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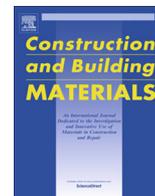
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Investigating the role of swelling-degradation degree of crumb rubber on CR/SBS modified porous asphalt binder and mixture



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HIGHLIGHTS

- Performance evaluation of CR/SBS modified porous asphalt binder and mixture.
- The influence of swelling/degradation degree of CR and SBS dosage are investigated.
- CR/SBS modified porous asphalt mixture shows sufficient engineering performance.
- CR/SBS modified bitumen could be used as a high-viscosity binder of porous asphalt.

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ABSTRACT

Porous asphalt pavement is widely used due to its adequate water permeability, noise reduction and skid resistance. The study aims at exploring the potential of using the crumb rubber/styrene-butadiene styrene (CR/SBS) modified bitumen as high-viscosity binder for porous asphalt mixture, and investigating the effect of swelling and degradation degree of crumb rubber as well as SBS dosage on the performance of porous asphalt binder and mixture. The conventional, rheological and engineering properties of CR/SBS modified high-viscosity porous asphalt binders and mixtures were characterized. The results revealed that the CR swelling-degradation degree significantly affected the physical and viscoelastic properties of CR/SBS modified high-viscosity binders. With the swelling time prolonged, the viscosity of rubber bitumen enhanced gradually until reaching the equilibrium state, which kept falling during the degradation process dramatically. The full-swelling binders exhibited the highest complex modulus, zero-shear viscosity, rutting resistance, which deteriorated as the degradation degree increasing. However, the degradation of crumb rubber would be beneficial to improve the workability, thermal cracking resistance and deformation recovery ability of high-viscosity binder. Meanwhile, the incorporation of SBS copolymer could further strengthen both high-and-low temperatures viscoelastic performance of high-viscosity bitumen. In addition, the performance of porous asphalt with CR/SBS modified high-viscosity bitumen could meet the requirements of Marshall stability, air void content, Cantabro loss, run-off loss, anti-rutting, moisture damage resistance and permeability performance. Although the full-swelling asphalt mixture presented the best rutting resistance, it showed the poor adhesive and moisture damage resistance when compared with partial and full-degradation asphalt mixtures.

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1. Introduction

With the development of the social economy, the demand for safe and functional asphalt pavement increases gradually [1,2]. To reduce the surface water and noise on the asphalt road, the porous asphalt (PA) pavement is developed. As defined, porous asphalt

mixture presents the characteristic of high air void content, which is beneficial to improve the drainage and skid resistance. Moreover, porous asphalt pavement is also called the Porous Asphalt Wearing Course (PAWC) or Open-graded Friction Course (OGFC). Compared to dense-grade asphalt pavement, porous asphalt has superior functions regarding the improvement of skid resistance, noise reduction and driving safety [3–5].

Due to the high air void, it is easy for porous asphalt to appear the raveling and rutting damages under the complex conditions of heavy loading, high temperature, moisture and oxygen

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penetration, etc. [6]. To construct the porous asphalt roads with sufficient strength and deformation resistance, the cohesive and adhesive properties of porous asphalt binder are of importance distinctly [7–9]. The durability requirement of porous asphalt would accelerate the development of binders with predominant high-temperature rutting, low-temperature cracking and aging resistance [10,11]. Many studies were conducted to develop the appropriate bitumen of porous asphalt. In the United States, the polymer modified bitumen or rubber binder were utilized to guarantee the durable performance for porous asphalt pavement [12–14]. In Europe, the porous asphalt binder was prepared by modifying bitumen with the fibers, epoxy resin, CR, SBS copolymers, etc. [15–17].

Amounts of works have been performed to seek the favorable modifiers to manufacture the high-viscosity bitumen for porous asphalt with excellent resistance to rutting and moisture-induced raveling damage [18]. The Taftack-Super (TPS) composite proposed from Japan is the most popular product utilized to manufacture the high-viscosity binder with the superior comprehensive properties [19]. However, because of the confidential formulation, the TPS modifier cost is expensive, which significantly inhibits the extensive application of porous asphalt roads. Afterwards, some self-developed high-viscosity modifiers (SINOTPS, RST, etc.) have also been developed [20]. The unclear constitute information of these high-viscosity additives leads to the difficulty studying the corresponding modification mechanism and performance improvement of porous asphalt binder and mixture.

It is essential to develop the suitable high-viscosity bitumen for porous asphalt by using the commonly-used additives to improve the overall properties of the binder, such as the crumb rubber and SBS copolymers. According to previous studies, the adjunction of CR and SBS could significantly enhance the rheological and engineering properties of bitumen [21,22]. Moreover, the application of CR or SBS modified bitumen into the porous asphalt also has been studied [23]. Shirini et al. systematically estimated the properties of PA mixtures prepared with CR or SBS modified binders and found that both CR and SBS could strength the rutting resistance dramatically [24]. Meanwhile, Sangiorigi et al. also reported that adding crumb rubber into porous asphalt mixture through the dry method enhanced the thermal and moisture susceptibility as well as the raveling resistance of porous asphalt [25]. Although the permeability reduced, the durability of porous asphalt was further improved by incorporating the CR or SBS copolymer.

Currently, the interaction mechanism between crumb rubber and bitumen has attracted more attention [26]. There are mainly two physical and chemical reactions containing of the swelling and degradation of crumb rubber particles in bitumen [27]. Due to the existence of network structure in crumb rubber, it could absorb the light components from bitumen easily. During the swelling process, the rubber volume and stiffness of the bitumen phase would enhance gradually, which significantly influences the physical and rheological properties of rubber bitumen [28,29]. When the reaction temperature or mixing time is high, the crumb rubber starts to degrade and release components into the bitumen matrix. Thus, the swelling and degradation of CR particles show a dominant influence on the properties of CRMB binder [23]. In addition, the interaction between CR and bitumen largely depends on the bitumen composition, rubber dosage and particle size, reaction temperature, mixing time [30]. It was found that the absorption preference of crumb rubber improved the rutting resistance of rubberized asphalt. However, there are few researches to investigate the influence of swelling and degradation degree of crumb rubber on the properties of rubber bitumen. Furthermore, the interaction mechanism between CR and bitumen is still unclear, which results in the difficulty for quality control of CRMB binder [31].

To sum up, the potential application of CR/SBS modified high-viscosity bitumen in porous asphalt considering the swelling and

degradation degree of crumb rubber has few been studied systematically. The objective of the study is to examine the applicability of CR/SBS modified high-viscosity bitumen as the binder of porous asphalt pavement, and evaluate the influence of swelling/degradation degree of crumb rubber as well as SBS dosage on the rheological and engineering properties of porous asphalt binder and mixture.

2. Materials and experimental methods

2.1. Materials

The virgin bitumen with 60/80 penetration-grade is employed, and its physical properties are listed in Table 1. Besides, crumb rubber powder is recycled from waste tires and its density, moisture content and ash content of rubber powder is 1.2 g.cm^{-3} , 0.3 wt% and 5.4 wt%, respectively. Fig.1 illustrates the size distribution of rubber powder. The SBS copolymer is the T6302H with an average molecular weight of 130,000 g/mol and S/B ratio of 30/70.

2.2. Determine the preparation conditions of CRMB binders with different swelling and degradation degrees

It was reported that the swelling and degradation of crumb rubber significantly influenced the rheological properties of rubber bitumen [26,30]. To determine the preparation conditions of CRMB binders with the stable and different viscoelastic behaviors, the viscosity variation of CRMB binders as a function of swelling and degradation time is monitored.

The 20 wt% CR powder was mixed with virgin bitumen under the rotational speed of 1500 rpm/min and temperature of 160 °C. The temperature was selected to maximize the swelling and minimize the degradation degree of rubber powder in bitumen phase

Table 1
Conventional properties of virgin bitumen.

Items	Measured value	Testing standard
25 °C penetration (0.1 mm)	67	ASTM D5 [32]
Softening point (°C)	48.4	ASTM D36 [33]
10 °C ductility (cm)	85.2	ASTM D113 [34]
Saturates (S, wt%)	13.35	ASTM D4124 [35]
Aromatics (A, wt%)	17.35	
Resins (R, wt%)	39.70	
Asphaltenes (At, wt%)	29.60	

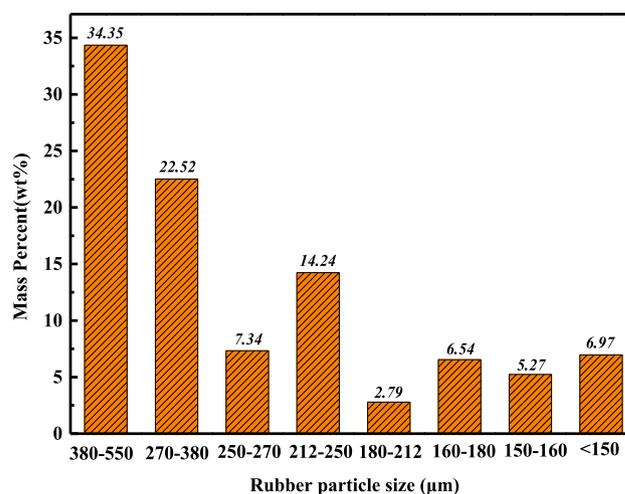


Fig. 1. The particle size distribution of crumb rubber powder

[26,28]. The 135 °C viscosity of CRMB binder during the swelling procedure was measured per 30 min, and the results are demonstrated in Fig. 2(a). With the increase of swelling time, the viscosity of CRMB binder shows an increasing trend gradually. During the swelling process, the crumb rubber absorbs the light components from the bitumen matrix, which results in the high stiffness of the bitumen phase and a large volume of rubber particle. That is the reason why the viscosity of CRMB binder significantly increases with the swelling time prolongs. Moreover, it should be noted that the viscosity of CRMB binder keeps consistent when the mixing time exceeds eight hours, where the mass exchange reaches equilibrium at that temperature. Hence, the corresponding stable CRMB binder at 160 °C and a mixing time of 8 h is defined as the sufficient swelling degree, denoted as a full-swelling CRMB binder and coded as QRZ0.

When the full-swelling CRMB binder is obtained, the reaction temperature rises from 160 to 200 °C, which accelerates the degradation and dissolution of the rubber particles in bitumen phase. This process is known as the degradation of crumb rubber. The 135 °C rotational viscosity of CRMB binder was tested per 2.5 h. The relationship between the viscosity of CRMB binder and degradation time is presented in Fig. 2(b). It should be noted that the viscosity of rubber bitumen increases first when the degradation time is less than 10 h, which is associated with the continuous swelling

of rubber particles in the binder as the increase of temperature. Afterwards, the viscosity of CRMA binder goes down remarkably with the prolongation of mixing time, which implies the degradation interaction of rubber modifier in bitumen. During the degradation process, the network structure of crumb rubber is broken and light components continue to release to the bitumen phase. Interestingly, when the degradation time gets to 35 h approximately, the viscosity of CRMB binder keeps consistent as the degradation time increases. Hence, the corresponding stable status of CRMA binder at 200 °C and a mixing time of 35 h is defined as the full-degradation degree, which is called as full-degradation CRMB binder and abbreviated QJJ0. Furthermore, in line with the viscosity variation of CRMB binder with the degradation time, one point of status with the mixing time of 18 h at 200 °C is deemed to be partial-degradation case, which is calculated as the average viscosity value of the largest and lowest viscosity for CRMB binder during degradation reaction. The aforementioned CRMB sample is called the partial-degradation CRMB binder and is abbreviated as BJJ0.

2.3. Preparation of CR/SBS modified high-viscosity binders

To control the swelling and degradation degree of CR particles, the intermixing method is adopted to fabricate the CR/SBS composite modified high-viscosity bitumen. Firstly, SBS modified binders with a high SBS dosage of 10.0, 20.5, 31.0 and 41.7 wt% were prepared using a high-shear blending device. The virgin bitumen and SBS copolymer were sheared and mixed for 2 h at 175 °C with the shear speeding of 4000 rpm/min to guarantee the homogenous dispersity of SBS copolymer in bitumen. Simultaneously, CRMB binders with full-swelling, partial-degradation and full-degradation status were prepared under different conditions of temperature and mixing time according to the results displayed in Fig. 2. Lastly, 1200 g CRMB binder, 133 g high-dosage SBS modified bitumen and 1.6 g sulfur were mixed under the temperature of 160 °C (full-swelling CRMB) or 200 °C (partial-degradation and full-degradation CRMB) and rotational speed of 1500 rpm/min for 2 h. The ultimate dosage of crumb rubber and sulfur in all samples is 15 wt% and 0.12 wt% to the total weight of high-viscosity bitumen. Meanwhile, CR/SBS composite modified high-viscosity binders with various SBS content of 1 wt%, 2 wt%, 3 wt% and 4 wt% were prepared with the same method. To compare these various bitumen samples easily, the abbreviation, preparation conditions and material compositions of CR/SBS modified high-viscosity binders are listed in Table 2. Further, the preparation illustration of bitumen samples is displayed in Fig. 3.

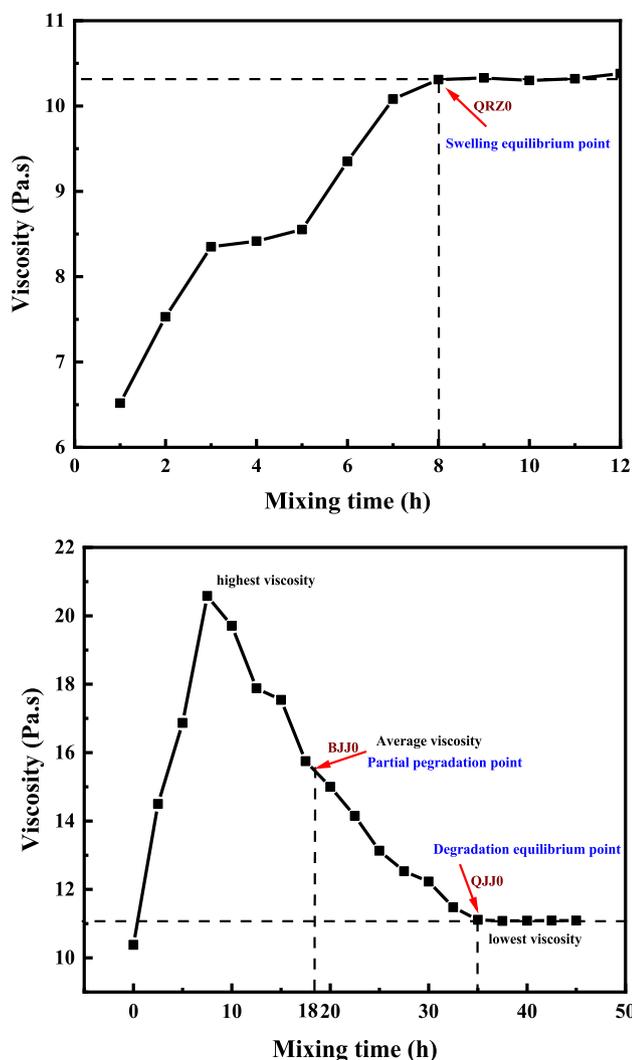


Fig.2. The 135 °C viscosity of CRMB binder during swelling (a) and degradation (b) processes.

Table 2 The preparation conditions and material compositions of CR/SBS modified high-viscosity bitumen.

Samples code	Preparation conditions	CR dosage (wt%)	SBS dosage (wt%)
QRZ0	Full-swelling CRMB and SBSMB binders are mixed for 2 h at 160 °C and 1200 rpm	15	0
QRZ1		1	
QRZ2		2	
QRZ3		3	
QRZ4		4	
BJJ0	Partial-degradation CRMB and SBSMB binders are mixed for 2 h at 200 °C and 1200 rpm	15	0
BJJ1		1	
BJJ2		2	
BJJ3		3	
BJJ4		4	
QJJ0	Full-degradation CRMB and SBSMB binders are mixed for 2 h at 200 °C and 1200 rpm	15	0
QJJ1		1	
QJJ2		2	
QJJ3		3	
QJJ4		4	

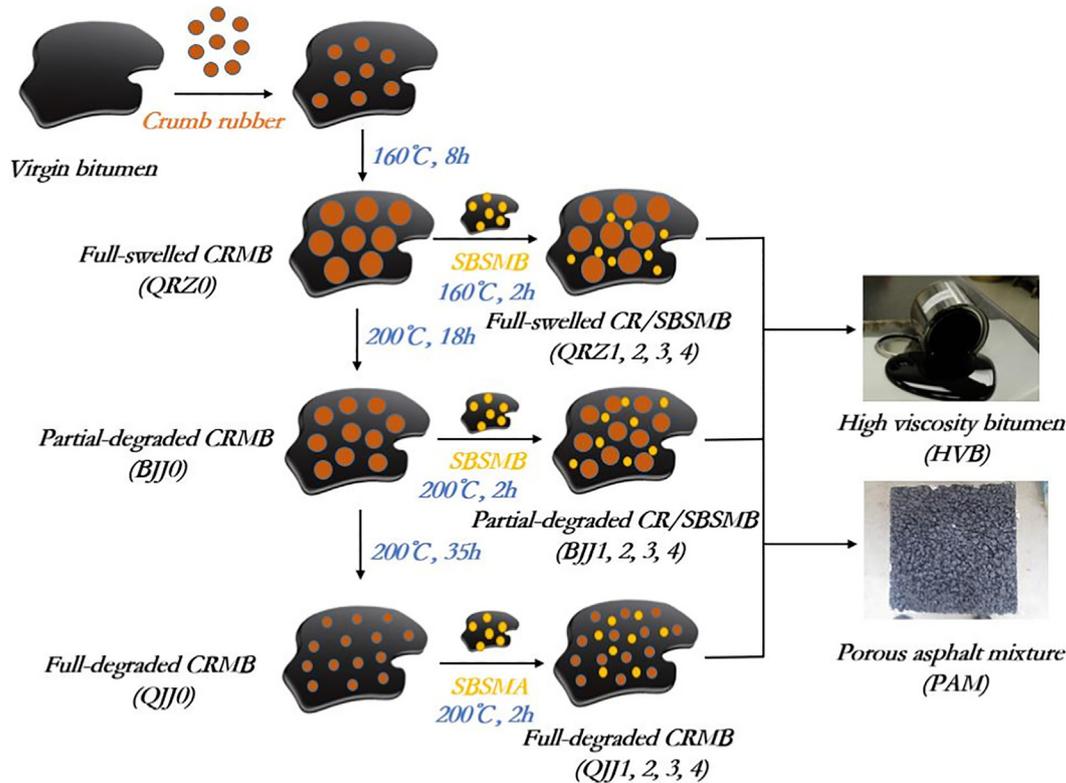


Fig.3. Preparation illustration of CR/SBS modified high-viscosity binders

2.4. Experimental methods

2.4.1. Characterization of high-viscosity bitumen

The conventional properties of bitumen, including the 25 °C penetration, softening point, 5 °C ductility as well as 135 °C rotational viscosity, were measured. The 60 °C-frequency sweep test and temperature sweep test at 10 rad/s were conducted on high-viscosity binders by using a dynamic shear rheometer (DSR, TA-HR1) with parallel plate geometry (25 mm plate diameter and 1 mm gap width). During the frequency and temperature sweep tests, loading frequency and temperature varies from 10^{-1} to 10^2 rad/s and from 52 °C to 82 °C with an increment of 6 °C, separately. In addition, all samples were subjected to 60 °C multiple stress creep and recovery (MSCR) tests at 0.1 and 3.2 kPa. Besides, 60 °C flow measurement was carried out to assess the flow behavior of high-viscosity bitumen. The shear rate range of the flow test was from 10^{-3}s^{-1} to 10^2s^{-1} .

2.4.2. Characterization of porous asphalt mixtures

To determine the lowest value of bitumen-aggregate ratio and evaluate the raveling resistance of porous asphalt mixtures, the Cantabro abrasion test was conducted on standard Marshall samples. The Cantabro mass loss was calculated using Eq.1, where m_0 and m_1 refer to the mass of asphalt mixture before and after Cantabro abrasion test.

$$\text{Cantabroloss} = \frac{m_0 - m_1}{m_0} \times 100\% \quad (1)$$

The run-off test was performed to determine the maximum point of bitumen-aggregate ratio. The Schellenberg loss value can be calculated by using Eq.2, where, m_0 , m_1 and m_2 represent the mass of empty beaker, total mass of beaker and sample before and after the Schellenberg drainage test.

$$\text{Schellenbergloss} = \frac{m_2 - m_0}{m_1 - m_0} \times 100\% \quad (2)$$

The total and connected air void content of asphalt mixture sample (VV, %) was measured by using Eqs.3 and 4, respectively. Where m_0 refers to the dry mass, g; V represents the total volume, cm^3 ; ρ_T shows the theoretical maximum density, $\text{g}\cdot\text{cm}^{-3}$; m_1 is the mass of sample measured in water, g; ρ_w is the density of water, $\text{g}\cdot\text{cm}^{-3}$.

$$\text{TotalVV} = \left(1 - \frac{m_0}{\rho_T V}\right) \times 100\% \quad (3)$$

$$\text{ConnectedVV} = \left(1 - \frac{m_0 - m_1}{\rho_w V}\right) \times 100\% \quad (4)$$

The 60 °C wheel tracking test was carried out to assess the rutting resistance of porous asphalt for 1 h with repeated wheel load of 0.7 MPa and wheel speed of 42 ± 1 passes per minute. The loading time t , rutting depth d and dynamic stability DS of each sample were recorded during the whole test period.

$$\text{DynamicstabilityDS} = \frac{(t_2 - t_1) * N}{(d_2 - d_1)} \quad (5)$$

The permeability of asphalt mixture was measured with the water permeability test device, which is shown in Fig. 4. The permeability time is recorded with the water capacity decreasing from 500 to 100 ml. The permeability coefficient C_w of porous asphalt mixture is calculated as Eq.6.

$$C_w = \frac{V}{t} * 60 \quad (6)$$

where C_w refers to the permeability coefficient, ml/min; V is the water volume passing the sample, which is 400 ml in this study; t represents the permeability time, s.



Fig.4. The permeability measurement device.

3. Results and discussion

3.1. Physical properties of high-viscosity bitumen

Fig. 5. Physical properties of CR/SBS modified high-viscosity bitumen

Compared to the partial or full-degradation bitumen, the full-swelling bitumen shows the highest softening point and viscosity but has the lowest penetration and ductility value. Moreover, the physical properties of full-degradation bitumen are contrary to that of full-swelling bitumen. Hence, the swelling degree of rubber in the binder is beneficial to high-temperature properties and flow resistance, which has an adverse influence on the workability and low-temperature ductility during pavement construction and service life. Further, with the degradation duration of crumb rubber deepening, the high-temperature performance of CRMB binder is weakened, but it would be beneficial to improve the low-temperature cracking resistance and workability for CR/SBS modified high-viscosity bitumen.

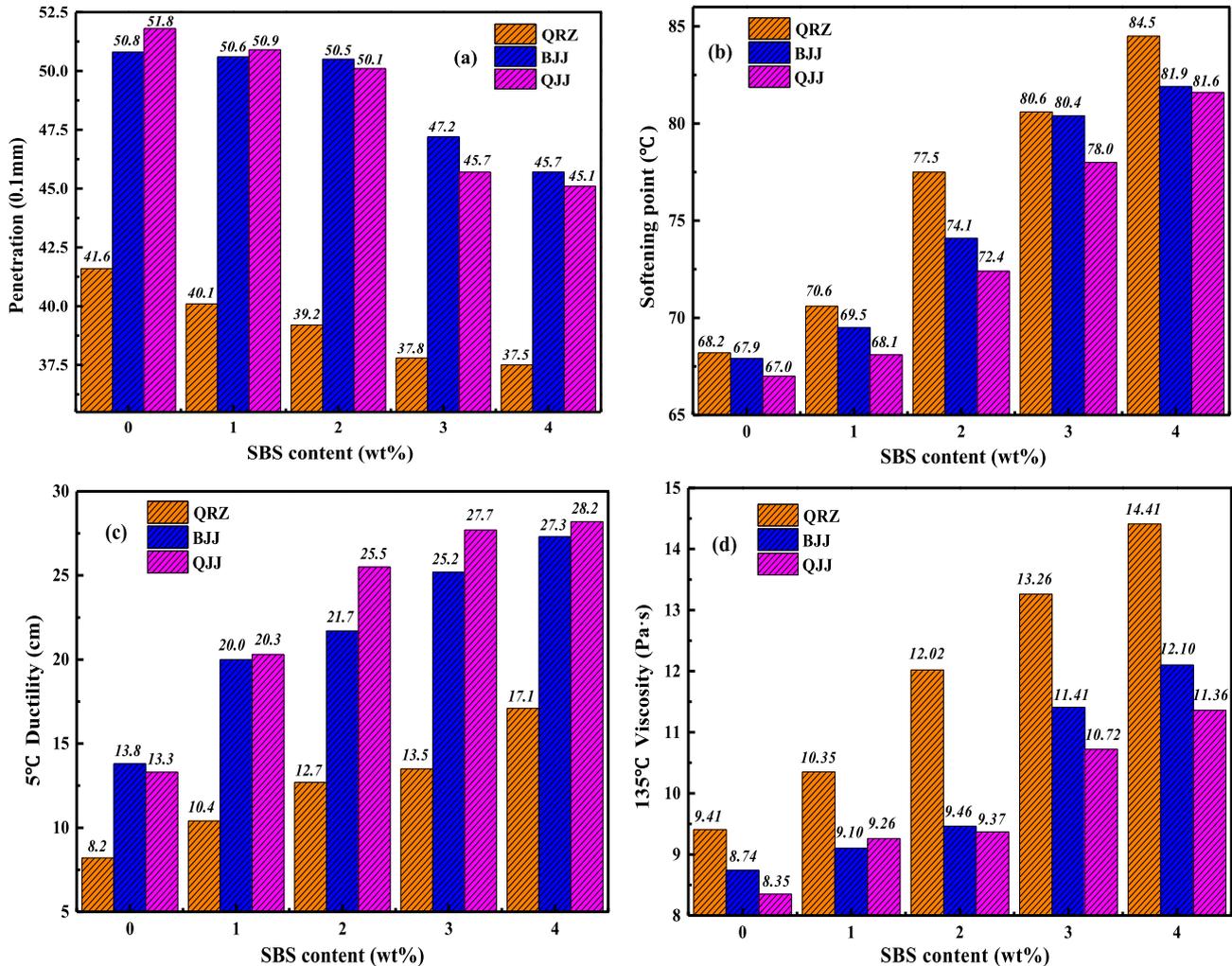


Fig.5. illustrates the penetration, softening point, 5 °C ductility and 135 °C viscosity values of different CR/SBS modified high-viscosity binders. Obviously, the swelling and degradation degree of crumb rubber significantly affects these physical properties of rubber bitumen. With the increase of mixing temperature and time of rubber binder, the penetration and ductility values of high-viscosity binders both enhance, while the softening point and viscosity values decrease dramatically. The penetration of full-swelling rubber bitumen is 4.16 mm, which increases to 5.08 and 5.18 mm for partial and full-degradation rubber binders. Meanwhile, the softening point of full-swelling, partial-degradation and full-degradation CRMB binders are 68.2, 67.9 and 67.0 °C, respectively, indicating the degradation of crumb rubber remarkably softens the rubber bitumen. The full-swelling CRMB shows the lowest 5 °C ductility of 8.2 cm, which is 13.8 and 13.3 cm for partial and full-degradation CRMB binders. Regarding the 135 °C rotational viscosity, with the increase of degradation degree, it reduces from 9.41 to 8.74 and 8.35 Pa·s. Therefore, the degradation of crumb rubber in bitumen would improve the flexibility and workability of rubber bitumen.

As expected, with the increase of supplementary SBS dosage, the penetration of CR/SBS compound modified high-viscosity bitumen decreases gradually, while the parameters of the softening point, ductility and viscosity were all enhanced. In other words, the addition of SBS copolymer remarkably improves both high and low-temperature properties of the high-viscosity binder for porous pavement. When 4 wt% SBS is incorporated, the penetration value of full-swelling, partial-degradation and full-degradation CRMB binder decreases from 4.16, 5.08 and 5.18 to 3.75, 4.57 and 4.51 mm, respectively. Meanwhile, the softening point increases by 23.9%, 20.6% and 21.8% for QZR, BJJ and QJJ CRMB binder. Regrading low-temperature property, the 4 wt% SBS copolymer would improve the ductility values by 8.9, 13.5 and 14.9 cm for three types of rubber binders. Further, the 135 °C viscosity of CRMB binder enhances to 14.41, 12.10 and 11.36 Pa·s. Interestingly, the susceptibility of conventional properties to SBS content for full-swelling, partial-degradation and full-degradation is significantly different. It is concluded that the stiffness and high-temperature performance of QRZ CR/SBS modified high-viscosity binder are the best, while the BJJ and QJJ CR/SBS modified high-viscosity asphalt have the best workability and low-temperature properties.

The influence of SBS on improving the softening point and shear viscosity of full-swelling rubber bitumen is more obvious than that of partial and full-degradation CRMB binders. On the contrary, the penetration and ductility properties of rubber bitumen are more sensitive to the additional SBS modifier with the increase of degradation degree of crumb rubber in the binder. The reason may be related to the light fraction content in rubber bitumen. In full-swelling CRMB, the light fraction in the bitumen phase is lower and the rubber particle size is larger than partial and full-degradation CRMB. Hence, the addition of SBS could significantly enhance the high-temperature properties and flow resistance of full-swelling CRMB, while it affects the low temperature cracking resistance of partial and full-degradation CRMB binders dramatically.

The conventional properties of CR/SBS modified high-viscosity binders are also compared with the control values of porous asphalt binders according to ASTM specifications, listed in Table 3. The physical properties of rubber bitumen could not meet the required standard of high-viscosity binder regardless of the swelling and degradation degree of crumb rubber, especially in terms of the softening point, and ductility parameters. Afterwards, SBS copolymer was further added into the CRMB binder to improve the high and low-temperature properties and prepare the CR/SBS modified high-viscosity bitumen for porous asphalt. To ensure that the penetration, softening point and ductility of partial and full-degradation high-viscosity binders meet the required standard, the additional SBS dosage should exceed 3 wt%. However, for the full-swelling binder, the penetration and softening point could not fulfill the standard simultaneously, and its ductility is out of the requirement no matter what SBS dosage is contained. Based on the conventional properties, CR/SBS modified high-viscosity binders with SBS content of 3 wt% and 4 wt% are selected to prepare the porous asphalt mixture to further investigate the influence of the swelling-degradation degree of crumb rubber and SBS dosage on the properties of asphalt mixture, plus verify the appli-

Table 3
The requirement standard of physical properties for high-viscosity bitumen

Physical properties	Required value	Specifications
Penetration (0.1 mm)	>40	ASTM D5 [32]
Softening point (°C)	>80	ASTM D36 [33]
Ductility (5 °C, cm)	>20	ASTM D113 [34]

cation potential of CR/SBS modified bitumen as the high-viscosity binder of porous asphalt pavement.

3.2. Complex modulus

The frequency sweep test was conducted to investigate the complex modulus of different CR/SBS modified high-viscosity binders, and the results are shown in Fig. 6. As expected, the increase of loading frequency would lead to the enhancement of complex modulus. When the frequency is determined, the complex modulus values of rubber bitumen with different swelling and degrada-

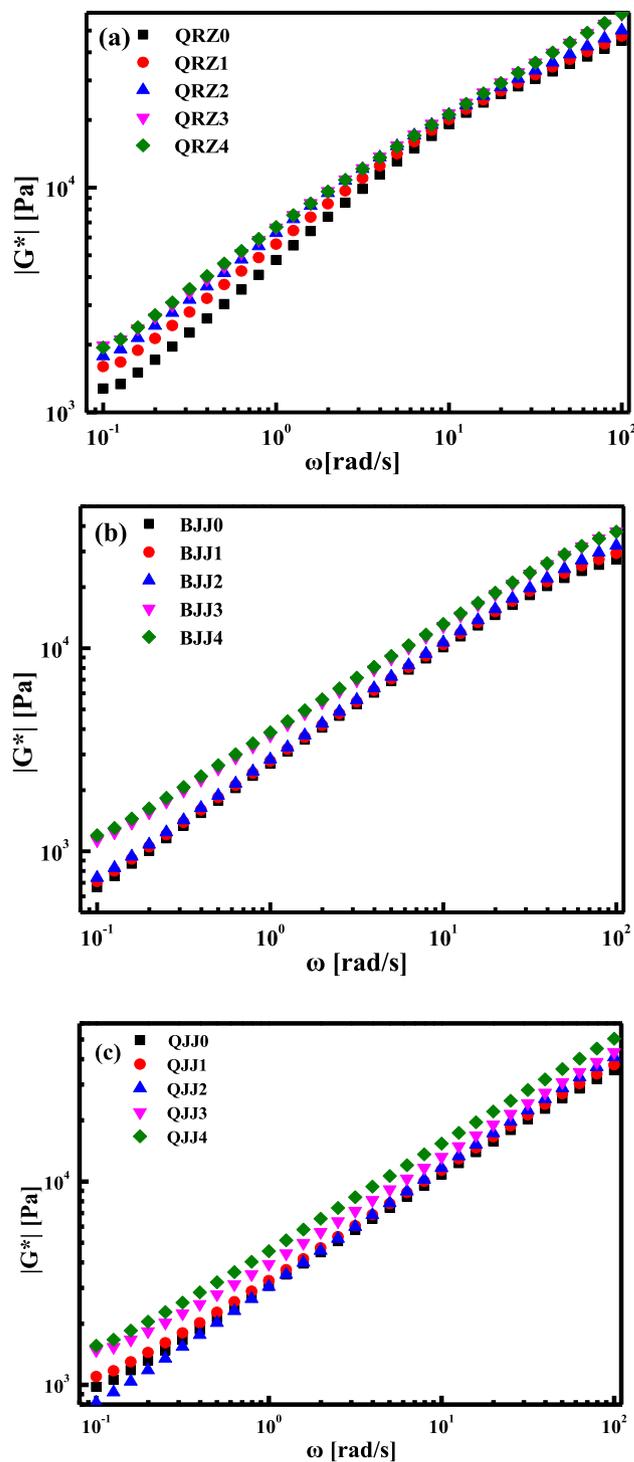


Fig.6. Complex modulus of CR/SBS modified high-viscosity binders.

tion degrees of crumb rubber are significantly different. The full-swelling rubber bitumen shows the highest complex modulus, followed by the partial and full-degradation rubber binders. The particle size of crumb rubber in the full-swelling rubber binder is the largest, which significantly increases the cohesive stiffness and complex modulus of bitumen. With the increase of degradation degree, the light fractions in rubber particles gradually release into the bitumen phase, which results in the reduction of internal interaction between rubber particles and the softening effect on the bitumen matrix. Thus, the full-swelling CRMB binder would exhibit the best permanent deformation resistance, while the degradation of crumb rubber deteriorates the high-temperature performance of rubber bitumen.

Take the inadequate stiffness of rubber bitumen into consideration, and the SBS modified binder with high SBS dosage is mixed with rubber bitumen to prepare the CR/SBS compound modified high-viscosity bitumen for porous asphalt. It could be deduced that the complex modulus of high-viscosity bitumen enhances remarkably with the increase of SBS dosage, regardless of the swelling and degradation condition of crumb rubber in the binder. That is to say, the addition of SBS is beneficial to improve the resistance to deformation of CR/SBS modified high-viscosity blends. Moreover, the effect of SBS on the complex modulus of high-viscosity bitumen is not obvious when the SBS content extends 3 wt%, especially for full-swelling and partial-degradation binders. Considering the lowest complex modulus of full-degradation bitumen, more SBS should be replenished to strengthen its stiffness. The reason may be explained that as the degradation of crumb rubber, more light components are released in the bitumen matrix, which could be absorbed by additional SBS modifiers. It accelerates the formation of polymer network and the significant improvement of complex modulus and stiffness of CR/SBS modified high-viscosity bitumen.

3.3. Rutting resistance

Fig. 7. Rutting factor $G^*/\sin\delta$ of CR/SBS modified high-viscosity bitumen

To further evaluate the effect of the swelling-degradation degree of crumb rubber and SBS dosage on the rutting performance of high-viscosity binder, the rutting failure temperatures (RFT) of all studied samples are calculated as the rutting parameter is equal to 1.0 kPa, listed in Table 4. It is noteworthy that mixing temperature and time have a significant influence on the high-temperature property of rubber bitumen. The full-swelling rubber binder shows the highest failure temperature of 95.39 °C, while the full-degradation binder has the lowest failure temperature of 89.30 °C. Moreover, the RFT value for partial-degradation rubber bitumen of 92.31 °C is in the middle. Herein, as the degradation degree of crumb rubber deepens, the failure temperature of rubber binder has a reduction trend. Besides, with the additional SBS concentration increases, the failure temperature of CR/SBS modified high-viscosity bitumen enhances dramatically. Compared to rubber bitumen, adding 4 wt% SBS would heighten the failure temperature value of full-swelling, partial-degradation and full-degradation high-viscosity binders by 6.23%, 7.52% and 9.52%, respectively. It can be seen that the influence of SBS on the rutting resistance improvement of both partial and full-degradation binder is more significant than that of the full-swelling bitumen, which agrees to the softening point result. Importantly, the failure temperatures of all CR/SBS modified bitumen are higher than 90 °C. Although the degradation of crumb rubber could have an adverse influence on the rutting resistance of high-viscosity binder, the full-degradation CR/SBS modified bitumen still shows the failure temperature larger than 94 °C when the SBS dosage exceeds 3 wt%. Thus, CR/SBS composite modified bitumen exhibits a satisfactory

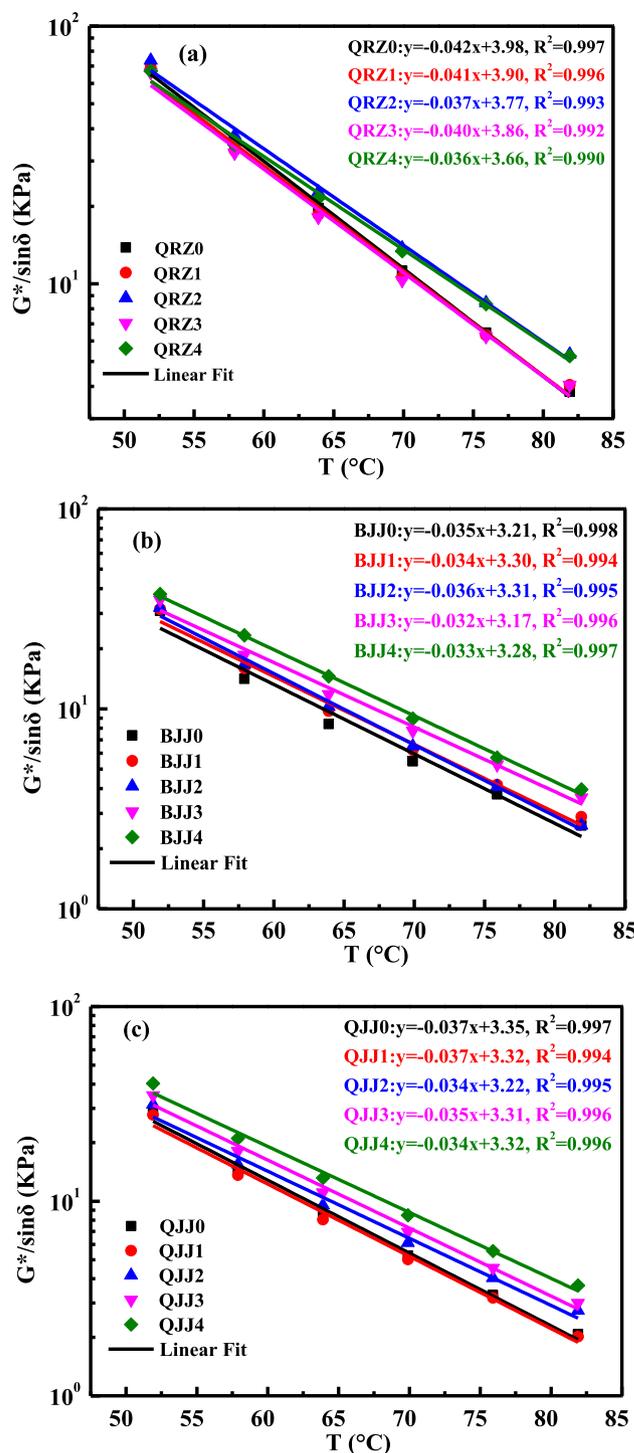


Fig. 7. shows the rutting parameter ($G^*/\sin\delta$) of high-viscosity binders. As expected, the rutting parameter of bitumen shows a reduction trend with the temperature increasing, and the corresponding linear correlation equations are displayed. The addition of SBS could significantly reduce the absolute slope and decrease the temperature-sensitivity of CR/SBS modified high-viscosity bitumen. Moreover, the increase of SBS dosage enhances the rutting resistance of high-viscosity binders. Interestingly, the absolute slope value of full-swelling CR/SBS modified bitumen is the highest, indicating that the performance of full-swelling CR/SBS modified binder is more susceptible to the variation of temperature. In addition, when the SBS dosage is the same, the value order of $G^*/\sin\delta$ parameter is $QRZ > BJJ > QJJ$, which indicates that the full-swelling CR/SBS modified high-viscosity bitumen exhibits the best rutting resistance, and it would deteriorate with the degradation degree of crumb rubber increases. To sum up, the high swelling degree of crumb rubber and SBS content could be beneficial to improve the rutting resistance and hardness of CR/SBS modified high-viscosity binder.

Table 4
The rutting failure temperature (RFT) of CR/SBS modified high-viscosity binders

Samples	RFT(°C)	Samples	RFT(°C)	Samples	RFT(°C)
QRZ0	95.39	BJJ0	92.31	QJJ0	89.30
QRZ1	95.81	BJJ1	94.19	QJJ1	90.62
QRZ2	95.93	BJJ2	96.05	QJJ2	93.47
QRZ3	100.69	BJJ3	98.17	QJJ3	94.66
QRZ4	101.33	BJJ4	99.25	QJJ4	97.80

anti-rutting property to guarantee the adequate high-temperature performance of porous asphalt.

3.4. Flow behavior

The high-temperature zero-shear viscosity (ZSV) parameter of bitumen is the key parameter to ensure the sufficient structural stability and rutting resistance of porous asphalt pavement, especially in the southern areas of China, where the climate temperature is higher than 40 °C in summer. Asphalt binder is a representative viscoelastic material, which is dependent on shear rate. Fig. 8. displays the flow curves of CR/SBS modified high-viscosity binders. The shear viscosity decreases remarkably with the shear rate rising, which is related to the non-Newtonian flow characteristic of CR/SBS modified bitumen. When the shear rate is lower than 10⁻² s⁻¹, the viscosity values of high-viscosity binders tend to be stable. The zero-shear viscosity parameter can be obtained by fitting the flow curve with the Carreau model.

$$\frac{\eta_0}{\eta} = \left[1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_c} \right)^2 \right]^s \quad (7)$$

where the η_0 refers to the zero-shear viscosity, Pa·s; η shows the complex viscosity, Pa·s; $\dot{\gamma}$ is the shear rate, s⁻¹; $\dot{\gamma}_c$ and s are constants.

From Fig. 8, the non-Newtonian flow region of full-swelling CR/SBS modified high-viscosity bitumen is narrower than the partial and full-degradation binders. The size of crumb rubber particle in the full-swelling CR/SBS modified bitumen is the largest. It is easy for rubber particles to agglomerate together at a low shear rate, while it could be separated at a high shear rate. Hence, the full-swelling CR/SBS modified high-viscosity bitumen shows the more distinct non-Newtonian flow behavior. Moreover, the increase of SBS content further shortens the Newtonian flow region because of the increase of polymer network density, as well as the decrease of light fractions in the bitumen phase.

Table 5 lists the 60 °C zero-shear viscosity values of CR/SBS high-viscosity bitumen. The swelling and degradation degree of crumb rubber and SBS dosage both significantly influence the ZSV value of binders. When the SBS dosage is the same, the order of ZSV value for CR/SBS modified binder is QRZ > BJJ > QJJ. The increase of degradation time could decrease the zero-shear viscosity and weaken the deformation resistance of porous asphalt. The addition of SBS copolymer significantly increases the ZSV of high-viscosity bitumen, especially when the SBS dosage exceeds 3 wt%. It can be found that the zero-shear viscosity values of all full-swelling CR/SBS modified binders are higher than 20000 Pa·s, while the ZSV values of partial- and full-degradation CR/SBS modified bitumen are larger than 20000 Pa·s only when the SBS content is more than 2 wt% and 3 wt%, respectively. It reveals that the increase of degradation degree of crumb rubber remarkably reduces the zero-shear viscosity and permanent resistance of CR/SBS high-viscosity binder. Meanwhile, it is expected that the addition of SBS copolymer significantly improves the flow resistance of high-viscosity bitumen. Previous studies reported that the zero-shear viscosity was an important parameter to evaluate the deformation resistance of bitumen [36,37]. To guarantee the flow and rutting resistance of CR/SBS modified high-viscosity bitumen for porous asphalt, the degradation degree of crumb rubber in the binder should be controlled.

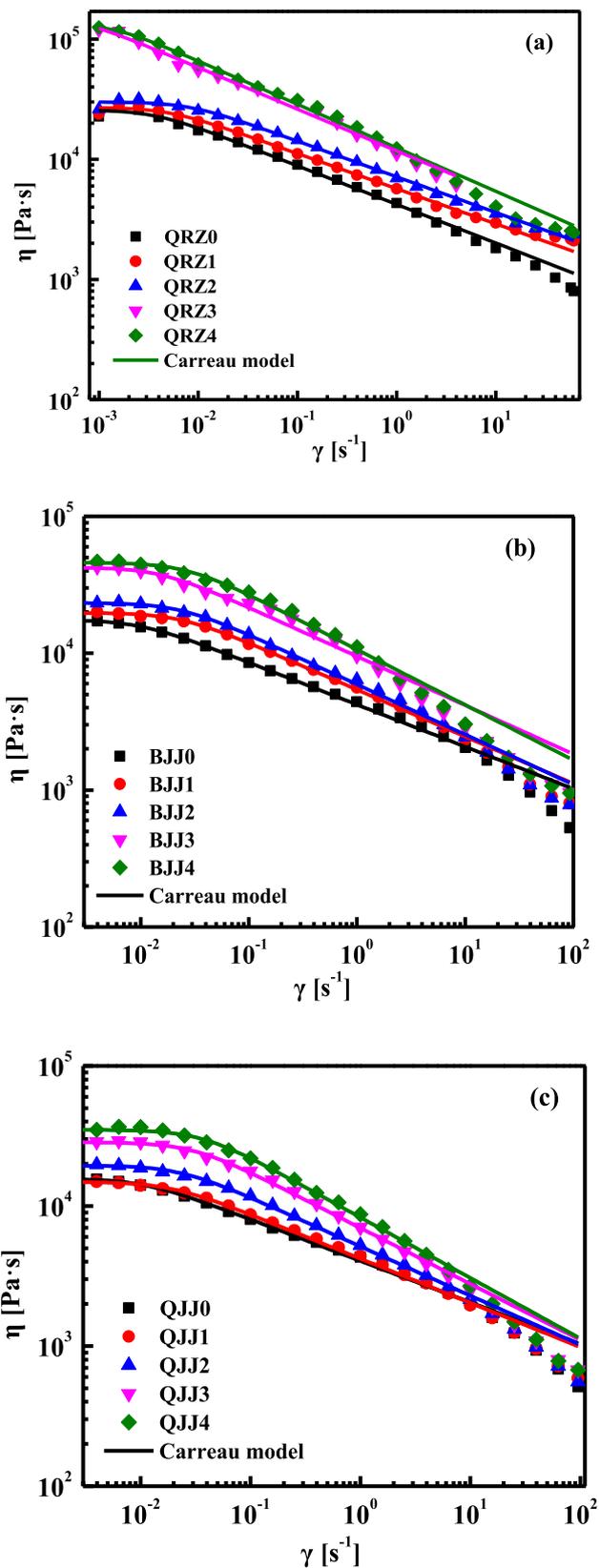


Fig.8. Flow curves of CR/SBS modified high-viscosity binders.

mation resistance of bitumen [36,37]. To guarantee the flow and rutting resistance of CR/SBS modified high-viscosity bitumen for porous asphalt, the degradation degree of crumb rubber in the binder should be controlled.

Table 5
The 60 °C zero-shear viscosity (ZSV) of CR/SBS modified high-viscosity binders.

Samples	ZSV(Pa·s)	Samples	ZSV(Pa·s)	Samples	ZSV(Pa·s)
QRZ0	25730.36	BJJ0	17486.67	QJJ0	15632.49
QRZ1	26978.85	BJJ1	19732.89	QJJ1	15849.56
QRZ2	29970.36	BJJ2	23300.65	QJJ2	19450.59
QRZ3	136252.12	BJJ3	42681.61	QJJ3	28484.77
QRZ4	153851.62	BJJ4	45926.11	QJJ4	35007.75

3.5. Elastic property

Multiple stress creep and recovery (MSCR) test was conducted to estimate the influence of swelling and degradation degree of rubber in bitumen as well as SBS dosage on the creep recovery and rutting resistance of high-viscosity binder. Fig. 9 illustrates the recovery percentage R% and non-recovery creep compliance Jnr of different

high-viscosity asphalts at 60 °C. The high-viscosity binders with the larger recovery percent and lower creep compliance would exhibit higher elasticity and better deformation resistance. The swelling and degradation levels show great influence on the elastic property of rubber bitumen. It denotes from Fig. 9(a) that the recovery percentage of full-swelling rubber binder presents the R% value of 48.23%, while the recovery percentage of rubber bitumen with partial-degradation rubber and full-degradation rubber is 67.46% and 68.73%, respectively. On the contrary, the creep compliance of full-swelling rubber bitumen is 0.16 kPa⁻¹, while the Jnr values of partial-degradation and full-degradation rubber binders are 0.15 and 0.13 kPa⁻¹, respectively. The above results demonstrate that the elasticity of partial and full-degradation CRMB are superior to that of full-swelling rubber bitumen. Meanwhile, as the degradation extent deepens, the high-temperature deformation recovery of CRMB improves gradually. Hence, the increase of degradation degree of crumb rubber would enhance its high temperature deformation resistance of CRMB binder.

Interestingly, it seems that the MSCR results are contrary to the aforementioned conclusions from the master curve and Superpave rutting parameters that the degradation of rubber in bitumen could adversely affect the high-temperature properties of rubber binder. Obviously, the general idea that MSCR results and rutting parameter always draw the same conclusion regarding the high-temperature behaviors of bitumen does not apply to rubber binder in terms of investigating the effects of the swelling and degradation degree of rubber asphalt on its high-temperature properties (complex modulus, rutting factor and elastic recovery). Although MSCR parameters and rheological indexes all can be utilized to evaluate the high-temperature performance of asphalt binder, there is an intrinsic difference. The rheological indexes, such as complex modulus and rutting parameter, are the indications of stiffness. And the bitumen with higher stiffness shows better deformation and rutting resistance. On the other hand, the R% and Jnr parameters in the MSCR test reflect the elastic recovery ability of the binder after deformation. The full-swelling rubber bitumen with larger G* and G*/sinδ possesses higher stiffness and deformation generation resistance, while it shows inferior elastic recovery performance according to the MSCR results. The degradation of crumb rubber in bitumen remarkably deteriorates the complex modulus and rutting parameter, but enhances the recovery percentage, suggesting that the increase of degradation level would decrease the stiffness and increase the risk of deformation generation of rubber asphalt, but enhance the elastic recovery ability of occurred deformation.

Due to insufficient elastic recovery and deformation resistance, the SBS copolymer is supplemented to further improve the high-temperature performance of the CRMB binder. The addition of SBS could significantly strengthen the R% value and reduce the Jnr parameter of rubber binder, indicating that adding SBS remarkably improves the elasticity and high-temperature deformation resistance. When the SBS content exceeds 3 wt%, the influence of swelling and degradation degree of CRMB binder becomes smaller to the recovery performance of CR/SBS modified high-viscosity bitumen. The recovery percentage of all binders with SBS dosage of 4 wt% is higher than 87%, revealing that the CR/SBS modified high-viscosity binder possesses sufficient resistance to permanent deformation. In the following section, according to the conventional and rheological properties, several CR/SBS modified binders (QRZ3, QRZ4, BJJ3, BJJ4, QJJ3 and QJJ4) are optimized to prepare the asphalt mixture to further validate the application potential of CR/SBS modified high-viscosity bitumen in porous asphalt.

3.6. Porous asphalt (PA) mixture design

In this study, porous asphalt type is the OGFC-13 and related recommended aggregate gradation is shown in Table 6. The final

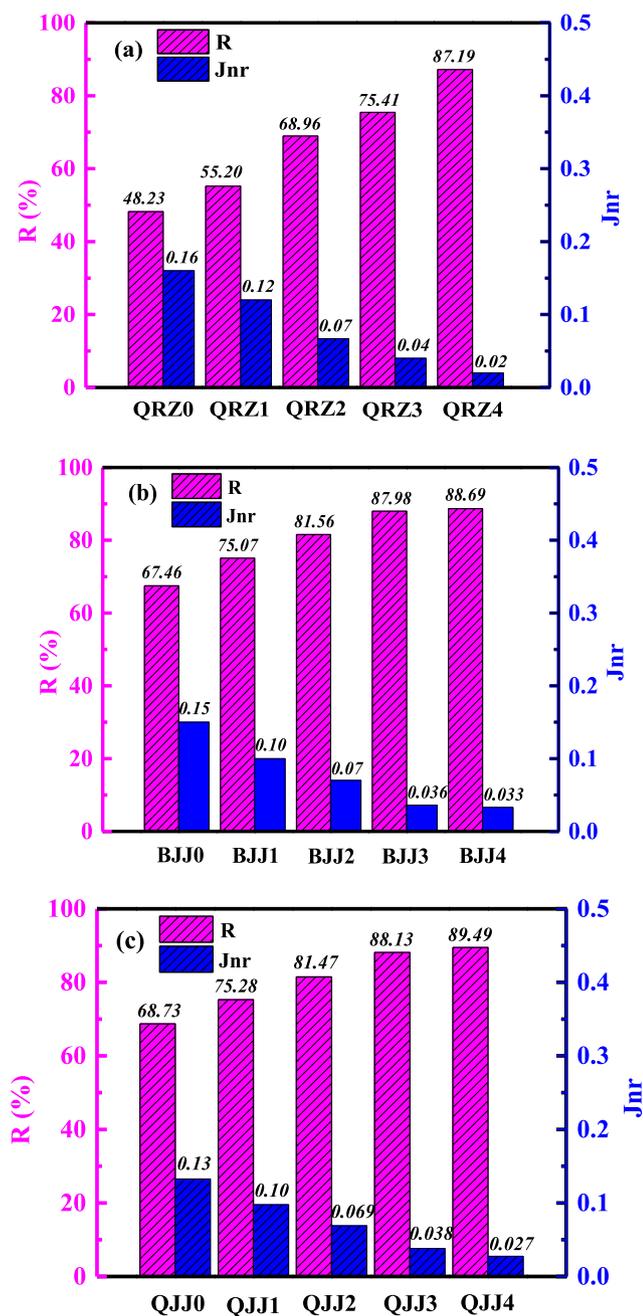


Fig.9. The R% and Jnr values of CR/SBS modified high-viscosity binders.

Table 6
The grading composition of PA mixtures.

OGFC-13 Sieve/mm	Passing percentage/%				Final grade	Standard
	Group A	Group B	Group C			
16.0	100	100	100		100.0	100–100
13.5	92.8	93.1	93.4		93.4	85–100
9.5	59.3	61.1	62.7		62.7	40–71
4.75	18.3	21.9	24.2		24.4	10–30
2.36	11.1	13.0	16.0		16.3	9–20
1.18	8.6	9.5	11.0		11.1	7–17
0.6	7.4	7.8	8.7		8.7	6–14
0.3	6.5	6.7	7.0		7.0	5–12
0.15	5.7	5.7	5.7		5.7	4–9
0.075	5.0	5.0	5.0		5.0	3–7

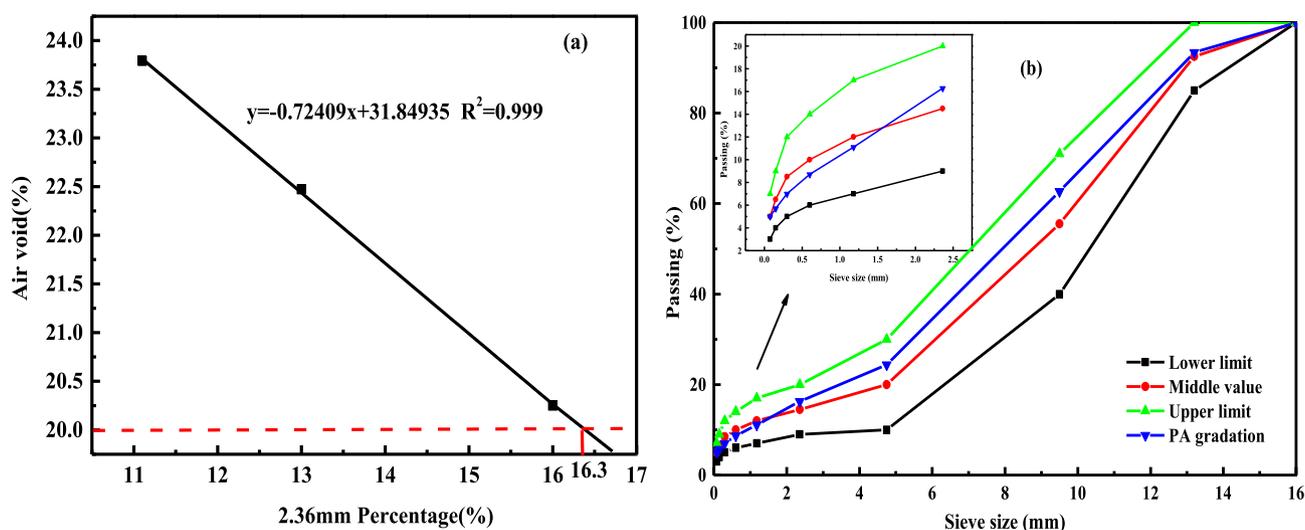


Fig.10. Determination of aggregate gradation for PA mixtures.

gradation for OGFC-13 porous asphalt is determined according to the target air void content of 20%. Table 6 also shows three aggregate gradation groups, called as group A, B and C, based on the lowest, the highest and middle value of passing percentage. These three grading composition groups are chosen to prepare the porous asphalt mixture and determine the final gradation of OGFC-13 porous asphalt with an air void content of 20%. The initial amount of high-viscosity binder for group A, B and C is 4.41%, 4.49% and 4.61% by weight of whole asphalt mixture, respectively. Then the Marshall samples for each gradation group are prepared and the corresponding air void content is obtained by volumetric method. The measured air void content values of three gradation groups are 23.79%, 22.47% and 20.25%, respectively.

There was a great relationship between the air void content of OGFC-13 asphalt mixture and the aggregate percentage with passing through the 2.36 mm sieve [10]. Thus, Fig. 10(a) presents the air void content of asphalt mixture as a function of aggregate percentage passing through 2.36 mm sieve. The air void content reduces linearly with the increase of fine aggregate amount. The amount of aggregate passing through the 2.36 mm of final gradation is obtained as 16.3% when the target air void content is 20%. The final aggregate gradation for OGFC-13 asphalt mixture with air void content of 20% is determined and shown in Table 6 as well as Fig. 10(b).

In addition, the optimum bitumen dosage is determined by using both Cantabro abrasion and the Schellenberg drainage tests, which could measure the maximum and minimum binder content of the OGFC-13 asphalt mixture, respectively. For the final aggregate gradation, the initial bitumen-aggregate ratio of 3.6, 3.9, 4.2,

4.5 and 4.8 were selected, and the run-off loss and Cantabro loss values of these corresponding Marshall samples were measured, which are shown in Fig. 11. It is illustrated that with the increase of bitumen-aggregate ratio, the run-off proportion increases gradually, while the Cantabro loss percentage declines dramatically. The OGFC-13 asphalt mixture with a higher bitumen dosage would have good raveling resistance but the bleeding phenomenon easily occurs, significantly affecting the skid resistance and driving speed. It is important to balance the raveling and bleeding resistance performance of porous asphalt pavement. According to the JTG E20-2011 specification, the maximum value of run-off proportion and Cantabro loss percentage is 0.3% and 20%. From Fig. 11, the run-off amount of all asphalt samples with different bitumen-aggregate ratio values are all lower than 0.2%, while their Cantabro loss percentage meets the requirement, except for one sample with the bitumen-aggregate ratio of 3.6%. The maximum and minimum value of the bitumen-aggregate ratio for OGFC-13 asphalt mixture is 4.29% and 4.18%. Finally, the optimum bitumen-aggregate mass ratio is calculated as the average amount of maximum and minimum value, which is equal to 4.23%.

To validate the accuracy of the aforementioned optimum bitumen-aggregate, the Marshall stability of porous asphalt mixtures with various bitumen-aggregate ratios are measured and displayed in Fig. 12. With the increase of bitumen-aggregate ratio, the Marshall stability of CR/SBS modified porous mixture firstly enhances and then decreases distinctly. The high-viscosity binder has the function of connecting the aggregate, and the initial increase of bitumen dosage would improve the structural stability and aggregate interaction. However, the overfull bitumen dosage

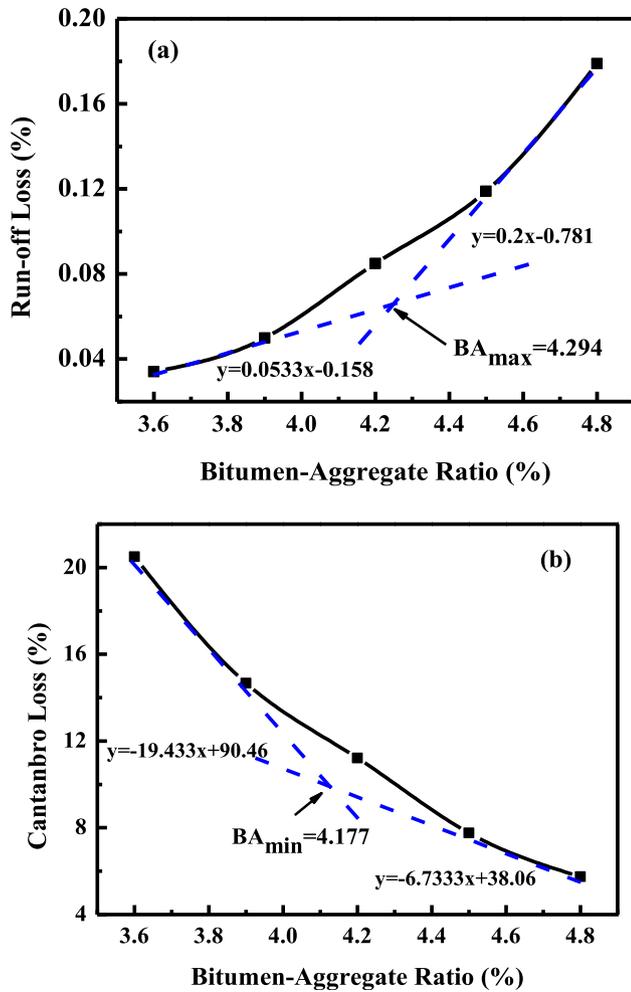


Fig.11. Influence of bitumen-aggregate ratio on the run-off and Cantabro loss of PA mixtures.

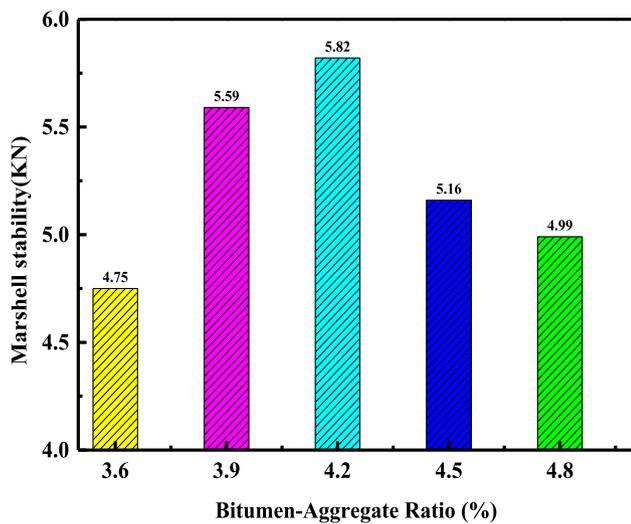


Fig.12. Influence of bitumen-aggregate ratio on the Marshall stability of PA mixtures.

would decline the strength of the overall asphalt mixture. The Marshall stability values of all asphalt mixtures are higher than 4.5kN, indicating that the prepared CR/SBS modified porous asphalt mixtures exhibit satisfied dynamic stability. The Marshall stability

reaches the maximum value of 5.82kN when the bitumen-aggregate ratio is 4.2%, which is in good agreement with the results from run-off and Cantabro loss tests.

3.7. Air void of PA mixtures

The total and connected air void content of CR/SBS modified porous asphalt mixtures are illustrated in Fig. 13. The total void content values of all mixture samples are close to the target value of 20%. As expected, the connected air void is lower than total air void because of the closed-form air void in mixture, which leads to the permeability reduction of porous asphalt pavement dramatically. The connected void content region for all samples is in 13.90–16.46%, showing the good permeability characteristic of CR/SBS modified porous asphalt mixture.

Although the air void content of porous asphalt is mostly determined by the aggregate gradation and bitumen dosage, the swelling and degradation degree of crumb rubber in high-viscosity bitumen significantly affects the air void of porous asphalt. When the SBS content is the same, the sequence of air void value of asphalt mixtures is $QRZ > BJJ > QJJ$. It illustrates that the lower the degradation degree of crumb rubber in bitumen is, the higher the air void of porous asphalt is. As mentioned before, the full-swelling CR/SBS modified high-viscosity bitumen possesses the highest viscosity and rutting resistance, which deteriorates with the increase of CR degradation degree. The higher viscosity characteristic of full-swelling bitumen could result in the increasing difficulty of compaction compared with the partial-degradation and full-degradation binders. In summary, the increasing degradation degree of CR/SBS modified high-viscosity bitumen could improve the compactivity and decrease the air void of porous asphalt. Furthermore, the increase of SBS content leads to the expansion of air void, which is associated with the viscosity improvement of CR/SBS modified high-viscosity binder.

3.8. Cantabro and run-off loss of PA mixtures

The Cantabro loss and run-off loss weight percentage of PA mixtures are shown in Fig. 14. Based on the OGFC-13 performance standard, the Cantabro loss and Schellenberg draindown loss weight percentage should be less than 20% and 0.3%, respectively. In this study, the Cantabro loss values of all asphalt samples are lower than 20%, while corresponding run-off percentages are smaller than 0.08%. Therefore, the CR/SBS modified porous asphalt possesses sufficient raveling and blending resistance. It is clear that the swelling and degradation degree of crumb rubber as well as SBS dosage in binder have great influence on the raveling property

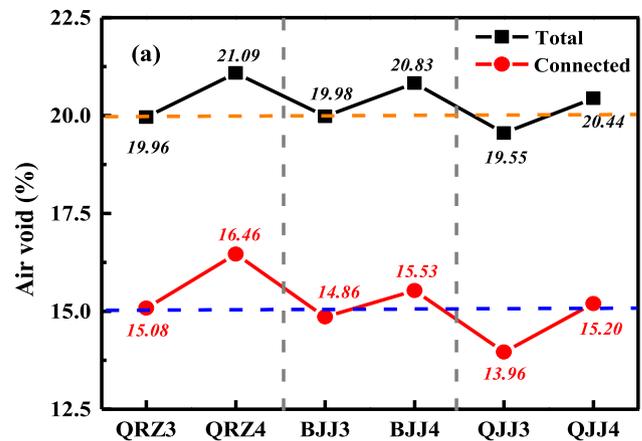


Fig.13. The total and connected air void values of porous asphalt mixtures.

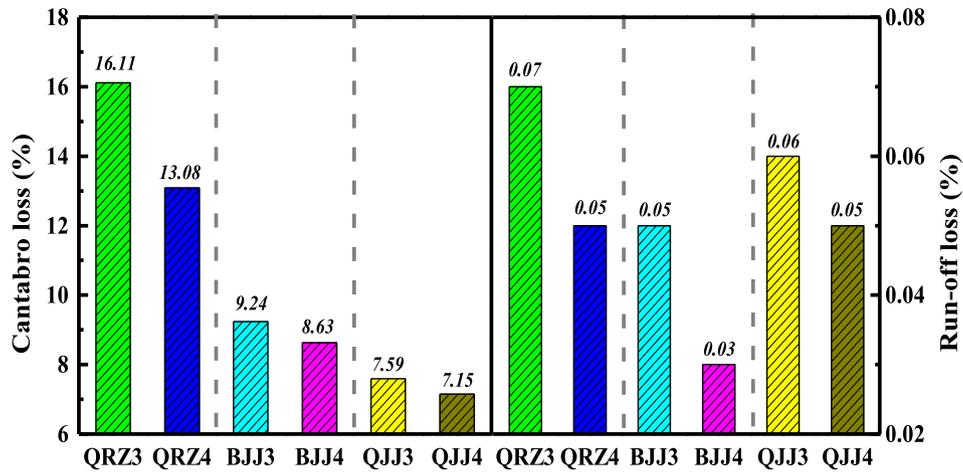


Fig.14. The Cantabro loss and run-off loss values of porous asphalt mixtures.

of CR/SBS modified porous asphalt. The order of Cantabro loss is QRZ > BJJ > QJJ, and the full-swelling CR/SBS modified bitumen shows the largest raveling potential, which could be improved by deepening the degradation degree of crumb rubber. Additionally, the increase of SBS content in high-viscosity binder could enhance the raveling resistance of porous asphalt dramatically according to the reduction of Cantabro loss percentage by 18.81%, 6.60% and 5.80% for the full-swelling, partial-degradation and full-degradation CR/SBS modified porous asphalt, respectively. Meanwhile, the difference between the run-off loss of various CR/SBS modified porous asphalts is not obvious, which is associated with the bitumen-aggregate ratio. Therefore, when considering the raveling resistance of PA mixture, the high-viscosity bitumen with lower degradation degree and higher SBS dosage is recommended.

3.9. Rut depth and dynamic stability of PA mixtures

To assess the high-temperature performance of CR/SBS modified high-viscosity porous asphalt mixture, the wheel tracking method at 60 °C is conducted and two parameters, rut depth as well as dynamic stability, are obtained. An asphalt mixture with lower rut depth and higher dynamic stability would exhibit better rutting resistance. Fig. 15 displays the rut depth and dynamic stability of CR/SBS modified porous asphalt mixture. The rut depth values of all mixture samples are lower than 1.8 mm, while the dynamic stability values are higher than the control point of 5000 times/min for OGFC-13 porous asphalt. Hence, the CR/SBS modified high-viscosity bitumen is suitable as the binder of porous asphalt with the adequate high-temperature rutting resistance. Regarding the influence of swelling and degradation degree of crumb rubber, the full-swelling CR/SBS modified porous asphalt exhibits the smallest rut depth and highest dynamic stability, followed by the partial-degradation asphalt mixture, while the full-degradation CR/SBS modified porous asphalt shows the largest rut depth and lowest dynamic stability. That is to say, full-swelling CR/SBS modified porous asphalt would show the best rutting resistance, which declines with the increase of degradation degree of crumb rubber in the binder. Considering the high-temperature performance of porous asphalt, the degradation degree of crumb rubber in the high-viscosity bitumen should be controlled.

The addition of SBS copolymer significantly reduces the rut depth and increases the dynamic stability of porous asphalt. For instance, when the SBS dosage rises from 3 to 4 wt%, the dynamic stability of QRZ, BJJ and QJJ CR/SBS modified PA mixtures increases

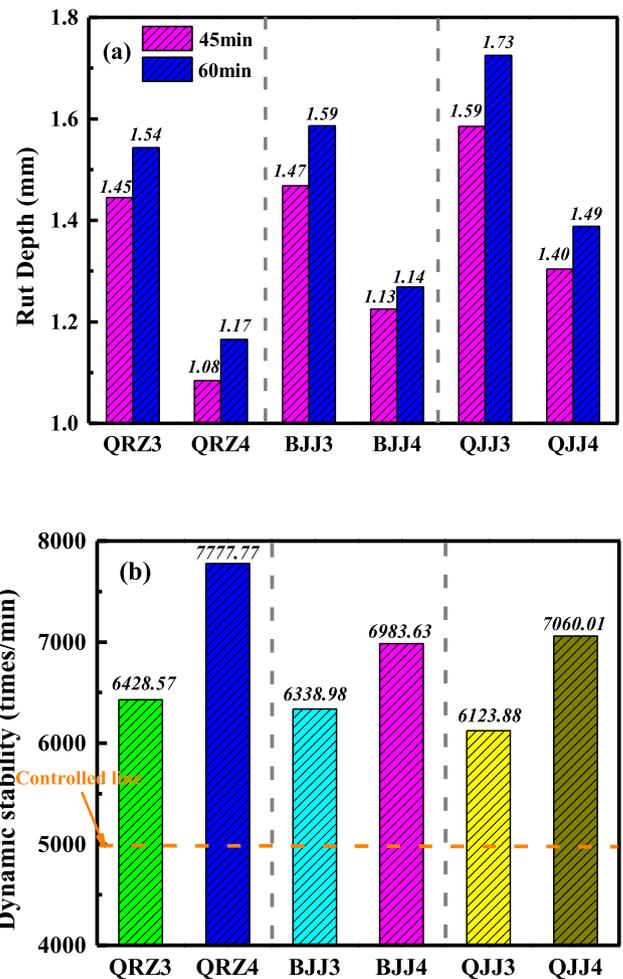


Fig.15. The rut depth (a) and dynamic stability (b) of PA mixtures.

by 20.99%, 10.17% and 15.29%, respectively. Moreover, the influence of SBS dosage on the rutting property of porous asphalt is more obvious than the effect of swelling and degradation degree of crumb rubber. To guarantee the adequate rutting resistance of porous asphalt, the SBS dosage in CR/SBS modified high-viscosity bitumen should be determined based on the swelling and degradation degree of crumb rubber. The QRZ4 sample possesses the highest dynamic stability of 7777 times/min, while the QJJ3 asphalt

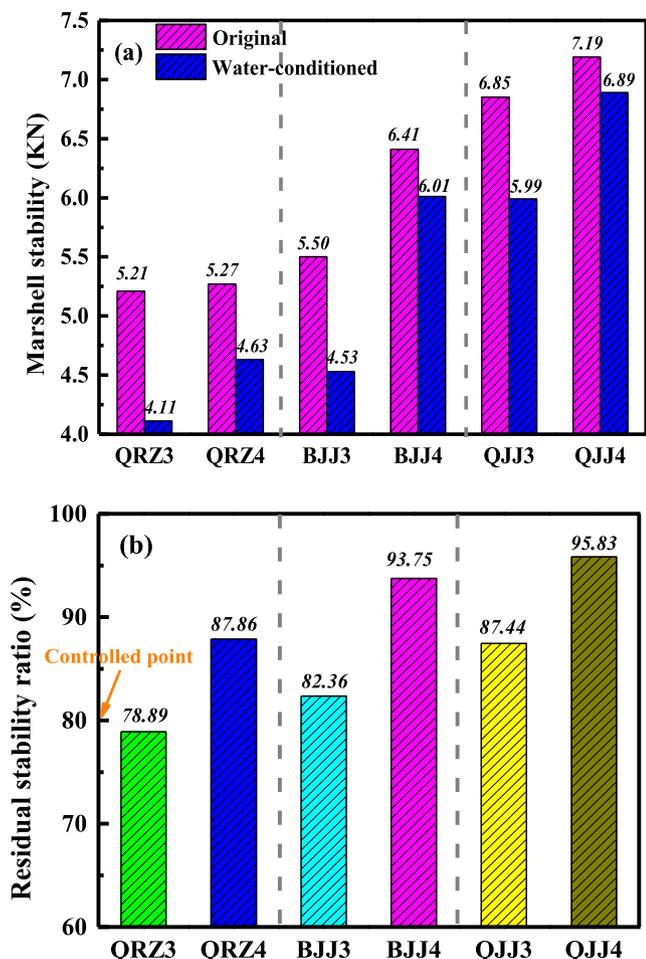


Fig.16. The standard Marshall stability (a) and residual stability ratio (b) of PA mixtures.

mixture shows the lowest dynamic stability. Therefore, less crumb rubber degradation and high SBS content would be beneficial to the high-temperature rutting resistance of porous asphalt.

3.10. Marshall stability and moisture susceptibility of PA mixtures

The Marshall stability is used to evaluate the structural stability and moisture susceptibility of different CR/SBS modified porous asphalt mixtures, and the results of original and residual Marshall stability are presented in Fig. 16(a). Under the dry and high loading condition, the Marshall stability values of asphalt samples are all larger than 5kN, showing that the CR/SBS modified porous asphalt exhibits a sufficient stable structure. It is demonstrated that the water condition deteriorates the Marshall stability of porous asphalt. The moisture molecules prefer to adsorb on the aggregate surface and weaken the adhesion energy of the interface between aggregate and bitumen. Interestingly, the swelling and degradation of crumb rubber in the CR/SBS modified high-viscosity bitumen shows an obvious influence on the Marshall stability of porous asphalt. With the increase of crumb rubber degradation degree, the Marshall stability remarkably enhances, which may be associated with the air void content in the asphalt mix. The full-degradation CR/SBS modified porous asphalt shows the lowest air void and best structural stability. When the SBS dosage increases from 3 wt% to 4 wt%, the Marshall stability of full-swelling, partial-degradation and full-degradation CR/SBS modified porous asphalts enhances by 1.15%, 16.55% and 4.96%, respectively.

To assess the moisture susceptibility of CR/SBS modified porous asphalt, the residual Marshall stability ratio after water condition is calculated and shown in Fig. 16 (b). The controlled value of the residual Marshall stability ratio for OGFC-13 porous asphalt is 80%. Only the residual stability value of QRZ3 asphalt mix is lower than the standard point, while other CR/SBS modified asphalt mixtures exhibit adequate resistance to moisture damage, especially for the BJJ4 and QJJ4 samples, the residual stability of which is larger than 90%. Thus, the CR/SBS modified high-viscosity bitumen is suitable as the binder of porous asphalt. Furthermore, the swelling and degradation of crumb rubber in binder plays an important role in the structural stability and moisture susceptibility of CR/SBS modified porous asphalt, and the results illustrate that high degradation degree of CR/SBS modified binder is beneficial to facilitate the structural stability and moisture damage resistance of porous asphalt. Overall, CR/SBS modified high-viscosity asphalt mixture exhibits the predominant deformation and moisture damage resistance performance.

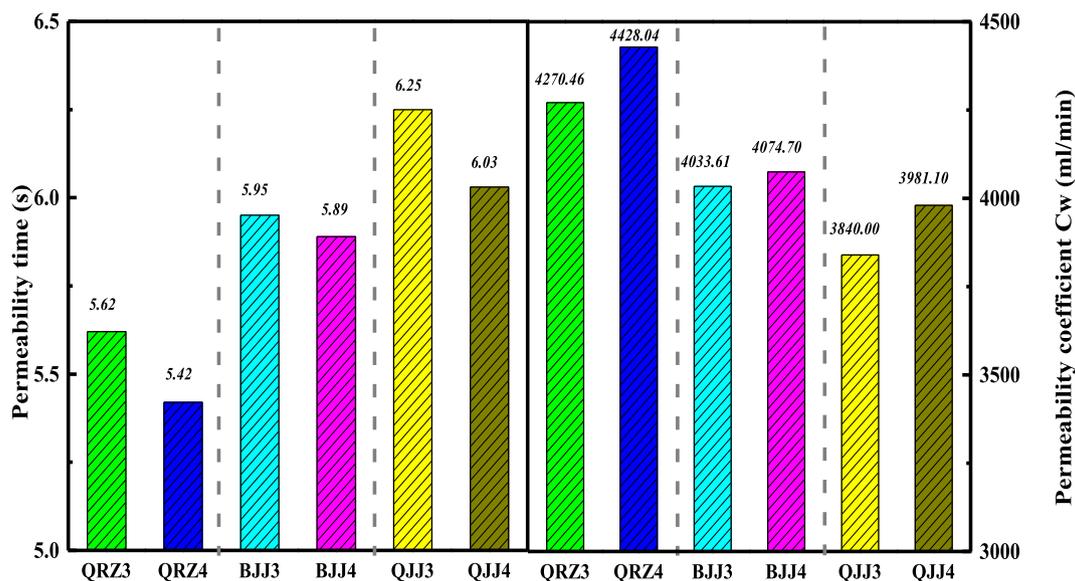


Fig.17. The permeability time tp and permeability coefficient Cw of PA mixtures.

3.11. Permeability of PA mixtures

The permeability of CR/SBS modified porous asphalt mixtures are estimated through the water permeability test. Two parameters, permeability time t_p and permeability coefficient C_w , are measured and illustrated in Fig. 17. The porous asphalt mixture with the shorter t_p and higher C_w value would perform the better drainage ability. The permeability time of all asphalt mixtures are lower than 6.5 s and the permeability coefficient values are larger than 3500 ml/min, indicating that CR/SBS modified porous asphalt exhibits the adequate permeability characteristic. It further validates the feasibility of using CR/SBS modified high-viscosity bitumen as the binder of porous asphalt. In addition, the swelling and degradation of crumb rubber has an obvious influence on the permeability performance of porous asphalt mixture. When the SBS dosage is constant, the order of permeability time of CR/SBS modified porous asphalt mixture is QRZ < BJJ < QJJ, and the sequence of permeability coefficient is opposite, which indicates that the increase of degradation degree of crumb rubber could deteriorate the permeability performance of porous asphalt. That is associated with the low viscosity and better workability of partial and full-degradation CR/SBS modified high-viscosity bitumen, which enhances the compaction degree and reduces the air void of porous asphalt. Additionally, the increase of SBS content notably decreases the permeability time, intensifies the permeability coefficient, and improves the permeability performance of CR/SBS modified porous asphalt. In detail, when the SBS dosage rises from 3 to 4 wt%, the C_w value of full-swelling, partial-degradation and full-degradation CR/SBS modified porous asphalt extends by 3.92%, 1.02% and 3.67%, respectively. Therefore, from the viewpoint of permeability and energy saving of porous asphalt, the degradation degree of crumb rubber in the CR/SBS modified bitumen should be controlled.

4. Conclusions and recommendations

This study aims to investigate the influence of swelling/degradation degree of crumb rubber and SBS dosage on the conventional and rheological properties of high-viscosity binder as well as the performance of porous asphalt mixture. The conclusions could be drawn as follows:

- (1) The viscosity of the CRMB binder rises gradually with the increase of swelling time and tends to be stable. With the increase of degradation time, the viscosity of CRMB decreases remarkably, which is associated with deepening the degradation of crumb rubber in the binder.
- (2) From the conventional and rheological results, the full-swelling CR/SBS modified high-viscosity bitumen exhibits the best rutting and deformation resistance, which reduces with the increase of CR degradation degree. The partial and full-degradation CR/SBS modified bitumen show better low-temperature cracking resistance, workability as well as elastic recovery than the full-swelling binder.
- (3) The increase of SBS dosage could further improve both high and low-temperature viscoelastic properties of the high-viscosity binder. Besides, when the SBS content exceeds 3 wt%, the CR/SBS modified high-viscosity bitumen shows the potential as the porous asphalt binder based on the comparison of binder properties with standard requirements.
- (4) The properties of porous asphalt with CR/SBS modified high-viscosity bitumen can meet the requirements of Marshall stability, air void content, Cantabro loss, run-off loss, anti-rutting, moisture damage resistance and permeability performance. Although the full-swelling asphalt mixture has

the best rutting resistance, it shows poor adhesive property and more susceptibility to moisture damage when compared with partial and full-degradation asphalt mixtures.

The study explored the potential of using CR/SBS composite modified bitumen for porous asphalt with favorable pavement performance, including the raveling, moisture damage and rutting resistance and permeability properties. Further research will be conducted to provide a better understanding regarding the effects of SBS content and swelling/degradation degree of crumb rubber in high-viscosity asphalt binder on the cracking and fatigue resistance of CR/SBS modified porous asphalt binder and mixture.

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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References

- [1] H. Wu, J. Yu, W. Song, J. Zou, Q. Song, L. Zhou, A critical state-of-the-art review of durability and functionality of open-graded friction course mixtures, *Constr. Build. Mater.* 237 (2020) 117759.
- [2] J. Chen, X. Yin, H. Wang, Y. Ding, Evaluation of durability and functional performance of porous polyurethane mixture in porous pavement, *J. Cleaner Prod.* 188 (2018) 12–19.
- [3] J. Hu, T. Ma, Y. Zhu, X. Huang, J. Xu, L. Chen, High-viscosity modified asphalt mixtures for double-layer porous asphalt pavement: Design optimization and evaluation metrics, *Constr. Build. Mater.* 271 (2021) 121893.
- [4] X. Qin, S. Zhu, X. He, Y.i. Jiang, High temperature properties of high viscosity asphalt based on rheological methods, *Constr. Build. Mater.* 186 (2018) 476–483.
- [5] X. Chen, C. Li, Y. Jiang, W. Zhang, G. Xu, Comparisons with high viscosity additive effects on base and modified asphalt, *Pet. Sci. Technol.* 37 (11) (2019) 1331–1337.
- [6] M. Wu, R. Li, Y. Zhang, J. Wei, Y. Lv, X. Ding, Reinforcement effect of fiber and deoiled asphalt on high viscosity rubber/SBS modified asphalt mortar, *Pet. Sci.* 11 (3) (2014) 454–459.
- [7] J. Cai, C. Song, B. Zhou, Y. Tian, R. Li, J. Zhang, J. Pei, Investigation on high-viscosity asphalt binder for permeable asphalt concrete with waste materials, *J. Cleaner Prod.* 228 (2019) 40–51.
- [8] J. Zhang, W. Huang, Y. Zhang, Q. Lv, C. Yan, Evaluating four typical fibers used for OGFC mixture modification regarding drainage, raveling, rutting and fatigue resistance, *Constr. Build. Mater.* 253 (2020) 119131.
- [9] J. Chen, J. Li, H. Wang, W. Huang, W. Sun, T. Xu, Preparation and effectiveness of composite phase change material for performance improvement of Open Graded Friction Course, *J. Cleaner Prod.* 214 (2019) 259–269.
- [10] J. Zhang, W. Huang, G. Hao, C. Yan, Q. Lv, Q.i. Cai, Evaluation of open-grade friction course (OGFC) mixtures with high content SBS polymer modified asphalt, *Constr. Build. Mater.* 270 (2021) 121374, <https://doi.org/10.1016/j.conbuildmat.2020.121374>.
- [11] J. Shi, P. Zhao, W. Fan, Z. Yang, Y. Lin, J. Ouyang, Facile preparation and application performance evaluation of SBS/C₉ petroleum resin blends as modifier for high viscosity asphalt, *Constr. Build. Mater.* 262 (2020) 120073.
- [12] X. Ma, Q. Li, Y.-C. Cui, A.-Q. Ni, Performance of porous asphalt mixture with various additives, *Int. J. Pavement Eng.* 19 (4) (2018) 355–361.
- [13] Y. Jiao, Y. Zhang, L. Fu, M. Guo, L. Zhang, Influence of crumb rubber and tapack super on performances of SBS modified porous asphalt mixtures, *Road Mater. Pavement Design.* 20 (sup1) (2019) S196–S216.
- [14] S. Ren, X. Liu, M. Li, W. Fan, J. Xu, S. Erkens, Experimental characterization of viscoelastic behaviors, microstructure and thermal stability of CR/SBS modified asphalt with TOR, *Constr. Build. Mater.* 261 (2020) 120524.
- [15] R. Imaninasab, B. Bakhshi, B. Shirini, Rutting performance of rubberized porous asphalt using Finite Element Method (FEM), *Constr. Build. Mater.* 106 (2016) 382–391.
- [16] A. Gupta, J.R. Hernandez, D.C. Fresno, Incorporation of additives and fibers in porous asphalt mixtures: A review, *Materials.* 12 (2019) 3156.
- [17] T.-W. Hsu, S.-C. Chen, K.-N. Hung, Performance evaluation of asphalt rubber in porous asphalt-concrete mixtures, *J. Mater. Civ. Eng.* 23 (3) (2011) 342–349.

- [18] M.A. Franesqui, J. Yepes, C. García-González, J. Gallego, Sustainable low-temperature asphalt mixtures with marginal porous volcanic aggregates and crumb rubber modified bitumen, *J. Cleaner Prod.* 207 (2019) 44–56.
- [19] C.J. Slebi-Acevedo, P. Lastra-González, I. Indacochea-Vega, D. Castro-Fresno, Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers, *Constr. Build. Mater.* 234 (2020) 117224, <https://doi.org/10.1016/j.conbuildmat.2019.117224>.
- [20] H. Zhang, H. Li, Y.i. Zhang, D. Wang, J. Harvey, H. Wang, Performance enhancement of porous asphalt pavement using red mud as alternative filler, *Constr. Build. Mater.* 160 (2018) 707–713.
- [21] M. Liang, X. Xin, W. Fan, H. Luo, X. Wang, B. Xing, Investigation of the rheological properties and storage stability of CR/SBS modified asphalt, *Constr. Build. Mater.* 74 (2015) 235–240.
- [22] S. Ren, X. Liu, H. Wang, W. Fan, S. Erkens, Evaluation of rheological behaviors and anti-aging properties of recycled asphalts using low-viscosity asphalt and polymers, *J. Cleaner Prod.* 253 (2020) 120048.
- [23] C. Qian, W. Fan, M. Liang, Y. He, S. Ren, X. Lv, G. Nan, H. Luo, Rheological properties, storage stability and morphology of CR/SBS composite modified asphalt by high-cured method, *Constr. Build. Mater.* 193 (2018) 312–322.
- [24] B. Shirini, R. Imaninasab, Performance evaluation of rubberized and SBS modified porous asphalt mixtures, *Constr. Build. Mater.* 107 (2016) 165–171.
- [25] C. Sangiorigi, S. Eskandarsefat, P. Tataranni, A. Simone, V. Vignali, C. Lantieri, G. Dondi, A complete laboratory assessment of crumb rubber porous asphalt, *Constr. Build. Mater.* 132 (2017) 500–507.
- [26] D. Dong, X. Huang, X. Li, L. Zhang, Swelling process of rubber in asphalt and its effect on the structure and properties of rubber and asphalt, *Constr. Build. Mater.* 29 (2012) 316–322.
- [27] M.A. Abdelrahman, S.H. Carpenter, Mechanism of interaction of asphalt cement with crumb rubber modifier, *Transp. Res. Rec.* 1661 (1) (1999) 106–113.
- [28] H. Yu, Z. Leng, Z. Zhang, D. Li, J. Zhang, Selection absorption of swelling rubber in hot and warm asphalt binder fractions, *Constr. Build. Mater.* 238 (2020) 117727.
- [29] I. Gawel, R. Stepkowski, F. Czachowski, Molecular interactions between rubber and asphalt, *Ind. Eng. Chem. Res.* 46 (9) (2006) 3044–3049.
- [30] H. Wang, X. Liu, P. Apostolidis, S. Erkens, T. Scarpas, Numerical investigation of rubber swelling in bitumen, *Constr. Build. Mater.* 214 (2019) 506–515.
- [31] N.S. Mashaan, A.H. Ali, M.R. Karim, M. Abdelaziz, Effect of blending time and crumb rubber content on properties of crumb rubber modified asphalt binder, *International Journal of the Physical Sciences.* 6 (9) (2011) 2189–2193.
- [32] ASTM D5-06. Standard test method for penetration of bituminous materials.
- [33] ASTM D36-06. Standard test method for softening point of bitumen (ring and ball apparatus).
- [34] ASTM D113-99. Standard test method for ductility of bituminous materials.
- [35] ASTM D4124-01. Standard test methods for separation of asphalt into four fractions.
- [36] X. Hu, K. Dai, P. Pan, Investigation of engineering properties and filtration characteristics of porous asphalt concrete containing activated carbon, *J. Cleaner Prod.* 209 (2019) 1484–1493.
- [37] S. Ren, X. Liu, W. Fan, C. Qian, G. Nan, S. Erkens, Investigating the effects of waste oil and styrene-butadiene rubber on restoring and improving the viscoelastic, compatibility, and aging properties of aged asphalt, *Constr. Build. Mater.* 269 (2021) 121338.