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Effect of Blending Behavior on the Performance of Hot Recycled Asphalt Mixtures

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Abstract: Blending behavior is the main factor influencing hot recycled asphalt mixtures' actual and design performance. The following steps were taken to investigate the above issues. Firstly, the component changes of asphalt mixtures were studied by thin-layer chromatography, with flame ionization detection to obtain the mechanism of asphalt aging and recycling. Secondly, according to the difference in the recycled asphalt components, the hot recycled asphalt mixtures were optimized based on the Marshall design method. Lastly, the hot recycled asphalt mixtures for the three mixing processes were prepared using the optimized design method described above. Laboratory tests were conducted to evaluate the correlation between the degree of blending (DoB) and the high-temperature stability, low-temperature crack resistance, water stability, and fatigue performance. The test results indicate that reducing light components (saturates and aromatics) and increasing heavy components (asphaltenes and resins) are the main reasons for asphalt aging, and asphalt recycling is an inverse process. Additionally, the performance of hot recycled asphalt mixtures is improved with an increase in DoB. Specifically, the DoB is only 50% to 60% under a normal mixing process, but by adjusting parameters the DoB will increase to 80% to 90%.

Keywords: hot recycled asphalt mixtures; asphalt component; blending behavior; optimization design; road performance



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1. Introduction

Asphalt pavement hot recycling technology plays a significant role in recycling natural resources, reducing energy consumption, and mitigating carbon emissions to promote sustainable development [1–3]. However, incorporating reclaimed asphalt pavement (RAP) into mixtures leads to variations in load performance when compared to conventional hot mix asphalt [4–6]. Extensive studies [7–9] have indicated that the blending behavior differences between the aged and virgin asphalt during the hot recycling process was a crucial factor influencing recycled asphalt pavement's performance and service life.

In the field of asphalt aging and recycling, a growing body of research focuses on understanding the mechanisms of asphalt recycling from a microscopic perspective [10–12]. Various techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Gel Permeation Chromatography (GPC), Atomic Force Microscopy (AFM), and other analytical tools are being utilized [13–15]. Additionally, molecular dynamics and other methods are employed

to simulate test conditions and determine the blending rate between aged and virgin asphalt. Experimental results have shown a strong correlation between Dynamic Shear Rheometer (DSR) tests and molecular simulation techniques [16–18]. The aged asphalt in RAP has undergone hardening and experienced a decline in road performance due to service life and environmental factors. Extensive studies have identified several factors contributing to asphalt aging, including thermo, oxygen, light, water, and being under the coupled effects of loading [19–21]. Among these factors, thermal-oxidative aging was the primary cause of asphalt aging, occurring throughout the entire service life. Asphalt deterioration was observed under the influence of heating and oxidation. Research findings indicate that the fundamental cause of aging lies in the volatilization or transformation of light components in asphalt into heavier components, increasing asphaltene and resin content [22–24]. However, the current testing methods for determining changes in asphalt components are complex, posing challenges in obtaining quick and accurate measurements of asphalt component content. The previous studies about different asphalt mixtures' aging and recycling are summarized in Table 1.

Table 1. Summary of previous research on asphalt aging and recycling.

Authors	Year	Type of Asphalt	Field of Study	Test Equipment
Sun et al. [25]	2014	SBS modified asphalt	Asphalt aging	GPC
Cong et al. [26]	2015	Regenerated SBS modified asphalt	Asphalt recycling	FTIR, Thin-Layer Chromatography with Flame Ionization Detection (TLC-FID)
Chen et al. [27]	2019	Crumb rubber modified asphalt	Asphalt recycling	FTIR, GPC, AFM, DSR, Bending Beam Rheometer (BBR)
Abdelaziz et al. [28]	2021	Recycled asphalt	Asphalt recycling	Indirect Tensile (IDT)
Yang et al. [29]	2022	High viscosity asphalt	Asphalt aging	DSR, BBR, FTIR, AFM
Schwettmann et al. [30]	2023	Naturally and artificially aged asphalt	Asphalt aging	Pressure Ageing Vessel (PAV), DSR, FTIR

Regarding hot recycled asphalt mixtures, the composition design methods used in most countries were similar to those employed for conventional asphalt mixtures [31–33]. Commonly used methods include the Marshall design method, the Superpave design method, and the Asphalt Institute (AI) design method [34–36]. In a study by Ma et al., laboratory mixing and sieving tests were performed to assess the gradation changes of field-produced hot recycled asphalt mixtures under different conditions [37–39]. The findings revealed that the fine particles within the RAP aggregates were not adequately separated from the original aggregates, resulting in decreased mixture density and increased void content [40–42]. Other relevant studies have demonstrated that the role of mineral particles and asphalt in RAP differs from that in conventional mixtures, leading to deviations in the expected gradation and compromising pavement compaction quality [43,44]. The RAP in the mixture can result in poorer performance if conventional design methods are applied. Some studies have investigated the influence of the degree of blending (DOB) between aged and virgin asphalt on the workability performance and mixture design of hot recycled asphalt [45,46]. They suggest that when the RAP content exceeds 30%, it is crucial to consider the impact of the DOB on performance. These studies have indicated that incomplete blending behavior leads to poor mixture uniformity and performance degradation [47]. Based on the findings mentioned above, it is evident that most current design methods do not account for the blending behavior differences between aged and virgin asphalt. This omission inevitably affects the performance of hot recycled asphalt mixtures.

Currently, extensive research is being conducted on enhancing the performance of hot recycled asphalt mixtures [48–50]. One of the critical areas of interest is the blending behavior differences between aged and virgin asphalt and their impact on mixture performance. Several studies have determined performance indicators of the mixtures and analyzed performance differences to evaluate the DOB difference between aged and virgin

asphalt [51–53]. However, it is essential to note that the change in the asphalt component was the fundamental reason for the different DOBs observed during the hot recycling process. The resulting variations in the performance of hot recycled asphalt mixtures can be attributed to the blending behavior differences between aged and virgin asphalt. Therefore, it is essential to study the relationship between the DOB and road performance to ensure that the road performance meets the requirements. Furthermore, in the production process [54], the differences in mixing processes impact the DOB of aged and virgin asphalt in hot recycled asphalt mixtures, thereby affecting their road performance. This aspect is particularly crucial for hot in-plant recycling [55], whether utilizing original hot recycling batch plants or modified batch plants with RAP heating drums, where the mixing parameters must be manually set. Considering factors such as mixing effectiveness, economic efficiency, and environmental impact, setting the optimal mixing parameters is critical to achieving the desired performance of hot recycled asphalt mixtures, maximizing output efficiency, and minimizing environmental pollution.

This paper aims to enhance the road performance of hot recycled asphalt mixtures. The novelty and originality of this article is that, for the first time, a new method (TLC-FID) has been used to determine the changes in the components of asphalt during aging and recycling to obtain the DOB and to explore the correlation between the DOB and the mixture performance. This research holds significant importance in improving road performance and promoting the application of hot recycled asphalt mixtures.

2. Objective and Research Approach

The following research objectives have been identified:

- (1) First, study the changes in component content during asphalt aging and recycling processes to reveal the mechanisms.
- (2) Next, based on Marshall testing, optimize the design of hot recycled asphalt mixtures to promote the blending of aged and virgin asphalt.
- (3) Finally, analyze the relationship between the DOB in hot recycled asphalt mixtures and their performance under different mixing conditions.

Figure 1 presents an overview of the research methodology employed in this study. Firstly, the changes in the component content of asphalt before and after aging and during the recycling process are investigated using TLC-FID. Secondly, aiming to enhance the blending of aged and virgin asphalt, an optimization design of hot recycled asphalt mixtures is conducted based on the Marshall design method, considering the current application status of hot recycling technology in China. Lastly, three mixing conditions (normal mixing process, optimal fusion mixing process, and inadequate mixing process) were designed to simulate the construction conditions of hot recycled asphalt mixtures. Several performance tests, including high-temperature rutting, low-temperature bending beam, freeze-thaw splitting, immersion Marshall, semi-circular bend fatigue, and DOB tests, are performed to assess the correlation between the DOB and the performance of the mixtures.

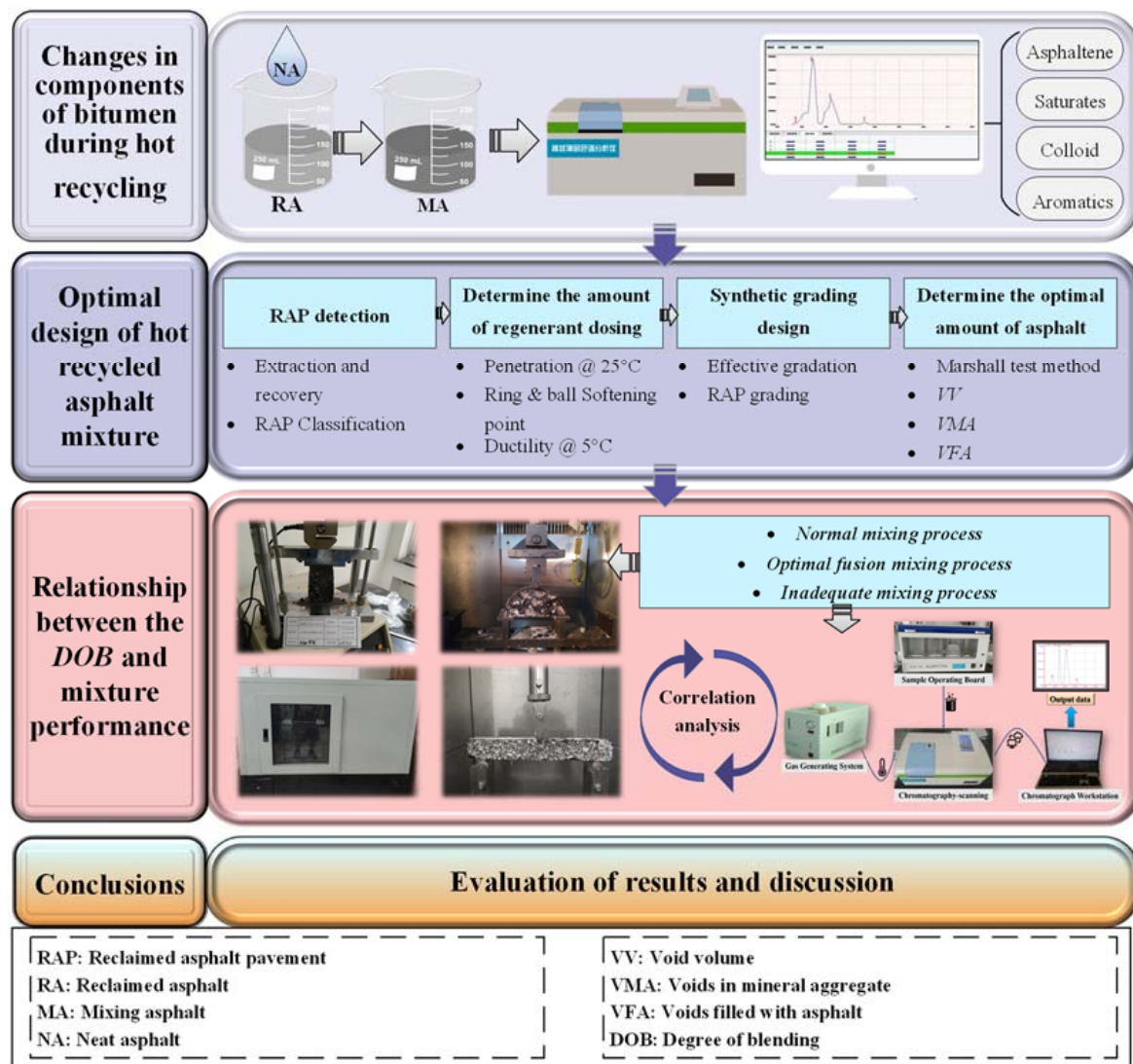


Figure 1. Research approach.

3. Materials and Methods

3.1. Experimental Materials

3.1.1. Asphalt and Mineral Material

(1) Asphalt

Asphalt samples were used in 70#QL, 90#KL, and 70#LT, they were from China Shandong Qilu brand, China Xinjiang Kelian brand, and China Shandong Lutong brand. The three kinds of asphalt are from different manufacturers with different performance indexes. Among them, 90#KL is softer and more fluid. These three kinds of asphalt can represent the neat asphalt often used in Chinese road engineering. The relevant testing indicators are shown in Table 2.

(2) Mineral Material

The specifications of the used mineral material are 10–20 mm limestone gravel, 5–10 mm limestone gravel, 0–2.36 mm manufactured sand, mineral powder, etc. In the DOB test, 4.75–9.6 mm magnetite aggregate was used, and the test results of technical indexes are shown in Table 3. All the technical indexes meet the technical requirements of “Technical Specifications for Asphalt Pavement Construction of Highways” (JTG F40-2004) [56].

Table 2. Test results of asphalt.

Items	Units	90#KL	70#LT	70#QL
Penetration (25 °C)	0.1 mm	89.8	72.0	74.2
Ductility (10 °C)	cm	>100.0	>100.0	55.1
Softening Point (Ring and Ball Method)	°C	48.4	49.2	47.6
Wax Content	%	0.8	0.9	1.6
Flash Point	°C	>260	>260	>260
Solubility	°C	99.5	99.7	99.8
Density (15 °C)	g/cm ³	1.027	1.038	1.035
Rotating Thin Film Oven Test (RTFOT)				
Mass Change	%	0.32	0.23	0.52
Residual Penetration Ratio (25 °C)	%	71.2	70.1	71.8
Residual Ductility (15 °C)	cm	2.5	0.7	15.4

Table 3. Mineral material technical index and test results.

Testing Indexes	Limestone Aggregate	Magnetite Aggregate	Technical Requirements
Crushing Value (%)	14.3	9.8	≤28
Abrasion Value (%)	10.3	9.1	≤30
Apparent Relative Density	2.715	3.82	≥2.5
Water Absorption (%)	0.6	0.21	≤3.0
Durability (%)	0.5	0.2	≤12
Adhesion to Asphalt	5	5	≥4
Needle-Shaped Particle Content (%)	0	0	≤18
Content of Particles with Diameter > 9.5mm (%)	0	0	≤15
Content of Particles with Diameter < 9.5mm (%)	0	0	≤20
Content of Particles Smaller than 0.075mm by Washing Method (%)	0.36	0	≥1
Polished Stone Value (PSV)	45	45	≥42

3.1.2. Reclaimed Asphalt Pavement

The relevant indexes of aged asphalt and aggregate in RAP were determined using an automatic extractor and a rotary evaporator. The technical index of aged asphalt and aggregate pass rate are shown in Tables 4 and 5.

Table 4. Technical index of aged asphalt.

Items	Units	Test Result	Technical Requirements
Penetration (25 °C)	0.1 mm	25.5	60~80
Ductility (10 °C)	cm	4.2	25
Softening Point (Ring and Ball Method)	°C	64.1	>46
Asphalt Content in RAP	%	5.6	-

Table 5. Aggregate pass rate.

Sieve Size (mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
RAP	100.0	99.6	97.4	65.5	35.9	27.4	18.4	13.3	10.4	8.4

3.2. Test Method

3.2.1. Thin-Layer Chromatography with Flame Ionization Detection Test

(1) The asphalt samples were subjected to aging at 163 °C for 48 h. The component contents of the three asphalt samples before and after aging were determined by TLC-FID.

(2) The virgin asphalt was blended with the aged asphalt to simulate the asphalt recycling process, and the component contents of the asphalt before and after recycling were determined by TLC-FID.

(3) The experimental steps include preparing the solution, spotting the samples, developing the samples, activating the chromatographic column, scanning, and processing the chromatograms. The developing solvents used are as follows:

First development: n-heptane (analytical grade).

Second development: toluene (analytical grade).

Third development: toluene (analytical grade) mixed with ethanol (analytical grade) in a ratio of 55:45.

3.2.2. Mix Design Test

According to the standard (JTG/T 5521-2019), the optimization design of hot recycled asphalt mixtures involves several steps, including RAP testing, determination of rejuvenator content, synthetic gradation design, and optimal asphalt content.

3.2.3. Blending Degree Test

(1) Experimental Design

Based on the current production status of hot recycled asphalt mixtures in China, this study designs three mixing processes to simulate different construction conditions. The aim is to investigate the relationship between the DOB and performance under different mixing conditions. The experimental conditions are outlined in Table 6. The conditions for the optimal fusion mixing process are based on conclusions from the literature [31].

Table 6. The setting of experimental design.

Mixing Conditions	Mixing Orders	Mixing Time (s)	Mixing Temperature (°C)	Film Thickness (μm)	Rejuvenator Content (%)
Normal Mixing Process	Order 2	90	150	8.2	3
The Optimal Fusion Mixing Process	Order 1	180	160	7	5
Inadequate Mixing Process	Order 3	45	140	9	0

Note: In Order 1, the mixing order is RAP, virgin asphalt, and aggregates. In Order 2, the mixing order is RAP, aggregates, and virgin asphalt. In Order 3, the mixing order is virgin asphalt, aggregates, and RAP.

(2) Experimental Procedure

This study employs the method described in a referenced study [31] to determine the DOB in the three mixing conditions. The correlation between the DOB and the performance of the mixture is also validated. The measurement steps are illustrated in Figure 2.

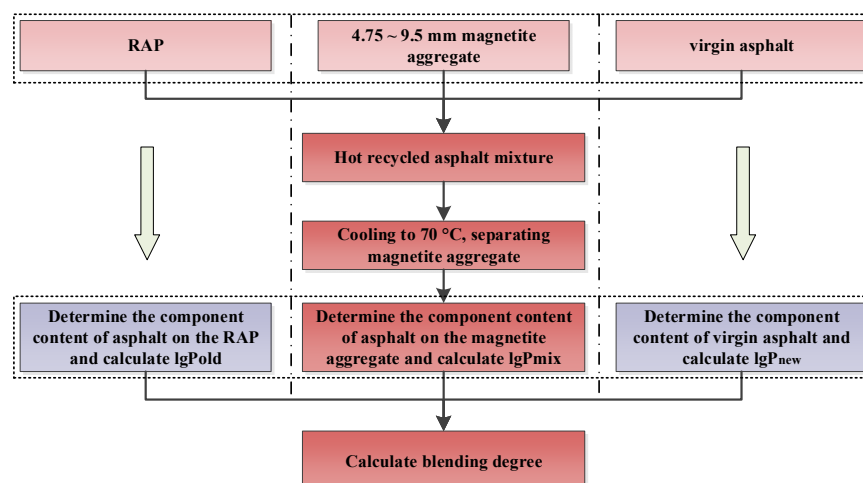


Figure 2. The measurement steps of the DOB.

3.2.4. Wheel Track Rutting Test

This study evaluates the high-temperature performance of hot recycled asphalt mixtures under different mixing conditions by the rutting test and verifies the correlation between the high-temperature performance and the DOB. According to the standard (JTG E20-2011), the rutting test is conducted at 60 °C and a tire pressure of 0.7 MPa. The formula for calculating the dynamic stability is shown in Equation (1).

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2. \quad (1)$$

In the equation, DS : the dynamic stability of the asphalt mixture, cycles/mm; d_1 : refers to the deformation at time t_1 , mm; d_2 : refers to the deformation at time t_2 , mm; C_1 : values 1.0; C_2 : values 1.0; N : 42 cycles /mm.

3.2.5. Low-Temperature Bending Test

The hot recycled asphalt mixture is prepared and compacted into rutting boards based on the three different mixing conditions. The rutting boards are then cut into small beam specimens with specified dimensions. According to the standard (JTG E20-2011), these specimens are subjected to a bending test on a small-scale MTS machine at a temperature of −10 °C and a 50 mm/min loading rate. The DOB of the hot recycled asphalt mixture is measured to validate its correlation with the bending strain. The calculation formula for the bending strain is given by Equation (2).

$$\varepsilon_B = \frac{6 \times h \times d}{L^2}. \quad (2)$$

In the equation, ε_B : the maximum tensile strain at failure of the specimens, $\mu\varepsilon$; d : the mid-span deflection at the failure of the specimens, mm.

3.2.6. Freeze–Thaw Splitting Test and Immersion Marshall Test

The water stability of the hot recycled asphalt mixture under different mixing conditions is evaluated by the freeze–thaw splitting test and immersion Marshall test. The correlation between the water stability and the DOB is verified based on the test results. The specimens used in the tests are standard Marshall specimens. According to the standard (JTG E20-2011), the specific test is conducted at a temperature of 25 °C and a loading rate of 50 mm/min. The calculation formulas for the strength ratio in the freeze–thaw splitting test and the residual stability in the immersion Marshall test are shown in Equations (3) and (4), respectively.

$$TSR = \frac{\bar{R}_{T2}}{\bar{R}_{T1}} \times 100. \quad (3)$$

In the equation, TSR : strength ratio of the freeze–thaw splitting test (%); \bar{R}_{T2} : average splitting tensile strength of the second set of intact specimens after freeze–thaw cycles (MPa); \bar{R}_{T1} : average tensile strength of the first set of valid specimens before freeze–thaw cycles (MPa).

$$MS_0 = \frac{MS_1}{MS} \times 100. \quad (4)$$

In the equation, MS_0 : residual stability of the specimens after immersion (%); MS_1 : stability of the specimens after 48 h of immersion (kN).

3.2.7. Semi-Circular Bending Test

The semi-circular bending test evaluated the fatigue performance of the hot recycled asphalt mixture under three mixing conditions. The well-mixed mixture was compacted and molded into Marshall specimens with a height of 50 mm. The specimens were then

cut into two halves along the diameter. According to the standard (JTG E20-2011), the test was conducted at an ambient temperature of 15 °C with a loading frequency of 10 Hz. A stress-controlled mode was employed, and the test parameters were set using an MTS universal testing machine. Stress ratio conditions were controlled during the semi-circular bending fatigue test. The correlation between the DOB and fatigue performance was also investigated.

In a logarithmic coordinate system of stress ratio (t) versus fatigue life (N_f), the stress ratio and fatigue life data under the three mixing conditions were plotted on the same coordinate system. Regression analysis was performed on the logarithms of stress ratio and fatigue life to obtain the fitted curve for the relationship between stress ratio and fatigue life.

4. Results and Discussion

4.1. Component Changes of Asphalt Mixtures

4.1.1. Component Changes during the Aging Process

The deterioration of asphalt performance is primarily attributed to changes in its internal structure or components [57]. Figure 3 shows that the content of light components in the three aged asphalts is significantly reduced compared to before aging. This is because, during the aging process, many unsaturated bonds in the aromatic fraction of asphalt undergo oxidation and polymerization, transforming into colloidal asphalt. Additionally, slight oxidation and volatilization of saturated fractions occur. Simultaneously, the colloidal asphalt transforms into more stable asphaltene, leading to an increase in the content of asphaltene. Asphalt aging, essentially, involves the irreversible migration of asphalt components, and understanding the migration pattern of asphalt components helps us to grasp the mechanism of asphalt aging. From Table 7, it can be observed that there is a strong correlation between the components and the performance of asphalt. When the content of light components in the asphalt decreases, the penetration, ductility, and softening point of the asphalt decrease. As aging progresses, the content of colloidal asphalt and asphaltene increases, resulting in a decline in the performance indicators of asphalt. The above data analysis shows that the primary reason for asphalt aging is the change in the content of asphalt components. Due to the volatilization or transformation of light components, asphalt becomes hard and brittle, showing the phenomenon of aging.

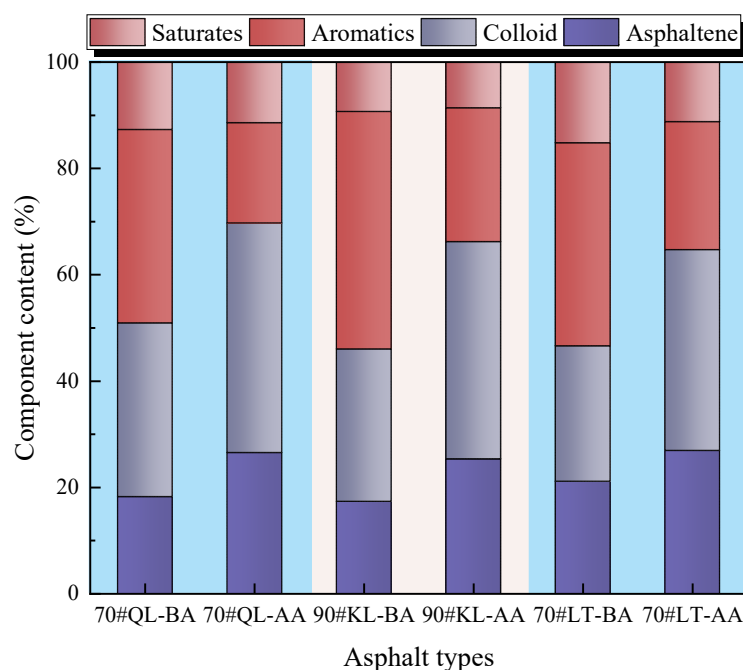


Figure 3. Component changes before and after aging.

Table 7. The basic properties before and after asphalt aging.

Types	Aging Condition	Penetration (25 °C/0.1 mm)	Softening Point (°C)	Ductility (10 °C/cm)
70#QL	Before Aging (BA)	63.5	49.6	25.0
	After Aging (AA)	22.3	63.4	1.8
90#KL	Before Aging (BA)	89.8	48.4	>100.0
	After Aging (AA)	33.2	59.8	2.5
70#LT	Before Aging (BA)	72.0	49.2	>100.0
	After Aging (AA)	28.3	60.0	0.7

4.1.2. Component Changes during the Recycling Process

Recycling aged asphalt is essentially the reverse process of asphalt aging, where the component content of the aged asphalt is adjusted to restore the asphalt performance to some extent, or to a usable state. Table 8 and Figure 4 show that the blending of aged and virgin asphalt can adjust the proportions of the aged asphalt's components. Under the condition of adding 30% of aged asphalt, the mixed asphalt, after complete mixing, although not fully restored to the level of the original asphalt, can meet the requirements for the use of Grade 50 asphalt from an engineering application perspective. In Figure 4, although the component contents of the mixed asphalt and the original asphalt are relatively close, there is still a certain gap, which is why the technical performance of the mixed asphalt does not reach the level of the original asphalt. Specifically, the content of light oil fraction (aromatics + saturates) in the mixed asphalt has not fully recovered to the level of the original asphalt, and the proportions of asphaltene and resin remain relatively high compared to the original asphalt. The regeneration mechanism of aged asphalt is the design of asphalt component blending, where the type of virgin asphalt or rejuvenator is selected, its dosage is determined, and the composition of the aged asphalt is adjusted. Theoretically, it is possible to produce rejuvenated asphalt with a reasonable component ratio and excellent performance.

Table 8. Comparison of general properties of asphalt.

State of Asphalt	Penetration at 25 °C (0.1 mm)	Softening Point (°C)	Ductility at 10 °C (cm)
Original Asphalt	63.5	49.6	25.0
Aged Asphalt	22.3	63.4	1.8
Virgin Asphalt	70.1	47.3	>100
Mixed Asphalt	50.1	54.2	14.8

In the experiments above, it can be assumed that the aged and virgin asphalt, after thorough mixing, achieve an ideal state of complete blending. However, in the hot recycling process, adding other materials (such as aggregates) and limited mixing conditions prevent the aged and virgin asphalt from reaching a state above the ideal blending state. The aged asphalt adhered to the surface of the reclaimed aggregates tends to become hardened and less flowable due to lower temperatures and aging issues. Under the short and restricted mixing conditions, the addition of virgin asphalt cannot thoroughly blend with the aged asphalt on the reclaimed aggregates, thereby affecting the effectiveness of the regeneration process. In the current hot recycling mix design, the blending behavior of aged and virgin asphalt is not considered. Typically, it is assumed that the aged and virgin asphalt are uniformly mixed, and the aged asphalt's contribution is considered. However, this design approach deviates from the actual conditions, significantly reducing the effectiveness of asphalt recycling and compromising the performance of the hot recycled asphalt mixture. It may even lead to premature pavement distress. Therefore, it is paramount to study the blending behavior of aged and virgin asphalt and its impact on the performance of hot recycled asphalt mixtures.

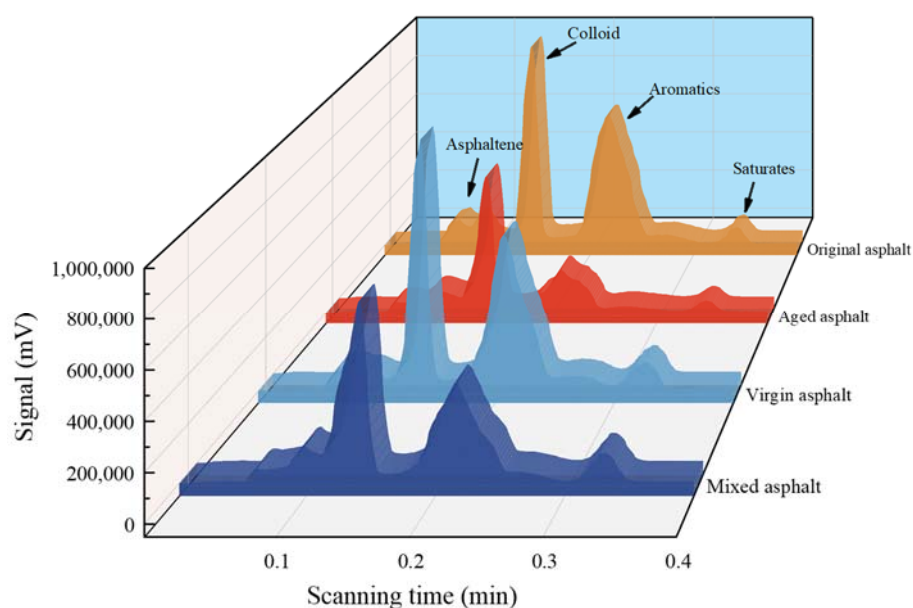


Figure 4. Comparison of asphalt components.

4.2. Optimization Design of Hot In-Plant Recycled Asphalt Mixture

4.2.1. Reclaimed Asphalt Pavement Testing

Before designing the proportioning of the recycled asphalt mixture, it is necessary to determine the relevant performance of the RAP material accurately. The test results of the aged asphalt are shown in Section 3.1.2. To promote the DOB of the aged and virgin asphalt and improve the performance of the mixture, the RAP is divided into two grades as shown in Table 9, which facilitates further refined utilization.

Table 9. Passage rate of each sieve opening in RAP sieving.

Sieve Openings (mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
RAP Coarse Material (%)	99.8	92.7	67.5	27.4	18.4	14.8	11	8.1	6.6	4.8
RAP Fine Material (%)	100	100	100	89.6	64.7	50.9	35.2	25.7	21.6	17.9

The testing of RAP reveals that the aged asphalt has undergone significant deterioration compared to the specifications for asphalt and aggregate gradation. The gradation of the pavement aggregate has, significantly, become finer. When designing the hot in-plant recycled asphalt mixture, it is recommended to incorporate a rejuvenator to blend and restore the performance of the aged asphalt. Additionally, virgin aggregates should be added to adjust the synthetic gradation to meet the specifications' requirements.

4.2.2. Determining the Rejuvenator Content

The addition of rejuvenators can improve the DOB between aged and virgin asphalt in hot recycled asphalt mixtures [58]. This study used rejuvenator inclusion rates of 1%, 3%, and 5%, and the corresponding tests were conducted on recycled asphalt. From Table 10, it can be observed that as the rejuvenator content increases, the penetration and ductility of the aged asphalt gradually increase, while the softening point decreases, indicating that the rejuvenator has a rejuvenating effect on the aged asphalt. However, when the rejuvenator dosage reaches 5%, there is little change in the performance of the aged asphalt, suggesting that the rejuvenating effect of the rejuvenator has certain limitations. When the rejuvenator content is set at 3%, the 25 °C penetration, softening point, and 10 °C ductility of the recycled asphalt meet the technical standards of 70# road petroleum asphalt. Considering both technical and economic factors, the rejuvenator content is determined to be 3% of the aged asphalt. The table shows that the rejuvenator effectively supplements the light

component of the aged asphalt and recovers the performance of the aged asphalt. Adding a certain amount of rejuvenator is a necessary step in the design of hot recycled asphalt mixtures to recover the performance of the mixtures.

Table 10. General properties of recycled asphalt with rejuvenators.

Content (%)	1	3	5
Penetration at 25 °C (0.1 mm)	53.5	71.1	82.1
Softening Point (°C)	63.2	53.7	45.3
Ductility at 10 °C (cm)	28.3	39.2	49.3

4.2.3. Synthetic Gradation Design

The proposed RAP content is set at 30%. Based on the aggregate gradation requirements for AC-16 and the sieving results of each material, the proportions of coarse and fine aggregates are controlled to adjust the mix proportions under different RAP inclusion rates. As shown in Figure 5, the synthetic gradation of the recycled mix is within the upper and lower gradation limits due to the division of the RAP into coarse and fine minerals. The grading curve is close to the median value of the gradation, which guarantees that the synthetic gradation meets the specification requirements. This shows that the optimization design method of hot recycled asphalt mixture proposed in this paper is reasonable and effective.

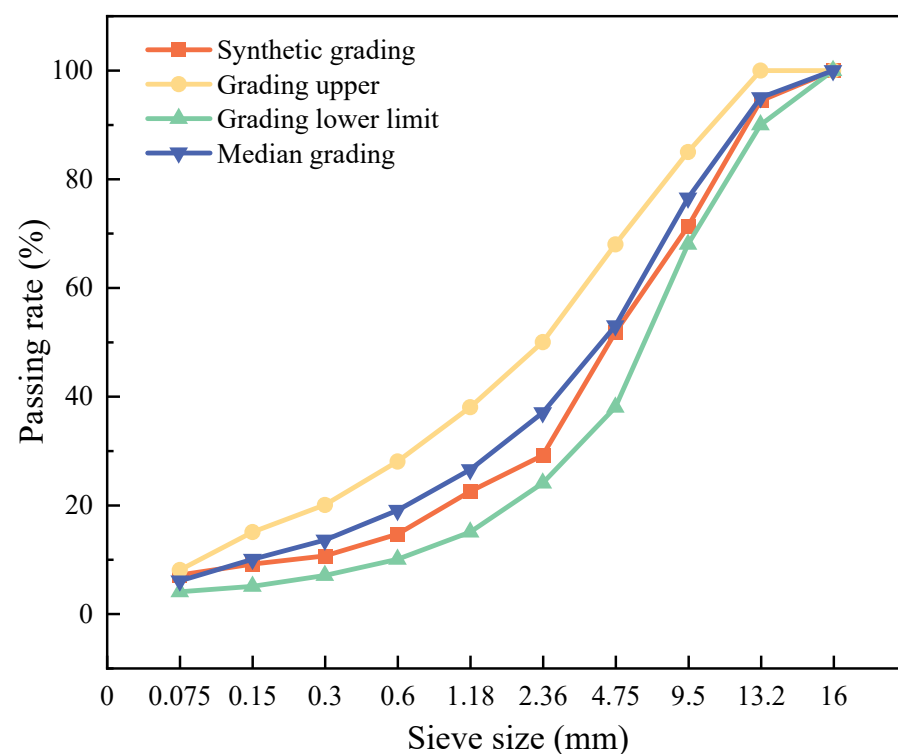


Figure 5. Gradation design of AC-13.

4.2.4. Determining the Optimal Asphalt Content

Determining the optimal total asphalt content for hot mix asphalt using the Marshall test method requires ensuring sufficient blending between aged and virgin materials. The RAP is preheated to 120 °C. The optimal asphalt content is determined to be 4.4%, achieving thorough mixing between the aged and virgin materials.

4.3. Relationship between the Degree of Blending and Performance

4.3.1. High-Temperature Stability

The dynamic stability and DOB of hot recycled asphalt mixtures prepared under three different mixing conditions are shown in Figure 6. As the DOB increases, the high-temperature stability of the hot recycled asphalt mixture also improves. This phenomenon is consistent with the findings of the literature [31]. Under the optimal fusion mixing process, the hot recycled asphalt mixture exhibits better resistance to rutting compared to the normal mixing process. This improvement is because a higher DOB allows for a more significant amount of rejuvenation of the aged asphalt, adjusting the surface-active substance content of the aged asphalt on most of the RAP particles. This enhances the asphalt's bonding ability and improves the cohesion of the hot recycled asphalt mixture, resulting in better high-temperature strength. However, when mixing temperature and time are insufficient, the dynamic stability values may be lower. This can be attributed to inadequate blending between aged and virgin asphalt, leading to uneven distribution of mineral particles in the hot recycled asphalt mixture, causing deformation under load. It is recommended to avoid mixing under such conditions whenever possible. Correlation analysis shows a significant relationship between DOB and rutting test results.

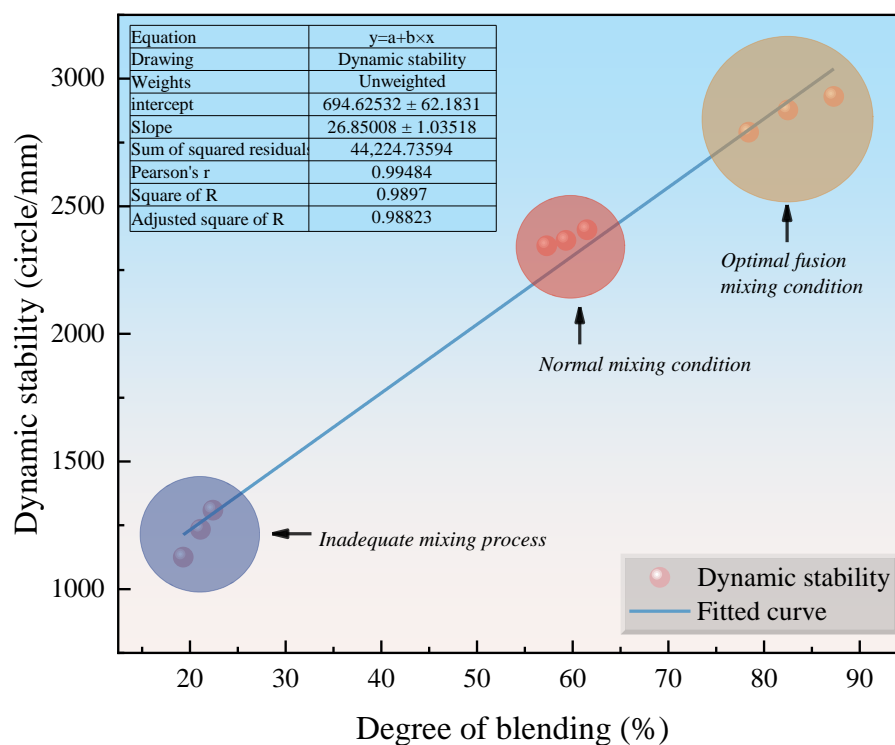


Figure 6. The relationship between DOB and high-temperature performance.

4.3.2. Low-Temperature Cracking Resistance

Figure 7 shows that improving the DOB contributes to enhancing the low-temperature crack resistance of hot recycled asphalt mixtures. By improving the mixing process of hot recycled asphalt mixtures and promoting the blending between aged and virgin asphalt, a more significant proportion of aged asphalt can participate in the recycling process, leading to the restoration of aged asphalt and improved bonding performance between asphalt and aggregates. This results in better ultimate tensile strength at low temperatures and reduces the occurrence of cracking. Furthermore, when the DOB between aged and virgin asphalt is poor, the low-temperature crack resistance of hot recycled asphalt mixtures is also compromised, failing to meet the specification requirements. This indicates that the blending performance between aged and virgin asphalt directly influences the low-temperature performance of hot recycled asphalt mixtures. This conclusion validates

previous research that the lower the DOB, the poorer the low-temperature performance. Correlation analysis shows a significant relationship between the DOB and the results of the low-temperature bending test.

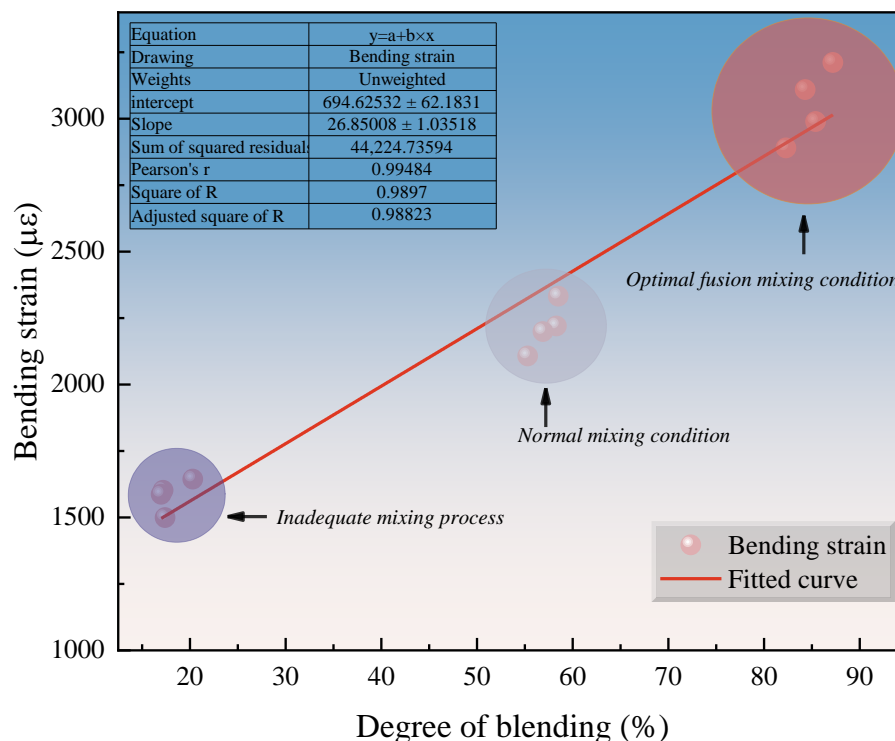


Figure 7. The relationship between DOB and low-temperature performance.

4.3.3. Water Stability

When the DOB between aged and virgin asphalt is high, the water stability of hot recycled asphalt mixtures is also improved. Under the premise of consistent aggregate gradation, different mixing processes of the mixtures lead to variations in water stability performance. Hot recycled asphalt mixtures with good blending between aged and virgin asphalt exhibit better overall integrity and strength, thus demonstrating a higher resistance to water damage. The differences in mixing conditions significantly impact the water stability of hot recycled asphalt mixtures, particularly under conditions of low environmental temperatures and rainfall. The bonding performance between virgin asphalt, aggregates, and RAP decreases, making it easier for moisture to enter the contact interface and consequently reducing the water stability performance. The planar projection in Figure 8 shows that the TSR value exhibits more robust aggregation under the same mixing conditions, while the MS value appears more dispersed. This indicates that the correlation between the freeze–thaw splitting test and DOB is stronger than between the immersion Marshall test and DOB. The variation rule of water stability of hot recycled asphalt mixtures mentioned in the literature [32] is verified in this paper. Correlation analysis confirms a significant relationship between DOB and water stability test results.

4.3.4. Fatigue Resistance

Under repeated loads, the semi-circular bending specimens deform and crack, eventually leading to fatigue failure. As shown in Figure 9, under the same stress ratio conditions, hot recycled asphalt mixtures exhibit the best fatigue life when favorable mixing conditions that promote blending between aged and virgin asphalt are applied. Based on the blending results of aged and virgin asphalt, it can be observed that a higher DOB corresponds to a longer fatigue life, and vice versa. By comparing and regression analysis of the semi-circular bending fatigue test data, it is evident that this test method can effectively assess the fatigue

performance of hot recycled asphalt mixtures. Compared to other fatigue tests, this method is simple to operate and provides accurate test results, allowing for the establishment of a stress ratio–fatigue life relationship equation. Analysis of the fatigue performance of the three mixing conditions of hot recycled asphalt mixtures reveals that under the same stress ratio level, the mixing condition with the highest DOB, indicating a more increased blending between aged and virgin asphalt, exhibits a higher fatigue life compared to the normal mixing process. This demonstrates that improving the DOB between aged and virgin asphalt in hot recycled asphalt mixtures is beneficial for enhancing their long-term fatigue performance. The above findings on the fatigue performance of hot recycled asphalt mixtures agree with the results of previous studies.

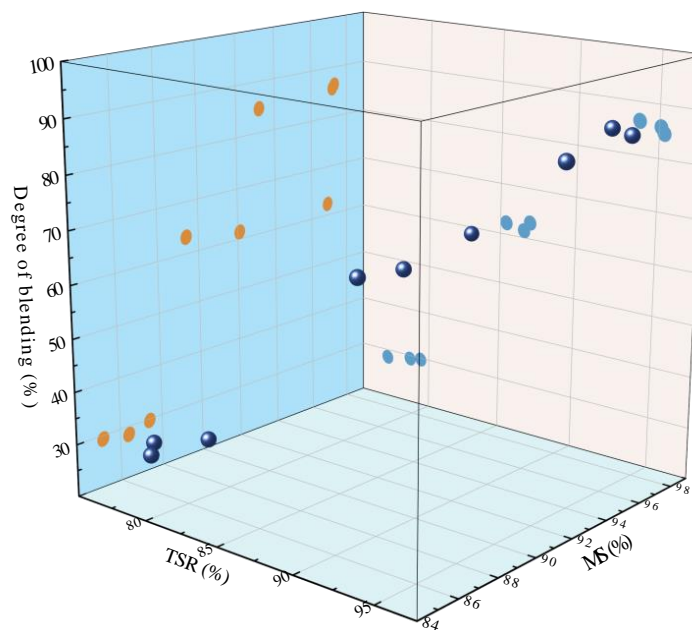


Figure 8. The relationship between DOB and water stability performance.

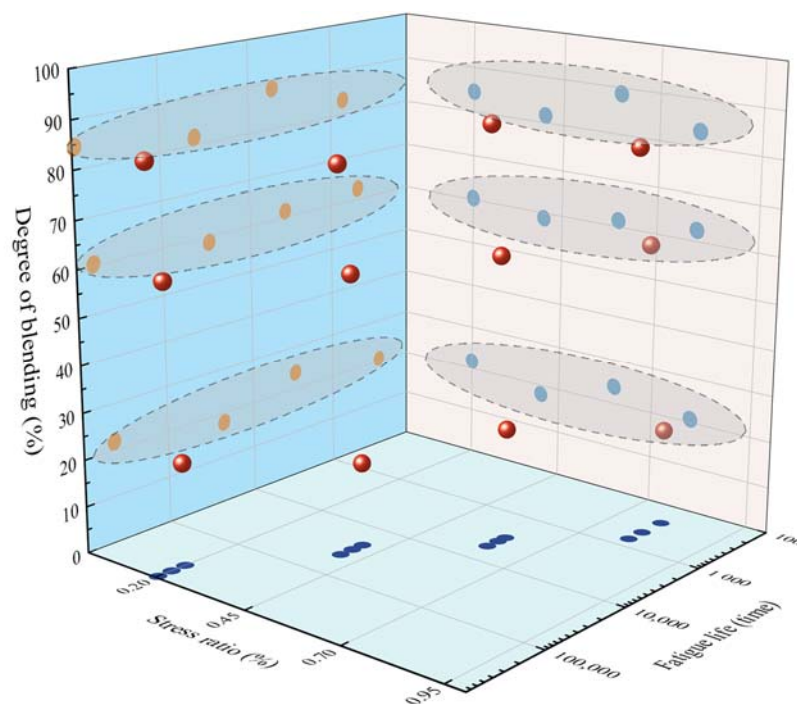


Figure 9. The relationship between fatigue life and DOB under different stress ratios.

Figure 10 shows that the logarithm of the fatigue life of hot recycled asphalt mixtures is linearly correlated with the stress ratio. As the stress ratio increases, the fatigue life of the hot recycled asphalt mixtures decreases. Under the same stress ratio conditions, the hot recycled asphalt mixture prepared with the optimal fusion mixing process exhibits the maximum fatigue life. This indicates that the internal uniformity of the mixture is improved by improving the mixing process and enhancing the DOB between aged and virgin asphalt. This enables the hot recycled asphalt mixture to withstand more repeated load cycles, enhancing its fatigue resistance. Moreover, the slope of the fitted curve indicates that the hot recycled asphalt mixture prepared with the optimal fusion mixing process exhibits less deterioration in fatigue performance as the load cycles increase. This implies that when subjected to long-term loading, the mixture prepared under these conditions will have better fatigue resistance.

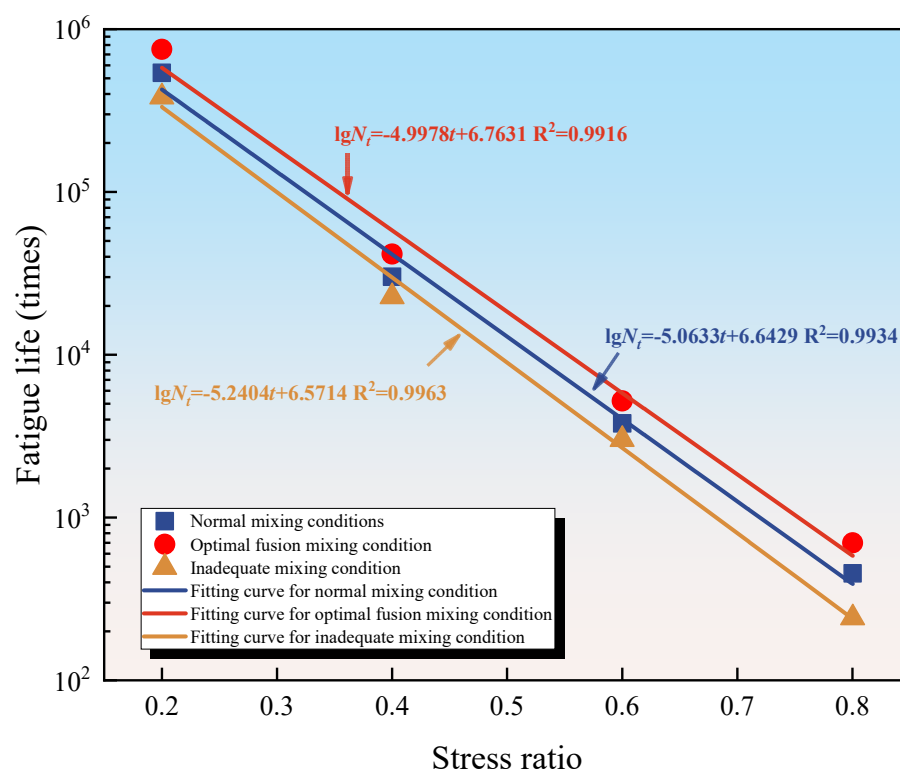


Figure 10. Stress ratio vs. fatigue life regression curve.

5. Conclusions

This study investigated the changes in the components of different asphalt mixtures during aging and recycling by TLC-FID. The optimization design of hot recycled asphalt mixtures was conducted based on the Marshall design. Laboratory experiments were performed to evaluate the correlation between the DOB and high-temperature stability, low-temperature crack resistance, water stability, and fatigue resistance under three different mixing conditions. The main conclusions are as follows:

(1) When asphalt ages, its components undergo selective transformations. The content of light components decreases, while the range of heavy components increases. When virgin asphalt or rejuvenators are added to aged asphalt, the changes in asphalt components show an opposite trend. Changes in asphalt components are the primary reason for changes in asphalt properties.

(2) The DOB is correlated with the performance of the recycled asphalt mixture. As the DOB increases, the high-temperature stability, low-temperature crack resistance, water stability, and fatigue resistance of the recycled asphalt mixture improve. The DOB represents the homogeneity of virgin and aged materials blending in recycled asphalt

mixtures. The performance of recycled asphalt mixtures can be effectively enhanced by controlling DOB.

(3) The DOB is typically only around 50% to 60% under normal mixing process. However, by adjusting the mixing process parameters, it is possible to increase the DOB to 80% ~ 90%. Establishing a DOB-centered design methodology for recycled asphalt mixtures will help to improve the performance of recycled asphalt mixtures.

(4) The semi-circular bending test can effectively characterize the fatigue performance of hot recycled asphalt mixtures. This test method is simple to perform, produces reasonable data, and is an essential means of evaluating the fatigue performance of hot recycled asphalt mixtures. Follow-up studies should pay attention to connections with field performance.

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