2.784	2.003	1.553	1.238	0.734
Group 5	3.436	2.743	2.053	1.550	1.233	0.733
Group 6	3.467	2.734	2.007	1.513	1.220	0.731
Mean value	3.451	2.765	2.016	1.534	1.224	0.727

Table 7: Compound equation of rejuvenation viscosity of rejuvenating agent with different models.

Equation name	Compound equation of viscosity of regenerated asphalt	Related coefficient
Arrhenius compound equation	$lg\eta_m = wlg\eta_s + (1-w)lg\eta_0$	0.949
Quadratic logarithmic compound equation of viscosity	$lglg\eta_m = wlglg\eta_s + (1-w)lglg\eta_o$	0.968
Logarithmic compound equation of viscosity	$lg\eta_m = w^{0.169}lg\eta_s + (1-w)^{0.169}lg\eta_o$	0.993
Modified viscosity deviation index equation	$lg\eta_m = w^{0.681}lg\eta_s + (1-w)^{0.681}lg\eta_o$	0.891
Grunberg–Nissan viscosity compound model	$lg\eta_m = wlg\eta_1 + (1-w)lg\eta_2 - 0.007w(1-w)$	0.979

3.3. Performance Recovery Verification of SBS I-C Modified Asphalt Based on Viscosity Compound Equation. The RAP is regenerated according to the method mentioned in Section 2.2, and then the extracted regenerated SBS I-C modified asphalt is measured for viscosity at 135°C, viscosity at 163°C, softening point, ductility at 5°C, penetration at 15°C, penetration at 25°C, and penetration at 30°C, respectively. The test results are shown in Table 8.

It can be seen from Table 8 that with the increasing content of regenerant, the rotation viscosity at 135°C and 163°C gradually decreased, but the rotation viscosity at 163°C decreased slightly, and the overall downward trend is flat. The measured value of rotation viscosity at 135°C is fitted by the logarithmic compound equation of viscosity, and the related coefficient is large. With the increase of rejuvenating agent content, the penetration at the same temperature shows a rising trend, and the measured values of penetration at different temperatures have a good correlation with the fitting values obtained by the logarithmic composite equation of viscosity. With the increase of rejuvenating agent content, the softening point decreases continuously, and the related coefficient between softening point and rejuvenating agent content is higher by the logarithmic composite equation of viscosity. With the increase of rejuvenating agent content, the ductility at 5°C increases. Due to the complex rejuvenation law, the rejuvenation equation cannot be obtained.

4. PG Grade Analysis of Regenerated SBS I-C Modified Asphalt

The PG Grading Test of regenerated SBS I-C modified asphalt includes the DSR test of regenerated SBS I-C modified asphalt as is, the DSR test of residue after heating in a rotating film oven and the residue detection test of residue after high-temperature pressure aging at 100°C, which are used to simulate three critical stage tests of asphalt binder. The test is described as follows: the dynamic shear modulus (G^*) and phase angle (δ) of asphalt are measured on the dynamic shear rheometer at high temperatures. The residue of the asphalt heated by a rotating film oven is subjected to a dynamic shear test at the high-temperature level. The residue after the film oven is subjected to pressure aging at 100°C and the residue after pressure aging is subjected to a dynamic shear test at room temperature. In addition, the creep stiffness S and creep rate m of asphalt are measured on the bending beam rheometer (BBR) at the minimum temperature level of pavement plus 10°C. The test results are shown in Tables 9 to 12.

The dynamic shear modulus G^* and phase angle δ of asphalt at high-temperature are measured by DSR. The standard value is $G^*/\sin\delta > 1\,kPa$, which represents the basic requirements for transportation, storage, and loading and unloading. The standard value of the dynamic shear test for the residue of asphalt heated by rotating film oven at high temperature is $G^*/\sin\delta > 2.2\,kPa$, which represents the asphalt performance requirements after the short-term aging of asphalt in the process of mixing and paving to prevent rutting. The standard value of the dynamic shear test at room temperature of asphalt residue after PAV at 100°C $G^*\sin\delta < 5000Kpa$, which represents the long-term aging process and simulates the requirements of aging and fatigue performance within the service life of the pavement—preventing fatigue cracking. The creep stiffness S and creep rate m of asphalt are measured on the bending beam rheometer (BBR) at the minimum temperature level of pavement plus 10°C, The standard is $S < 300\,MPa$, $m > 0.3$. If the measurement result is $S > 300$ MPa, the direct tensile test needs to be carried out at the lowest temperature level plus 10°C, and the failure strain is required $\varepsilon_f > 1\%$, $m > 0.3$ to represent whether the asphalt has the performance of resisting the lowest pavement temperature in this area—preventing low-temperature shrinkage cracking. According to the

Table 8: Effect of rejuvenating agent content on regenerated asphalt.

Rejuvenating agent content, %	Ductility at 5°C, cm	Rotation viscosity, Pa.s		Penetration, 0.1 mm			Softening point, °C
		135°C	163°C	15°C	25°C	30°C	
0	4.6	3.451	0.682	20.6	39.5	65.7	72.6
4	24.9	2.765	0.583	22.7	50.3	75.2	59.0
8	32.4	2.016	0.433	30.5	69.3	92.9	55.7
12	34.5	1.534	0.353	36.4	78.1	122.6	54.6
16	35.8	1.224	0.273	45.9	108.1	160.1	44.7
100	—	0.727	—	—	—	—	—

Table 9: Test results of $G^*/\sin\delta$.

Rejuvenating agent content, %		$G^*/\sin\delta$, kPa				
		0	4	8	12	16
Test temperature, °C	52	40.32	29.25	18.75	13.69	9.19
	58	21.70	15.17	10.04	7.63	5.12
	64	12.38	8.98	5.87	4.40	2.70
	70	7.29	5.24	3.31	2.45	1.49
	76	4.30	3.04	1.97	1.38	0.93
	82	1.96	1.40	0.92	0.73	0.44

Table 10: Test results of $G^*/\sin\delta$ after RTFOT.

Rejuvenating agent content, %		$G^*/\sin\delta$, kPa				
		0	4	8	12	16
Test temperature, °C	52	61.68	44.76	27.56	20.40	13.14
	58	31.46	24.27	15.47	10.92	7.38
	64	19.20	13.47	8.28	7.00	3.97
	70	10.79	7.49	4.81	3.46	2.30
	76	6.75	4.77	2.82	2.10	1.46
	82	2.92	2.22	1.48	1.17	0.71

Table 11: Test results of $G^*\sin\delta$.

Rejuvenating agent content, %		$G^*\sin\delta$, kPa				
		0	4	8	12	16
Test temperature, °C	19	2249	5732	8755	9654	9912
	22	1357	3401	6259	6642	7016
	25	796	2546	5127	5629	5315

Table 12: Test results of BBR.

Rejuvenating agent content, %		S, MPa					m				
		0	4	8	12	16	0	4	8	12	16
Test temperature, °C	−12	263	145	105	89	72	0.293	0.34	0.454	0.469	0.523
	−18	328	283	206	178	156	0.251	0.281	0.329	0.394	0.427
	−24	599	497	452	386	324	0.201	0.225	0.266	0.333	0.366

requirements, the PG grading results of regenerated SBS I-C modified asphalt with different contents of the rejuvenating agent are shown in Table 13.

It can be seen from Table 13 that the content of rejuvenating agent has a certain impact on the PG of SBS-modified asphalt, which is mainly reflected in the low-temperature critical temperature. With the gradual increase of the content of regenerant, the low-temperature critical temperature also gradually decreases, indicating that the low-temperature performance of asphalt has been restored

Table 13: PG results.

Rejuvenating agent content, %	High temperature critical temperature, °C	Low temperature critical temperature, °C	PG
0	> 82	−11.0	PG70-10
4	> 82	−16.2	PG70-16
8	78.7	−20.7	PG70-16
12	76.3	−21.9	PG70-16
16	71.8	−23.2	PG70-22

to a great extent. However, it is worth noting that the high-temperature performance will be reduced, but within the scope of use of regenerants involved in this paper, it does not lead to the change of high-temperature grade.

5. Pavement Performance of Regenerated SBS I-C Modified Asphalt Mixture

AC-16 mix proportion design is carried out by using new aggregate, mineral powder, and the mineral mixture of RAP. The mixing ratio of RAP is 0%, 20%, 40%, 60%, and 80% (the percentage of the total mass of mineral mixture and mineral mixture of RAP), and the mixing amount of rejuvenating agent (the percentage of asphalt in RAP) is 0%, 4%, 8%, 12%, and 16%. Ensure that the gradation of each mixture is the same, and determine the best asphalt aggregate ratio, respectively. Dynamic stability (DS), maximum bending tensile strain (ε_B), residual stability (MS'), and percentage of Residual strength ratio of the freeze-thaw splitting test (TSR) are tested.

5.1. Influence of Rejuvenating Agent Content on the Performance of Asphalt Mixture. Figures 1–4 are the DS, ε_B, MS', and TSR test results of AC-16 containing RAP under different content of regenerant. The test temperature of DS is 60°C, the wheel pressure is 0.7 MPa, the frequency of the test wheel is 42 times/min ±1 time/min, and the number of each type of test specimen is 3. The test temperature of ε_B is −10°C ± 0.5°C, the loading frequency is 50 mm/min, and the number of each type of specimen is 3. In the process of MS', a total of 8 Marshall test specimens were prepared for each type of test piece, of which 4 were immersed in 60°C ± 0.5°C water for 30 min to test MS, and the other 4 were immersed in 60°C ± 0.5°C water for 48h to test MS. During the test of TSR, a total of 8 Marshall specimens were prepared for each type of specimen. After fully absorbing water, 4 specimens were placed in an environment of −18°C for 16 h ± 1 h and then kept in the water of 60°C ± 0.5°C for 24 h, finally, they were immersed with the other 4 specimens in the water of 25°C ± 0.5°C for 2 h to test the cleavage strength.

Figure 1 shows that the rejuvenating agent has a certain effect on the DS of the SBS-modified asphalt mixture. With the increase of the content of regenerant, the DS first increases and then decreases, that is, there is an optimal content of rejuvenating agent to maximize the dynamic stability. The description of this law is applicable to any mixture with RAP content. A reasonable content of regenerated asphalt admixture can improve the stability of the asphalt mixture at high temperatures. This phenomenon is closely related to the recovery of the technical indicator of the asphalt by the regenerant. As shown in the test results in Section 3, the rejuvenating agent not only comprehensively recovers the mechanical and pavement performance of the asphalt, but it also reduces the softening point, penetration,

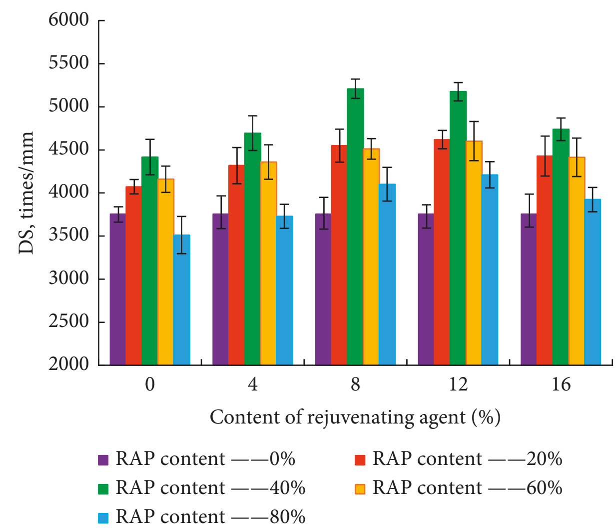

Figure 1: DS test results with different content of regenerant.

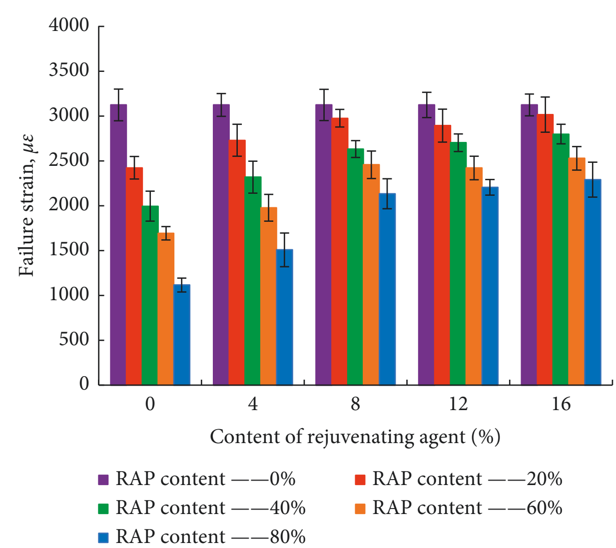

Figure 2: Failure strain test results with different content of regenerant.

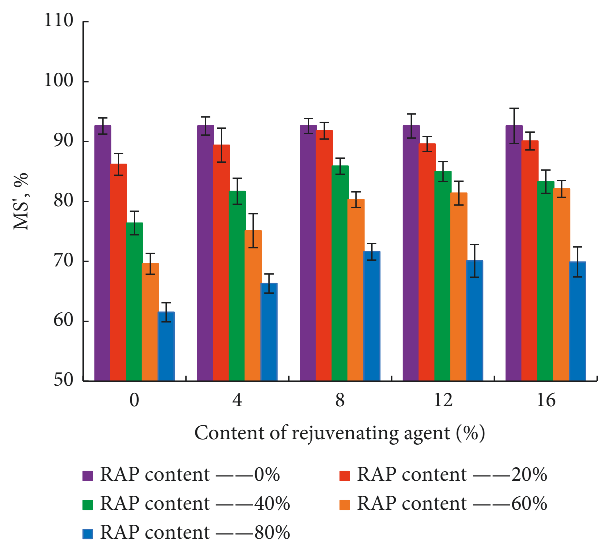

Figure 3: MS′ test results with different content of regenerant.

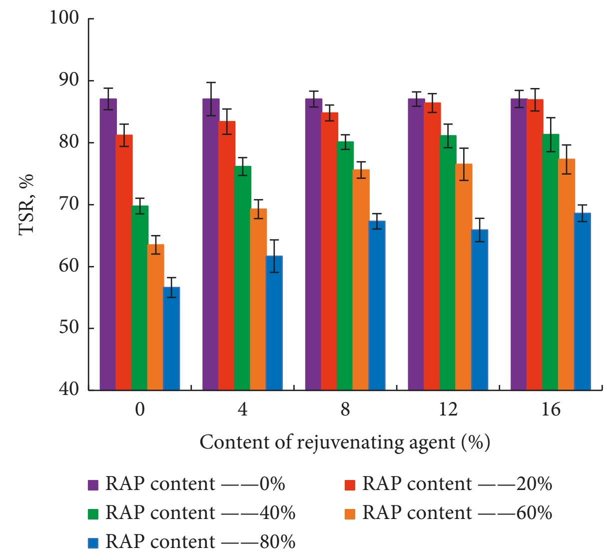

Figure 4: TSR test results with different content of regenerant.

and rotation viscosity of the regenerated asphalt. The greater the content of regenerant, the greater the reduction. Therefore, when the content of rejuvenating agent exceeds a certain value, the DS of the regenerated asphalt mixture begins to decrease.

Figure 2 shows that the rejuvenating agent also has a certain effect on the low-temperature performance of the SBS-modified asphalt mixture. It is shown that the failure strain increases gradually with the increase of rejuvenating agent content, but when the rejuvenating agent content reaches a certain value, the increasing trend of failure strain is no longer obvious. The description of this law is also applicable to the mixture with any RAP content. This shows that a reasonable content of rejuvenating agent can effectively improve the low-temperature crack resistance of the asphalt mixture. At the same time, when the content of rejuvenating agent reaches a certain value, more content will not bring significant improvement in low-temperature crack resistance. Rejuvenating agent can effectively restore the ductility of asphalt, but when its content reaches a certain value, the growth of ductility is no longer obvious, indicating that the continuous recovery of low-temperature performance of regenerated asphalt is no longer obvious, resulting in the failure strain of regenerated asphalt mixture, which increases first and then tends to be stable with the increase of rejuvenating agent content.

Figures 3 and 4 show that the rejuvenating agent also has a certain effect on the water stability of the SBS-modified asphalt mixture. With the increase of rejuvenating agent content, MS′ and TSR gradually increase, but when the rejuvenating agent content reaches a certain value, the increased range is no longer obvious. The description of this law is also applicable to the mixture with any RAP content. This shows that a reasonable content of rejuvenating agent can effectively improve the water stability of the asphalt mixture. At the same time, when the content of rejuvenating agent reaches a certain value, no more content will bring significant improvement in water stability.

5.2. Influence of RAP Content on the Performance of Asphalt Mixture. The content of RAP in asphalt mixture directly determines the utilization rate of RAP. The test results of different RAP content are shown in Figures 5 to 8, which are the relationship among DS, ε_B, MS′, and TSR and RAP content, respectively.

Figure 5 shows that with the increase of the RAP content, the DS of the asphalt mixture increases first and then decreases, and the maximum value is obtained at about 40% of RAP content. This law exists in asphalt mixtures with different rejuvenating agent content. The reason for this rule is related to the high viscosity of asphalt in RAP.

Figures 6 to 8 show that with the continuous increase of RAP content, the failure strain, MS′, and TSR of asphalt mixture are significantly reduced, that is, the addition of RAP leads to the reduction of low-temperature crack resistance and water stability of asphalt mixture. This also provides a certain idea for the determination of the content of rejuvenating agent under a certain RAP content, that is, on the premise of ensuring that the low-temperature resistance type and water stability of regenerated asphalt mixture meet the relevant requirements, it should correspond to the content of rejuvenating agent corresponding to the best value of high-temperature stability as far as possible.

6. Determination of Rejuvenating Agent Content

The idea of determining the optimal content of rejuvenating agent proposed in this paper is described as follows: the first level, with reference to relevant specifications [37], determines the range of rejuvenating agent according to the conventional indexes such as penetration, rotation viscosity, ductility, and softening point of regenerated asphalt, which is recorded as C1. The second level, the range of rejuvenating agent, determines according to the PG grade of regenerated asphalt and the performance of asphalt mixture, which is recorded as C2. The third level, the median value of the

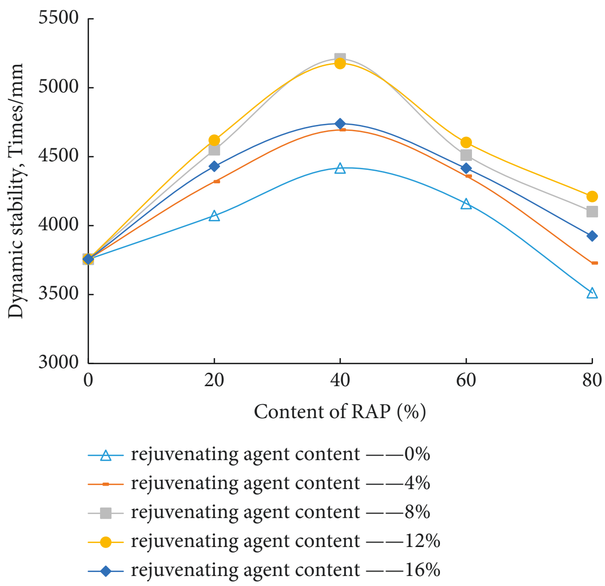

Figure 5: DS test results with different content of RAP.

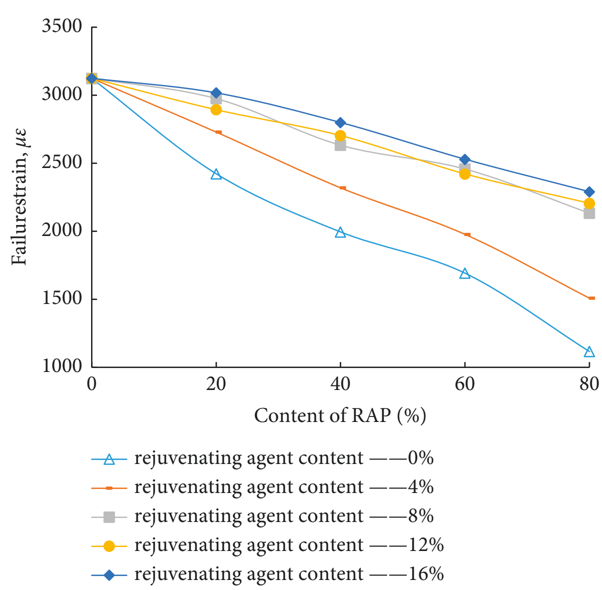

Figure 6: Failure strain test results with different content of RAP.

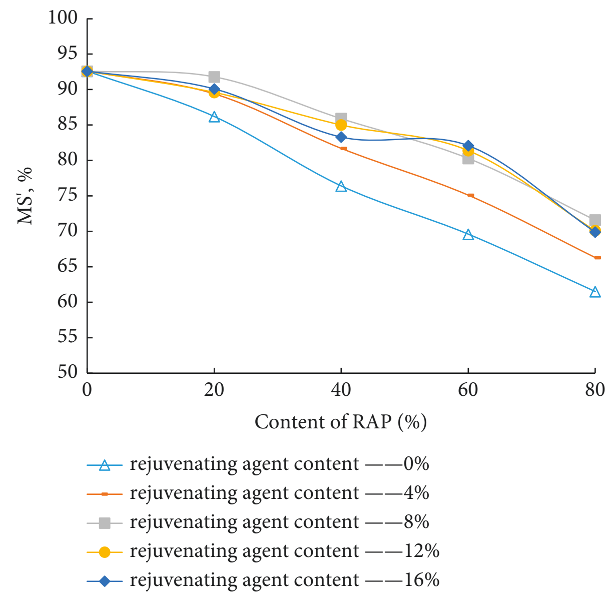

Figure 7: MS′ test results with different content of RAP.

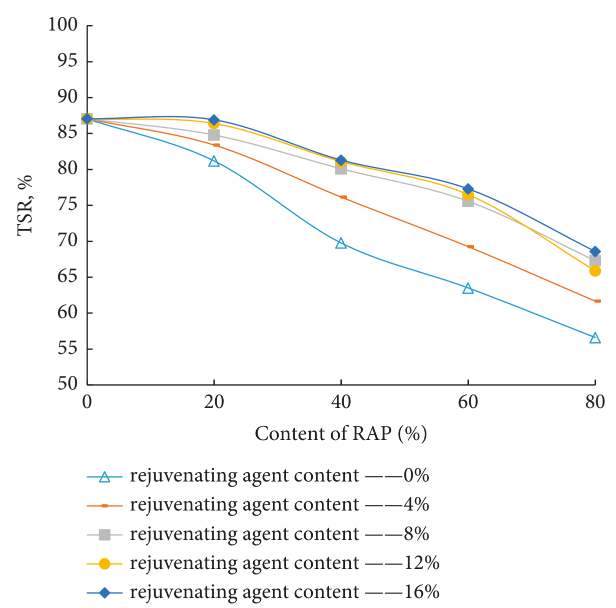

Figure 8: TSR test results with different content of RAP.

common range of C1 and C2, is calculated as the best content, and the best content ±1% is the range of the best content. Referring to Technical Specification of Construction of Highway Asphalt Pavement (JTG F40-2004) [33], this paper takes the technical standard of SBS I-C modified asphalt, the minimum service environment of −16°C, DS ≥ 2800 times/mm, $\varepsilon_B \geq 2500\mu$, MS′ ≥ 85% and TSR ≥80%, the optimal content of rejuvenating agent is determined with the target of RAP content of 40%. Figure 1 is the first level determination diagrammatic sketch of the optimal content of regenerant.

As shown in Figure 9, according to the proposed method for determining the optimal content of regenerant, the range in which the penetration, softening point, ductility, and rotation viscosity meet the specification requirements is solved [37], and the range of C1 is 6.0%–10.9%.

Figure 10 is the second level determination diagrammatic sketch of the optimal content of regenerant.

As shown in Figure 10, according to the proposed method for determining the optimal content of regenerant, the range of PG grade, DS, ε_B, MS′ and TSR that meet the service temperature requirements are solved [37], and the range of C2 is 7.0%–11.8%. Then the common range of C1 and C2 is 7.0%–10.9%.

The third level of the optimal content of rejuvenating agent is determined as follows: the median value of the common range of C1 and C2 is 8.95%, then 8.95% of the content of rejuvenating agent is the optimal content for performance recovery, and 7.95%–9.95% is the optimal content range of regenerant.

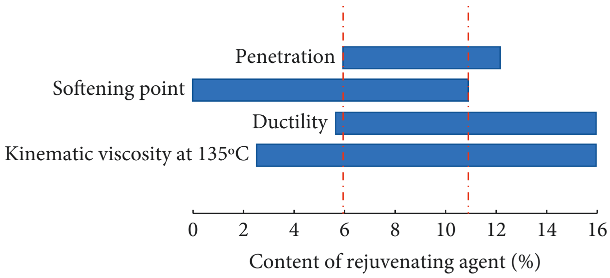

Figure 9: Optimum content of rejuvenating agent (first level).

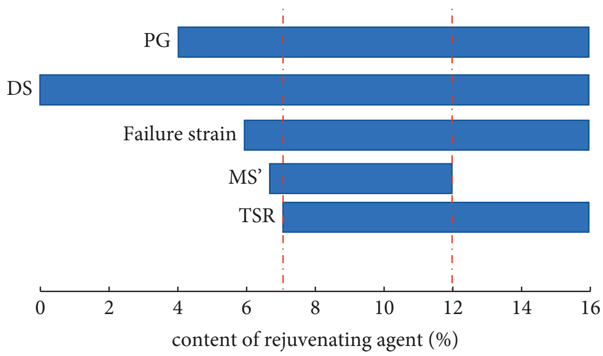

Figure 10: Optimum content of rejuvenating agent (second level).

7. Conclusions

This paper abandons the traditional addition method of rejuvenating agent in the laboratory, adopts the addition method consistent with the construction site, studies the composite equation of regenerated viscosity of SBS-modified asphalt, tests the PG grade of regenerated SBS-modified asphalt, detects the pavement performance and influence law of regenerated SBS-modified asphalt mixture, and puts forward the determination method of the optimal content of regenerant. The main conclusions: it is reliable to predict the viscosity, penetration, and softening point of regenerated asphalt by viscosity logarithmic composite equation. The content of rejuvenating agent has a certain influence on the PG classification of SBS-modified asphalt, which is mainly reflected in the low-temperature critical temperature. There is a certain content of rejuvenating agent to make the high-temperature stability of regenerated SBS-modified asphalt mixture reach the maximum. When the content of rejuvenating agent reaches a certain value, the low-temperature crack resistance and water stability of regenerated SBS-modified asphalt mixture no longer increase significantly with the increase of the content of regenerant. Using the three-level determination method of the optimal content of rejuvenating agent proposed in this paper, the optimal content and reasonable content range of rejuvenating agent that makes the technical performance of regenerated asphalt, PG grade and the pavement performance of regenerated SBS-modified asphalt mixture meet the specification requirements can be obtained.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

The authors thank Key Laboratory Base of New Building Materials and Energy-Efficient Building in Gansu Province for providing necessary instruments and equipment for the test. This work was supported by the Natural Science Foundation of Gansu Province, China, Grant no. 17JR5RA288.

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