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Study on rheological properties of warm mix large proportion recycled asphalt

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Abstract

In order to explore the rheological properties of high content warm mix recycled asphalt binder, recycled asphalt was added into warm mix asphalt to prepare warm mix recycled asphalt. The optimum content of regenerant and Sasobit REDUX was determined by asphalt basic performance test and temperature scanning test. The chemical composition of recycled asphalt was studied by FITR. The rheological properties and low temperature crack resistance of warm mix recycled asphalt were analyzed by DSR and BBR tests, and the optimum content of recycled asphalt was determined. The results show that when the content of regenerant is 10%, its basic performance recovers to the level of base asphalt. Sasobit REDUX can reduce the high temperature viscosity of asphalt, and the optimum content is 1%. With the increase of recycled asphalt content, the shear modulus and phase angle of warm mix recycled asphalt gradually decrease, and its high temperature stability gradually increases. Under low frequency and high temperature conditions, warm mix recycled asphalt with 50% content has better high temperature deformation resistance. Under the action of stress, the strain accumulation decreases with the increase of the content of recycled asphalt. When the content of recycled asphalt is 50%, the ability of warm mix recycled asphalt to resist load deformation and temperature sensitivity in the middle temperature zone is similar to that of matrix asphalt, and it has good deformation resistance and low temperature crack resistance. Comprehensive analysis of the best content of recycled asphalt should be 50%, then warm mix recycled asphalt mixture has excellent road performance.

1. Introduction

At present, the plant-mixed hot recycling method is mainly used to recycle RAP. Although this technology can restore the road performance of asphalt pavement to the greatest extent, it is also easy to cause secondary aging of RAP due to its high mixing temperature during construction, thus limiting the amount of RAP\cite{1}. Warm mix regeneration technology is by adding warm mix agent, not only can make the construction temperature is reduced by 30\textdegree C–40\textdegree C, with good construction workability, but also can make the content of RAP more than 40\%, reduce the amount of asphalt and aggregate\cite{2}; The existing warm mix regeneration technologies mainly include viscosity reduction, foaming and surface active warm mix regeneration technologies. Among them, viscosity reduction and surface activity warm mix regeneration technology are widely used\cite{3}. The technology of hot mix plant recycling asphalt is mainly aimed at the recycling of old asphalt mixture\cite{4}. Excessive RAP
content will reduce the fatigue performance and water stability of recycled asphalt mixture [5], and the excessive heating temperature of the old material will cause secondary aging of asphalt in the old material. In response to this problem, domestic and foreign scholars have done different aspects of research on warm mix regeneration technology [6–8]. Carrion et al designed the mixture of HMRA and WMRA in the upper layer. The RAP content in WMRA can reach 90%, and the amount of RAP is closely related to the characteristics of asphalt binder in RAP [9]. Zhu et al [10] concluded that the recycled asphalt mixture with 45% RAP content had good road performance and saved about 20% of economic benefits. Increasing RAP content in recycled asphalt mixture can not only save construction costs, but also reduce energy consumption and pollution emissions [11].

At present, the commonly used warm mix additives are organic additive Sasobit and chemical additive Evotherm. Organic additive Sasobit is a kind of paraffin material, which is a fine crystalline long chain aliphatic hydrocarbon produced from the gasification of coal. The appearance is flake or powder, and the melting point is greater than 100 °C, which is higher than that of ordinary paraffin. It can be completely dissolved in asphalt or asphalt mixture when it exceeds its melting point. Adding Sasobit to asphalt or asphalt mixture can reduce the viscosity of asphalt at high temperature, so as to reduce the temperature of asphalt mixture mixing, paving and rolling. Therefore, Sasobit is also known as ‘asphalt viscosity reducer’. Sasobit REDUX can reduce the viscosity of asphalt at high temperature without reducing the low temperature viscosity of asphalt. It is a substitute for Sasobit. It can be completely dissolved in asphalt when the temperature is greater than 85 °C, while Sasobit can be completely dissolved in asphalt at 115 °C. Sasobit REDUX also has good cooling potential and high environmental benefits [12]. Sargand [13] found that compared with ordinary asphalt, warm mix asphalt binder and mixture showed better high and low temperature performance and anti-aging properties. Wang Weiying [14] tested the influence of two different mechanisms of synthetic wax and surface active warm mix agent on recycled asphalt. The results show that the synthetic wax warm mix agent has obvious viscosity reduction effect and can significantly improve the low temperature performance of asphalt. The surface active warm mix agent has no viscosity reduction effect, but it has a certain promoting effect on the high temperature performance and fatigue performance of asphalt. Mallick [15, 16] successfully prepared asphalt mixture with 75% old material content at a lower temperature by using Sasobit H8 warm mix agent; Zhang Jizhong [17] studied the compaction characteristics of warm mix recycled asphalt mixture with Sasobit warm mix agent, and believed that warm mix agent can effectively reduce the molding temperature of recycled asphalt mixture, and improve the high temperature stability and water stability, but reduce the low temperature crack resistance.

The performance of warm mix recycled asphalt mixture mainly depends on the rheological properties of warm mix recycled asphalt, RAP content and warm mix agent type. The rheological properties and chemical composition of asphalt binder play a key role in the road performance of recycled pavement, which is a hot issue in the research of road building materials at home and abroad. At present, the research of warm mix recycled asphalt mixture is mostly focused on macro performance, and the research on rheological properties of warm mix large proportion recycled asphalt binder is relatively weak. Therefore, based on the new additive Sasobit REDUX, this paper studies and analyzes the rheological properties of warm mix large proportion recycled asphalt binder, and determines the appropriate content of large proportion recycled asphalt, which provides a wider discussion for the practical application of high content warm mix recycled asphalt mixture.

### 2. Raw material

#### 2.1. Asphalt

The original asphalt is 70# A grade asphalt (70#) provided by Qilu Branch of SINOPEC. The long-term aging of asphalt (70#PAV) is simulated by PAV aging test, and the aging asphalt (70#RA) is recovered from RAP by extraction method. The basic performance test was carried out according to the ‘Test Specification for Highway Engineering Asphalt and Asphalt Mixture’ (JTG E20–2011). The test results are shown in table 1.

#### 2.2. Regenerant

When selecting regenerant, safety and environmental protection should be considered, and its performance should also meet the technical requirements of the specification. According to the ‘Highway Asphalt Pavement...
Recycling Technical Specification’ (JTG/T 5521–2019), and combined with the actual needs, this test selects LJK type recycling agent, which is dark brown oil at room temperature and has good fluidity. Its performance indicators are shown in table 2.

2.3. Warm mix agent
Sasobit REDUX additive can reduce the viscosity of asphalt at high temperature without reducing the low-temperature viscosity of asphalt. It is a substitute for Sasobit. It can be completely dissolved in asphalt when the temperature is higher than 85 °C, while Sasobit can be completely dissolved in asphalt at 115 °C. Sasobit REDUX has good cooling potential and high environmental benefits [18]. It is a round flake solid particles at room temperature, as shown in figure 1, and the comparison of the two specifications is shown in table 3.

3. Test method
3.1. Preparation of aged asphalt and warm mix recycled asphalt
In this study, 70# matrix asphalt was used as the original asphalt. According to AASHTO T240 and R18 regulations [19, 20], the short-term aging of asphalt was simulated by rotating thin film oven (RTFOT), and the setting conditions were 163 °C and 85 min. The pressure aging test (PAV) was used to simulate the long-term aging of asphalt. The pressure aging vessel was set at 100 °C, air pressure of 2.1 MPa and aging time of 20 h.
The preparation method of recycled asphalt is to mix 10% regenerant into the asphalt which has been artificially aged by PAV, and shear 30 min by high speed shearing machine under 140 °C heating condition. The preparation method of warm mix asphalt is to first add 1% warm mix agent to the matrix asphalt, and continuously shear for 30 min at 140 °C to obtain warm mix asphalt; finally, the recycled asphalt was added to the warm mix asphalt with 30%, 50%, 70% and 100% respectively to obtain the warm mix recycled asphalt.

### 3.2. Determination of optimum dosage of admixture

#### 3.2.1. Asphalt performance test

In this paper, four groups of samples were selected, including matrix asphalt, recycled aged asphalt, asphalt after short-term aging by RTFOT and asphalt after long-term aging by PAV. The penetration, softening point, ductility, viscosity test and temperature scanning test of asphalt mixed with regenerant and Sasobit REDUX were carried out respectively. The effects of adding different amounts of regenerant and Sasobit REDUX on the performance of asphalt were analyzed, so as to select the appropriate amount. In this experiment, the content of regenerant was 2%, 4%, 6%, 8% and 10%, and the content of Sasobit REDUX was 0%, 1%, 2%, 3% and 4%.

#### 3.2.2. DSR temperature sweep test

Temperature sweeping of 70# asphalt, aged asphalt and four kinds of recycled asphalt was carried out by DSR test in AASHTO M320 specification. The specification stipulates that the rutting factor of the original asphalt and the asphalt after short-term aging should be greater than 1.0 KPa and 2.2 KPa, respectively. The DHR-1 type dynamic shear rheometer (see table 4) was used to scan the temperature of asphalt. The temperature range was 40 °C ∼ 80 °C, and the loading frequency was unified at 10 rad s⁻¹. The recycled asphalt content of each warm mix recycled asphalt binder was 0%, 30%, 50%, 70% and 100%, respectively. The samples were uniformly scanned between 25 mm parallel plates (spacing 1 mm).

#### 3.3. Fourier infrared spectroscopy test

Fourier transform infrared spectroscopy test can not only judge the types of functional groups contained in the medium and qualitatively analyze their characteristics according to the influence of intermolecular rotation or vibration on the absorption capacity of infrared rays, but also quantitatively compare the relative content of characteristic functional groups before and after asphalt aging and regeneration according to the integral strength method.

In this experiment, Fourier infrared spectrometer (FITR) was used to scan and analyze the infrared spectrum of recycled asphalt samples. The specific experimental parameters were as follows: the wave number range of the test was 400–4000 cm⁻¹, the resolution was 4 cm⁻¹, and the number of scans was 32 times. The pitch and carbon tetrachloride solvent were prepared into a solution with the same concentration at a mass ratio of 1:18, and the infrared spectrum scanning test was performed after pressing.

#### 3.4. Study on rheological properties of warm mix recycled asphalt

#### 3.4.1. Temperature sweeping

Asphalt as a temperature sensitive material, its viscoelastic properties will change greatly with the change of temperature. Because the rutting of asphalt pavement mainly occurs in the early stage of pavement construction, the high stability index of asphalt adopts the rutting factor $G^*/\sin\delta$ of original asphalt and residual asphalt after PAV aging as the evaluation index. In the SHRP plan, the complex modulus $G^*$ is the complex sum of the storage
elastic modulus and the loss elastic modulus, reflecting the ability of the asphalt material to resist shear deformation. Phase angle $\delta$ refers to the angle of strain lagging stress after asphalt is subjected to shear load, which reflects the proportion of viscoelastic components in asphalt. Viscoelastic index Rutting factor $G^*/\sin\delta$ is the evaluation index of high temperature performance of asphalt, reflecting the resistance to permanent deformation of asphalt.

3.4.2. Frequency sweeping
The viscoelastic properties of warm mix recycled asphalt in a wider frequency range were analyzed by frequency sweeping. The test frequency was 10 rad s$^{-1}$, and the constant strain level was 0.01%. The selected strain level is small, which can ensure that the sample is within the specified viscoelastic range. The selected test temperatures was 14°C, 40°C and 64°C, the rotor diameter were 25 mm, and the parallel plate gap was 2 mm. An 8 mm parallel plate with a gap of 2 mm was used during the test.

3.4.3. Linear amplitude scanning
Elastic deformation and plastic deformation of asphalt occur under load. When the asphalt reaches yield, the strain continues to increase and the stress gradually decreases. At this time, the peak stress is defined as the yield stress, and the strain corresponding to the yield stress value is the yield stress. The yield stress reflects the deformation resistance of asphalt under load, and the yield strain reflects the elasticity of asphalt, that is, the deformation of asphalt under the maximum load. The viscoelastic properties of warm mix recycled asphalt in a wider temperature range were analyzed by linear amplitude scanning.

In this study, the asphalt binder samples after PAV aging were selected for LAS linear amplitude scanning. The test frequency was 10 rad s$^{-1}$, and the constant strain level was 0.01%. The selected strain level is small, which can ensure that the sample is within the specified viscoelastic range. The selected test temperatures was 14°C, 40°C and 64°C, the rotor diameter were 25 mm, and the parallel plate gap was 2 mm. An 8 mm parallel plate with a gap of 2 mm was used during the test.

3.4.4. Multiple stress creep recovery test
The specimen size of multi-stress creep recovery test is also $\varphi 25$ mm$^2$ 2 mm, and the test temperature is controlled at 64°C. The viscoelastic properties of asphalt were comprehensively considered in this test. When the traffic load acts on the asphalt pavement, the elastic and viscous deformation mainly occurs. When the driving load is removed, the elastic deformation recovers and the viscous deformation accumulates [21]. MSCR test simulated the stress state of asphalt under continuous load. In this test, 0.1 KPa and 3.2 KPa stress levels were selected to analyze the creep recovery ability of asphalt under continuous loading under different levels of low stress and high stress. Repeated and cyclic loading and unloading at the same stress level. The loading completion time in a creep cycle was 1 s and the unloading time was 9 s. The dynamic shear rheometer was used to measure 20 cycles at a time. The stress level of the first 10 cycles was 0.1 KPa and the stress level of the last 10 cycles was 3.2 KPa. It better simulated the creep recovery process of asphalt material from bearing the vehicle load stress to after the vehicle drives.

3.5. Study on low temperature crack resistance of warm mix recycled asphalt
The bending beam rheometer (BBR) was used to load 240 s under constant stress, and the test temperature was set to $−18$ °C. The low temperature performance of asphalt binder is characterized by measuring the low temperature stiffness modulus and creep rate of asphalt trabecular specimens. SHRP study suggests that if the stiffness of asphalt material is too large, it is easy to present brittleness, making asphalt pavement easy to crack under traffic load. The larger the change rate of asphalt stiffness with time, namely, the larger the value of m, means that when the temperature decreases to make the pavement shrink, the tensile stress in the pavement material will be reduced, and the possibility of low temperature cracking of the pavement will be reduced [18]. Therefore, in order to limit the cracking of pavement, the stiffness modulus and m values of SHRP specification for 60 s are not greater than 300 MPa and 0.30, respectively.

4. Test results and analysis

4.1. Determination and analysis of optimum content of regenerant
The test results are shown in table 5.

The penetration index of asphalt reflects the soft and hard degree of asphalt. The penetration change of recycled asphalt under different dosage of regenerant is shown in figure 2. It can be seen from figure 2 that the penetration of recycled asphalt increases with the increase of the content of regenerant. When the content of regenerant is 10%, the penetration of recycled asphalt returns to the level of...
70# matrix asphalt. The softening point of asphalt can characterize the high-temperature stability of asphalt. The change of softening point of recycled asphalt under different dosage of regenerant is shown in figure 3.

It can be seen from figure 3 that the softening point of recycled asphalt decreases with the increase of the content of regenerant. When the content of regenerant is 10%, the softening point of recycled asphalt is closest to that of matrix asphalt. The softening point of recycled asphalt with 10% regenerant content is about 2 °C higher than that of matrix asphalt, and the high temperature stability is better. The ductility represents the

Table 5. Test results of asphalt performance index.

| Sample              | Needle penetration at 25 °C | Softening point/°C | Duration/mm | Viscosity at 135 °C |
|---------------------|-----------------------------|--------------------|-------------|---------------------|
| Matrix asphalt      | 74.6                        | 48.5               | >100        | 1.21                |
| Recycled asphalt    | 15.8                        | 63.9               | 61          | 3.36                |
| RTFOT aged asphalt  | 49.8                        | 54.5               | 76          | 2.88                |
| PAV aged asphalt    | 20.4                        | 60.2               | 58          | 3.20                |

Figure 2. Aged asphalt penetration with different contents of regenerant.

Figure 3. Aged asphalt softening point with different contents of regenerant.
ductility and crack resistance of asphalt at low temperature. The variation of ductility of recycled asphalt under different dosage of regenerant is shown in figure 4.

It can be seen from figure 4 that the ductility of recycled asphalt decreases with the increase of regenerant dosage. When the regenerant dosage is 10%, the ductility of recycled asphalt is restored to the level of 70\# matrix asphalt. In conclusion, when the content of regenerant is 10%, the penetration, softening point and ductility of recycled asphalt basically return to the level of 70\# matrix asphalt, which has good high temperature stability and low temperature performance, but the construction workability is inferior to that of matrix asphalt. Therefore, the optimum content of regenerant is determined to be 10%.

4.1.1. Performance analysis of asphalt with the optimum amount of regenerant
The test results are shown in figures 5, 6 and 7.

It can be seen from figure 5 that the complex modulus of aged asphalt, recycled asphalt and base asphalt change with temperature is basically the same, and decreases exponentially with the increase of temperature. At the same temperature, the complex modulus of recycled asphalt decreases with the increase of regenerant content, the complex modulus of aged asphalt is the largest, and the complex modulus of matrix asphalt is the smallest. Asphalt aging can enhance the high temperature performance of asphalt, while the increase of regenerant content will weaken the high temperature performance. This is because after asphalt aging, with the
increase of asphaltene in the colloidal structure, the anti-deformation ability of asphalt is enhanced. After adding the regenerant, the regenerant dissolves and disperses the asphaltene, the complex modulus of asphalt decreases, and the anti-deformation ability decreases. Under the optimum amount of regenerant, the complex modulus of recycled asphalt is slightly larger than that of matrix asphalt. Chen Sixian et al. [22] concluded in the analysis of the rheological properties of recycled asphalt that under high RAP content, the complex modulus of recycled asphalt with regenerant is lower than that of recycled asphalt without regenerant. The more the regenerant content, the smaller the complex modulus.

It can be seen from figure 6 that the phase angle of aging asphalt, recycled asphalt and matrix asphalt has a good linear relationship with temperature. The phase angle of matrix asphalt is the largest, while that of aging asphalt is the smallest. The phase angle of recycled asphalt increases with the increase of regenerant dosage. Chen Jingyun and Teng Jianxing [23] found that the addition of self-made regenerant can effectively restore the complex shear modulus and phase angle of aged SBS modified asphalt and reduce its temperature sensitivity through the study of warm mix recycled SBS modified asphalt. The addition of the rejuvenating agent restores the elastic properties of the aged asphalt and improves the recovery ability after deformation. After the aging of the asphalt, the asphaltene increases, the light component decreases, the asphalt becomes hard and brittle, and the elasticity decreases. It shows that the rejuvenating agent has dissolved and dispersed the asphaltene gathered in the aged asphalt and changed the viscoelasticity of the asphalt. At this time, the asphalt is closer to the viscous body, and the time difference between stress and strain is shortened, resulting in the reduction of the phase angle.
of the aged asphalt. The results show that the deformation resistance of recycled asphalt at 10% content is equivalent to that of matrix asphalt, the performance of aged asphalt has been basically restored, and 10% regenerant content can be used as the best content.

It can be seen from figure 7 that the ordinate is in logarithmic form, and the rutting factor \( \lg (G^*/\sin\delta) \) of base asphalt, aged asphalt and recycled asphalt is linearly related to temperature, and decreases with the increase of temperature. The rutting factor of aged asphalt is the largest, and that of matrix asphalt is the smallest. The rutting factor of recycled asphalt decreases with the increase of regenerant content, indicating that the anti-shear deformation ability and anti-rutting ability of asphalt after aging increase. The incorporation of regeneration agent makes the recycled asphalt soft and the elastic properties gradually recover. Under the optimum content of regenerant, the rutting factor of recycled asphalt is greater than that of matrix asphalt, and the high-temperature stability of recycled asphalt is better than that of matrix asphalt. AASHTO M320 requires the original asphalt \( G^*/\sin\delta \geq 1.0 \text{ kPa} \), after short-term aging \( G^*/\sin\delta \geq 2.2 \text{ kPa} \), the test material meets the requirements. Wang Hengheng et al\(^{[24]}\) found that the change curve of rutting factor with temperature was basically the same as that of complex modulus in recycled asphalt with regenerant, and the rutting factor gradually decreased with the increase of temperature.

Asphalt rejuvenator generally contains rich small molecular aromatic oil, low viscosity and solubility, and has good fluidity. It can fully diffuse in the aged asphalt and be well compatible with it, and rebuild the balance of the four components to restore the performance of the aged asphalt.

### 4.2. Determination and analysis of the optimum content of Sasobit Redux

#### 4.2.1. Analysis of optimum Sasobit Redux content

Test results of asphalt performance with different Sasobit REDUX contents are shown in table 6.

It can be seen from table 6 that compared with the viscosity of matrix asphalt, the addition of Sasobit REDUX can effectively reduce the high-temperature viscosity of asphalt. When the content is 1%, the viscosity of asphalt decreases by 30.4%. With the increase of Sasobit Redux content, the penetration, ductility and viscosity of asphalt decrease. When the content is 2%, the penetration does not meet the technical requirements of 70# matrix asphalt. Therefore, the optimum content of Sasobit REDUX is 1%.

#### 4.2.2. Performance analysis of asphalt with optimum Sasobit REDUX content

In the DSR temperature scanning test, the change curve of rutting factor is shown in figure 8.

It can be seen from figure 8 that the ordinate is the logarithmic coordinate. The \( \lg (G^*/\sin\delta) \) of 1% Sasobit REDUX asphalt and matrix asphalt decreases with the increase of temperature, and both of them show good linear relationship with temperature. The \( \lg (G^*/\sin\delta) \) value of 1% Sasobit REDUX asphalt is slightly larger than that of matrix asphalt, indicating that the incorporation of Sasobit REDUX has a certain improvement effect on the high temperature stability of asphalt, but the improvement effect is not obvious. This is because after adding Sasobit REDUX to asphalt, Sasobit REDUX reacts with –OH and C–H in asphalt, these chemical reactions lead to the emergence of new aromatic C-O bonds in asphalt, and make the long chain alkyl of Sasobit REDUX cocrystal with asphalt wax in asphalt, thus changing the crystal structure, component ratio and colloidal structure of asphalt, so that the performance of asphalt has been significantly changed. In the study of composite recycled SBS modified asphalt mixed with warm mix agent, Zhang Mengyuan and Tian Yaogang\(^{[25]}\) found that Sasobit has good compatibility with recycled SBS modified asphalt, the viscosity is greatly reduced, the \( G^* \) is significantly increased, but the ductility value is decreased, the adhesion with aggregate is insufficient, and a series of chemical reactions can occur with recycled asphalt.

| Technical indicators | Sasobit Redux dosage/% |
|----------------------|------------------------|
|                      | 0          | 1          | 2          | 3          | 4          |
| Needle penetration/0.1 mm | 74.6      | 63.1      | 57.2      | 53.4      | 49.3      |
| Softening point/ °C | 49.1      | 51.4      | 54.1      | 56.8      | 60.2      |
| Duration/cm          | >100      | >100      | >100      | 814.6     | 698.3     |
| Viscosity at 135 °C/Pa⋅s | 0.69     | 0.48      | 0.42      | 0.40      | 0.38      |
4.3. Fourier infrared spectroscopy test analysis
The recycled asphalt with the same quality and different dosages was dissolved in toluene organic solvent to prepare the sample solution with the same concentration. The chemical composition and structure of asphalt changed after aging, and the absorption peak and absorption peak intensity of functional groups in asphalt were determined by infrared spectrum. The infrared spectra of recycled asphalt, PAV aged asphalt and regenerant are shown in figures 9 and 10.

It can be seen from figure 9 that there are two strong absorption peaks in the range of 2800–3000 cm\(^{-1}\), and the absorption peak at 2930 cm\(^{-1}\) is the result of C-H stretching vibration of saturated carbon and C-H stretching vibration of aldehyde group, in which the absorption of \(-\text{CH}_2-\) is the strongest. The absorption peak at 2856 cm\(^{-1}\) is the result of the stretching vibration of methylene C-H of saturated hydrocarbons such as alkanes and cycloalkanes, indicating that alkanes contain nonpolar methyl and methylene functional groups. The C-C stretching vibration occurs at 1540 cm\(^{-1}\), and the characteristic peak near 1461 cm\(^{-1}\) is formed by the superposition of C-H in-plane bending vibration in \(-\text{CH}_2-\) and C-H in-plane angular vibration in methyl C-CH\(_3\). The symmetric stretching bending vibration of C-H bond on \((\text{CH}_2)_n\) occurs at 1370 cm\(^{-1}\), and the stretching vibration of sulfoxide S = O occurs at 1030 cm\(^{-1}\). Therefore, the positions of characteristic peaks of regenerant and asphalt before and after aging are basically the same, but the intensities of some absorption peaks are different. This shows that the components are basically the same, mainly composed of aromatic and heteroatom derivatives, cycloalkanes and cycloalkanes. Due to the different relative content of each component,
the intensity of the absorption peak is different. 1700 cm\(^{-1}\) is the bending absorption band of carbonyl group without interference from other groups; 1030 cm\(^{-1}\) is caused by the stretching vibration of sulfoxide S = O, indicating that the content of carbonyl and sulfoxide functional groups can be used to characterize the aging degree of asphalt.

Figure 10 is the infrared spectrum of warm mix recycled asphalt with different recycled asphalt content. The research on asphalt aging and regeneration mainly focuses on the changes of oxygen-containing functional groups such as carbonyl and sulfoxide \[14, 15\]. In this paper, with the help of omnic software, the peak area of characteristic peaks were calculated by baseline method, and the state of asphalt aging and regeneration was characterized by calculating carbonyl and sulfoxide functional group indexes. The calculation method of peak area took the tangent of the lowest point on both sides of the absorption peak as the baseline, and the change of the absorption intensity index of sulfoxide and carbonyl was calculated according to the formula (1) and (2). The calculation results are shown in table 7.

\[
I_{S\equiv O} = \frac{A_2}{A_1} \\
I_{C\equiv O} = \frac{A_3}{A_1}
\]

In the formula: \(A_1\)-carbon single bond peak area (centered at 1400 ~ 1500 cm\(^{-1}\)); \(A_2\)-sulfoxide peak area (centered at 930 ~ 1080 cm\(^{-1}\)); \(A_3\)-carbonyl peak area (1670 ~ 1750 cm\(^{-1}\)).

It can be seen from table 7 that the content of sulfoxide group increases due to the oxidation of sulfide after asphalt aging, and the carbonyl functional group is composed of ketone, carboxylic acid and carboxylic anhydride, which has strong activity. The oxygen absorption aging of asphalt increases the carbonyl and content, indicating that the oxidation reaction occurs in the aging process of asphalt. The reduction effect of sulfoxide group is not obvious after adding regenerant into aging asphalt, and the sulfoxide group index of warm-mixed recycled asphalt decrease with the decrease of recycled asphalt content; After adding regenerant to the aged

| Specimen         | \(I_{S\equiv O}\) | \(I_{C\equiv O}\) |
|------------------|------------------|------------------|
| matrix asphalt   | 0.1702           | 0.0176           |
| PAV aged asphalt | 1.1992           | 0.1271           |
| 30%-RW           | 0.7117           | 0.4387           |
| 50%-RW           | 0.9477           | 0.3737           |
| 70%-RW           | 1.0168           | 0.2938           |
| 100%-RW          | 1.1607           | 0.1999           |

Figure 10. Test results of recycled asphalt.

Table 7. Functional group index of recycled asphalt binder with different aged asphalt content.
asphalt, the carbonyl content increases, and the carbonyl functional group index gradually decreases with the increase of the content of aged asphalt, indicating that with the increase of the content of recycled asphalt, the content of new asphalt gradually decreases, and the content of polar functional groups after regeneration decreases. The regenerant dilutes and dissolves the polar substances in the aged asphalt.

4.4. Analysis of rheological properties

4.4.1. Temperature scanning analysis

The test results are shown in figures 11, 12 and 13.

It can be seen from figure 11 that the complex modulus of warm mix recycled asphalt and matrix asphalt with different recycled asphalt content decreases gradually with the increase of temperature. Since the larger the complex modulus $G^*$, the stronger the anti-deformation ability, which indicates that raising the temperature of asphalt shear resistance and anti-rutting ability unfavorable. The relationship of complex shear modulus is: $30\%-RW > 50\%-RW > 70\%-RW > 100\%-RW >$ matrix asphalt. The complex shear modulus $G^*$ of warm mix recycled asphalt decreases with the increase of recycled asphalt content, and is greater than that of matrix asphalt. Zhang Ran et al [26] found that the complex shear modulus of recycled asphalt and warm mix recycled
asphalt showed a good logarithmic linear relationship with temperature, and $G^*$ gradually decreased with the increase of temperature.

It can be seen from figure 12 that the rutting factors of warm mix recycled asphalt are larger than those of matrix asphalt. With the increase of temperature, the change trend is basically the same, indicating that the shear resistance and rutting resistance of warm mix recycled asphalt are enhanced.

It can be seen from figure 13 that with the increase of temperature, the phase angle of matrix asphalt and warm mix recycled asphalt increases with the increase of its content. Because the smaller the phase angle $\delta$ is, the more elastic components in the asphalt are, the less likely the asphalt is to deform after being subjected to the same load. Therefore, with the increase of temperature, the viscosity ratio of asphalt increases and the elastic ratio decreases, which makes the deformation difficult to recover and its high temperature deformation resistance weakened. The content of recycled asphalt will significantly change the viscoelastic ratio of warm mix recycled asphalt. The phase angle of recycled asphalt is smaller than that of matrix asphalt, and decreases with the increase of recycled asphalt content, indicating that warm mix recycled asphalt has good high-temperature stability. The larger the content of aging asphalt, the better its high-temperature stability.

4.4.2. Frequency scanning analysis
The test results are shown in figures 14, 15, 16.

From the modulus change curves 14, 15 and 16 of warm mix recycled asphalt at 14 °C, 40 °C and 64 °C, the following points can be analyzed:

① At the same temperature, the complex modulus of warm mix recycled asphalt and matrix asphalt increases with the increase of angular frequency. With the increase of loading frequency, the vibration per unit time increases, which reduces the strain of asphalt, and the complex modulus of warm mixed recycled asphalt and matrix asphalt gradually increases. Under the condition of low temperature and high frequency, the complex modulus value of matrix asphalt is larger, and the deformation under the load is smaller, which means that higher driving speed will reduce the damage to the pavement; The complex modulus of warm mixed recycled asphalt decreases with the increase of recycled asphalt content, indicating that increasing RAP content under low temperature and high frequency conditions is unfavorable to the stability of warm-recycled asphalt mixture. Based on the rheological properties of asphalt, Wang Weiying et al[27] studied the performance of a large proportion of warm mix recycled asphalt binder and the interaction effect of warm mix agent and aging asphalt. It was found that no matter what kind of asphalt, when the temperature is higher, the frequency has a greater impact on the complex shear modulus of asphalt, and the multiple of reduction from high frequency to low frequency can reach 400 times.

② At 14 °C, 40 °C and 64 °C, the change rate of complex modulus of warm mixed recycled asphalt is basically the same, and the complex modulus decreases gradually with the increase of temperature. Temperature and frequency are the main factors affecting the complex modulus of asphalt. As asphalt is a viscoelastic material, with the increase of temperature, asphalt softens, and asphalt transforms from elasticity to viscoelasticity. The
bonding effect between asphalt components is weakened, which makes the complex modulus decrease gradually.

The complex modulus of 50%-RW at three temperatures is close to that of matrix asphalt, indicating that the temperature susceptibility of 50%-RW is similar to that of matrix asphalt.

Figure 17 shows the master curve of complex modulus of warm mixed recycled asphalt with different recycled asphalt content, and the reference temperature is 40°C. Through the main curve analysis of warm mix-recycled asphalt binder, Zhang Ran et al. [26] found that the main curve of aged asphalt in the low frequency region is higher than that of matrix asphalt, and the main curve in the high frequency region is basically coincident with matrix asphalt. Aged asphalt is not sensitive to high frequency scanning, but has a greater impact on the low frequency region. It can be seen from the figure that the complex modulus of 70# matrix asphalt is the smallest under the condition of low frequency and high temperature, indicating that the high temperature deformation resistance of matrix asphalt is poor, and the high temperature deformation resistance of warm mix recycled asphalt is better than that of matrix asphalt. Under the condition of high frequency and low temperature, the complex modulus of warm mix recycled asphalt with different content of recycled asphalt has little difference, indicating that the content of recycled asphalt has no obvious effect on the complex modulus under the condition of high frequency and low temperature; Under the condition of low frequency and high...
temperature, the complex modulus of 50%-RW is the largest, indicating that the warm mix recycled asphalt with 50% recycled asphalt content has better high temperature deformation resistance.

4.4.3. Linear amplitude scanning analysis

The test results are shown in figures 18 and 19.

The shear stress-strain curve can reflect the dependence of asphalt material on the applied strain and the damage during the application of load. It can be seen from figure 18 that the relationship between the yield stress of warm mixed recycled asphalt under different recycled asphalt content is: 30%-RW > 50%-RW ≈ Base asphalt > 70%-RW > 100%-RW. At 20 °C, the yield stress of 30%-RW is the largest, indicating that it has the strongest ability to resist deformation. With the increase of recycled asphalt content, the deformation degree under the action of yield stress increases gradually. The above analysis shows that when the content of recycled asphalt is not more than 50%, the resistance to load deformation in the medium temperature zone of warm mixed recycled asphalt is higher than that of matrix asphalt; When the content of recycled asphalt is more than 50%, its resistance to load deformation decreases gradually, but the deformation degree of warm mixed recycled asphalt increases under the action of yield stress; When the content of recycled asphalt is 50%, the width of its peak is the largest, which reflects that the dependence of warm mixed recycled asphalt on applied strain is

Figure 16. The variation curve of complex modulus at 64 °C.

Figure 17. Master curve diagram of warm mix recycled asphalt.

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weakened, indicating that the elastic performance and fatigue resistance of warm mixed recycled asphalt with the content of 50% recycled asphalt are increased. Wang Weiying et al. [27] found that the addition of aged asphalt did not reduce the fatigue resistance of asphalt binder, and the change of aged asphalt content had different effects on different recycled asphalt binders. The addition of R-type and M-type warm mix agents improves the fatigue life of recycled asphalt binder, and the improvement effect of R-type warm mix agent is more obvious.

With the gradual increase of strain, the phase angle increases first and then decreases, and there is a peak. The peak shear stress is the yield stress of the material, and the peak phase angle can be used as the basis for judging the final failure of the material. It can be seen from figure 19 that the peak value of phase angle lags behind the yield stress, indicating that the asphalt undergoes yield first and then fails during LAS test.

4.4.4. Multiple stress creep recovery test analysis

The results of multiple stress creep recovery test are shown in figures 20 and 21.

It can be seen from figures 20 and 21 that under 64 °C and creep stress of 0.1 KPa and 3.2 KPa, the matrix asphalt basically has no creep recovery ability, and the cumulative strain increases linearly; For warm mix recycled asphalt, with the passage of time, the cumulative strain decreases gradually with the increase of recycled asphalt.
asphalt content, indicating that its high-temperature deformation resistance is enhanced. The strain increases gradually, but the strain hardly recovers in the stress unloading stage, which indicates that under this temperature condition, the warm mixed recycled asphalt is a viscous body, the elastic component almost disappears, and has obvious nonlinear viscoelastic characteristics. In ten creep recovery cycles, the strain relationship is as follows: 30%-RW > matrix asphalt > 50%-RW > 70%-RW > 100%-RW, indicating that warm mixed recycled asphalt has good deformation resistance. In conclusion, the content of recycled asphalt binder should not be greater than 50%. Guo Yunfei et al. [28] conducted further analysis on the high temperature performance of recycled asphalt through MSCR test, and concluded that the increase of aging asphalt content can improve the anti-deformation ability of recycled asphalt at high temperature. When the content of aging asphalt increased to more than 50%, BR recycled asphalt showed lower creep recovery rate, and the proportion of elastic components decreased.

4.5. BBR test analysis

4.5.1. BBR test results

The BBR test results of warm mix recycled asphalt mixture with different recycled asphalt content at −18 °C are shown in figures 22 and 23.

As can be seen from figure 22, the strain increases with time, resulting in stiffness modulus decreases, reflected in the figure shows different recycled asphalt content of asphalt stiffness modulus decreased with time.
Under the same time condition, with the increase of recycled asphalt content, the stiffness modulus increases, which indicates that the brittleness of asphalt increases and the low temperature crack resistance decreases gradually. The relationship between the low temperature crack resistance is: 100%-RW > 70%-RW > 30%-RW > 50%-RW > matrix asphalt.

The creep rate m value reflects the speed of the change of the stiffness modulus S value under low temperature conditions, that is, the slope in the stiffness modulus S curve. The larger the m value, the faster the change rate of the stiffness modulus S value, indicating that the better the stress relaxation ability. Therefore, when the S value is the same, the greater the m value, the better the low temperature performance of asphalt. It can be seen from figure 23 that the slope m value increases with time, indicating that the change rate of creep deformation gradually increases. At the same time, with the increase of recycled asphalt content, the m value gradually decreases, indicating that the ability of asphalt to resist temperature tensile stress is weakened, and the low temperature cracking resistance is reduced. Its low temperature cracking resistance is: matrix asphalt > 50%-RW > 30%-RW > 70%-RW > 100%-RW.

It indicates that SHRP plan stipulates that the stiffness modulus should not exceed 300 MPa for 60 s, and the m value should not be less than 0.30. It can be seen that the warm mix recycled asphalt meets the requirements of the specification at −18°C.

**Figure 22.** −18°C variation of stiffness modulus of warm-mixed recycled asphalt with time.

**Figure 23.** −18°C variation of m value of warm-mixed recycled asphalt with time.
4.6. Performance of warm mix recycled asphalt mixture

Since the content of recycled asphalt binder should not be greater than 50%, the road performance test is carried out with rap content of 50%, and compared with the road performance of ordinary hot mix recycled asphalt mixture. The results are shown in table 8.

It can be seen from table 8 that compared with ordinary hot mix recycled asphalt mixture, the dynamic stability of warm mix recycled asphalt mixture with 50% rap is increased, the high temperature performance is improved, and the low temperature performance and water stability meet the specification requirements, indicating that the warm mix recycled asphalt mixture with 50% rap has excellent road performance.

5. Conclusion

The softening point of asphalt increases after aging, and the penetration and ductility decrease. When the content of regenerant is 10%, the three indexes of recycled asphalt are basically restored to the level of 70# matrix asphalt, so the optimal content of regenerant is 10%. The warm mix agent has a good effect on the viscosity reduction of asphalt. The incorporation of Sasobit REDUX has a certain improvement effect on the high temperature stability of asphalt. The optimum content of Sasobit REDUX is 1%. After asphalt aging, the complex modulus and rutting factor increase, and the phase angle decreases, indicating that the shear deformation resistance and high temperature stability of the aged asphalt are improved, and the fatigue resistance is weakened. The temperature sweeping test shows that the regenerant can effectively reduce the complex shear modulus of the warm mix recycled asphalt and increase the phase angle. The rutting factor is larger than that of the matrix asphalt, indicating that the shear resistance and rutting resistance of the warm mix recycled asphalt are enhanced. Frequency sweeping and master curve analysis show that the influence of recycled asphalt content on complex modulus is not obvious under high frequency and low temperature conditions, while under low frequency and high temperature conditions, 50% warm mix recycled asphalt has better high temperature deformation resistance. The linear amplitude sweeping test can be found that when the content of recycled asphalt is 50%, the ability of warm mix recycled asphalt to resist load deformation and temperature sensitivity in the middle temperature zone is similar to that of matrix asphalt, and it has better deformation resistance. For warm mix recycled asphalt, the strain accumulation decreases with the increase of recycled asphalt content under stress, indicating that its high temperature deformation resistance is enhanced. With the increase of the content of recycled asphalt, the brittleness of asphalt increases, and the low temperature crack resistance of warm mix recycled asphalt decreases. When the content of recycled asphalt is 50%, warm mix recycled asphalt has good low temperature crack resistance. The optimum content of recycled asphalt should be 50%, and the warm mix recycled asphalt mixture has excellent road performance.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

CRediT authorship contribution statement

Zhenxia Li: Conceptualization, Investigation, Project administration, Supervision, Writing-Review & Editing. Tengteng Guo: Conceptualization, Formal analysis, Methodology, Visualization. Yuanzhao Chen: Supervision, Project administration, Data curation, Formal analysis. Xuewei Bian: Conceptualization, Writing-Original Draft, Supervision, Investigation. Xiaoxiao Jiang: Conceptualization, Supervision, Writing-Original Draft. Menghui Hao: Conceptualization, Project administration, Super-vision, Investigation. Xu Zhao: Funding acquisition, Investigation. Jinyuan Liu: Project administration, Resources.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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