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Evaluation of rheological behaviors and anti-aging properties of recycled asphalts using low-viscosity asphalt and polymers

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ABSTRACT

Recycling technology is widely used in the asphalt road construction due to its environmental and economic effects. Many efforts have focused on the performance restoration of aged base asphalt by adding light oil, but the possibility of recycling the aged asphalt using low-viscosity asphalt and polymers has been few explored. Therefore, the objective of this research is to use polymer-modified low-viscosity asphalt as rejuvenator to recycle the aged asphalt. The conventional properties, rheological behaviors as well as anti-aging performance of polymer-modified recycled asphalts were evaluated by rotational viscosity (RV) tests, dynamic shear rheometer (DSR) tests and bending beam rheometer (BBR) tests. Moreover, the effects of the concentration ratio between polymer-modified low-viscosity asphalt rejuvenator and aged asphalt on the high-temperature anti-rutting, low-temperature cracking resistance, fatigue and aging resistance abilities of recycled asphalt were studied. The results show that the low-viscosity asphalt can increase viscous components and restore the workability of aged asphalt. However, the addition of low-viscosity asphalt weakens the high-temperature properties, temperature sensitivity and anti-aging performance of aged asphalt. Fortunately, the high-temperature rutting resistance, temperature sensitivity, viscoelastic properties, low-temperature cracking resistance, anti-fatigue and aging resistance performance of recycled asphalt can be enhanced remarkably by adding SBS and CR. Meanwhile, SBS-modified recycled asphalt has better fatigue and low temperature cracking resistance properties, while CR-modified recycled asphalt has the advantages on the rutting resistance, anti-aging and temperature sensitivity performance. Furthermore, SBS5-5 and CR6-4 modified recycled asphalts both have better pavement performance than others, which is superior to the requirements of polymer modified asphalt. Therefore, it is meaningful and feasible to recycle the aged base asphalt to be polymer-modified asphalt.

1. Introduction

It is a known fact that the application of reclaimed asphalt pavement (RAP) has numerous advantages in terms of saving natural resources, protecting environment and reducing construction cost (Liu et al., 2019), which has been widely used to produce the asphalt mixture with new asphalt binder and aggregate together for several decades (Song et al., 2018; Aguirre et al., 2016). However, the incorporation of RAP always has passive influence on the pavement performance owing to the existence of aged asphalt (Mokhtari et al., 2017; Ameri et al., 2018). It is recognized that asphalt ageing lead to the dramatic weakening of workability, cohesiveness, fatigue resistance and low-temperature anti-cracking properties of asphalt pavement (Ruan et al., 2003; Cavalli et al., 2018; Ma et al., 2019). Thus, it is essential to restore and enhance the viscoelastic and engineering performance of aged asphalt.

Currently, many studies focused on the performance recovery of aged asphalt in reclaimed asphalt pavement (Aguirre et al., 2016; Cai et al., 2019; Chen et al., 2018). The asphalt performance relies on the compounds dramatically, and the loss of light component is the substantial reason for the performance change of aged asphalt (Wang et al., 2016; Menapace et al., 2018; Yu et al., 2014). According to researches on ageing mechanism, adding light oil or fresh asphalt is the main method to balance chemical components and recover

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properties of aged asphalt (Ma et al., 2019; Zhu et al., 2017; Pahlavan et al., 2018; Zeng et al., 2018). Many rejuvenators were developed and used into recycling of aged asphalt, such as aromatic oil, bio-oil, waste vegetable oil, waste engine oil and fresh asphalt, which can effectively regain and further enhance the performance of aged asphalt (Pahlavan et al., 2018; Chen et al., 2014).

Zhang et al., 2018, 2019 investigated the possibility of using bio-oil as a rejuvenator to recycle aged asphalt and found that rheological properties, viscous components and stiffness of aged asphalt can be restored significantly (Ren et al., 2018). Meanwhile, Jiang et al. (2018) explored the experimental assessment on engineering properties of aged asphalt by incorporating a developed rejuvenator, which contained rubber oil, plasticizer and anti-aging agent. The results showed that self-designed rejuvenator could improve and restore the elastic recovery and aging resistance of aged binder. Besides, Cao et al. (2018) evaluated the effects of waste vegetable oil on rejuvenating aged asphalt in terms of rheological and chemical properties, which illustrated that the workability and fatigue resistance of aged asphalt were both improved by adding waste vegetable oil, while the sulfoxide index and large molecule size content decreased due to the physical dilution. Therefore, light oil is the main resource to strengthen the rheological properties and chemical components in aged asphalt. However, many previous studies (Wang et al., 2018a,b; Cai et al., 2019; Im et al., 2014; Yu et al., 2014) were attributed to restore the aged asphalt to be primary base asphalt, and very few researches tried to recycle the aged base asphalt to be polymer-modified asphalt, which is widely used into asphalt road because of its excellent engineering properties. Leng et al., 2018a,b) investigated the effects of waste polyethylene terephthalate (PET) additives on the performance of bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP). The results showed that the samples containing RAP and PET had better overall pavement performance than the conventional asphalt, including rutting and fatigue cracking resistance. Besides, another study (Bonicelli et al., 2017) focused on effectiveness of rejuvenator and plastomeric polymer on the performance of high RAP content (40%) asphalt mixture and drawn the conclusion that a proper calibration of rejuvenation agent and polymer could enhance the overall durability of high RAP content mixes.

It has been recognized that benefits of using polymer-modified asphalt are to reduce the amount and severity of pavement distresses and increase service life of asphalt road. Styrene-butadiene-styrene (SBS) and crumb rubber (CR) are the most common asphalt modifiers. It is known that SBS belongs to the group of the thermoplastic elastomeric block copolymer and could strengthen high and low-temperature properties of asphalt (Shadmani et al., 2018; Cong et al., 2015; Bai, 2017). Many studies (Cong et al., 2015; Dong et al., 2017, 2018; Wang et al., 2015; Zhao et al., 2016) were concentrated on the rheological properties, anti-aging resistance, modification mechanism as well as compatibility of SBS modified asphalt. On the other hands, crumb rubber modified asphalt (CRMA) has been extensively studied and applied in asphalt pavement for decades. The addition of CR into asphalt is an efficient method for environmental protection and low cost for asphalt road. Previous studies (Wang et al., 2018a,b; Saberi et al., 2017; Leng et al., 2018a,b; Ding et al., 2019) showed that adding CR could enhance the mechanical and rheological performance of asphalt through weakening fatigue as well as low-temperature cracking distinctly. Meanwhile, Gao et al. (2019) evaluated the comprehensive performance of polyurethane rubber particle mixture and found that polyurethane rubber particle mixtures exhibited high rutting resistance and high temperature performance. Many researchers (Qian et al., 2018; Dong et al., 2019; Liang et al., 2015) also used the SBS/CR composite modified asphalt to further improve the asphalt performance, such as compatibility, rutting resistance and anti-aging performance. Dong et al. (2016) investigated the influence of SBS and CR on the rheological behaviors and microstructure of composite hard asphalt, which showed that CR and SBS made remarkable improvements on viscoelastic behavior and temperature sensitivity of asphalt binder (Ren et al., 2018).

In consideration of the importance of recycling and modification technology in asphalt, the aim of this research is to explore the possibility of recycling and modifying the aged asphalt to be polymer-modified recycled asphalt by using polymer-modified low-viscosity asphalt rejuvenator. In order to achieve this goal, SBS or CR were added firstly into low-viscosity asphalt to prepare various polymer-modified asphalt rejuvenators. After that, aged asphalt and polymer-modified asphalt rejuvenators were mixed with different concentration ratio to prepare polymer-modified recycled asphalt. The conventional properties, rheological behaviors and anti-aging performance of aged and polymer-modified recycled asphalt were measured by utilization of rotational viscosity (RV) tests, dynamic shear rheometer (DSR) tests and bending beam rheometer (BBR) tests. Moreover, the effects of the concentration ratio between polymer-modified low-viscosity asphalt rejuvenator and aged asphalt on the high-temperature anti-rutting, low-temperature cracking resistance, fatigue and aging resistance abilities of recycled asphalt were studied.

2. Research objectives

The specific objectives of this study are as follows:

(1) To explore the possibility of recycling the aged asphalt using low-viscosity asphalt and polymers.
(2) To investigate the rheological behaviors and anti-aging properties of polymer-modified recycled asphalt.
(3) To analyze the effects of polymer-modified asphalt rejuvenator concentration on the high and low-temperature properties of polymer-modified recycled asphalt.

3. Materials selection and sample preparation

3.1. Raw materials

Neat asphalt with 60/80 pen grade was selected for further aging. The conventional properties and chemical compounds of 70# base asphalt were shown in Table 1. The styrene-butadiene-styrene (SBS, Grade T6302H) containing 30 wt% styrene and 130,000 g/mol average molecular weight was provided by Petrochemical Co., Ltd., China. Meanwhile, crumb rubber with the particle size of 30 mesh was made from waste vehicle tires. Furthermore, 200# base asphalt was selected as low-viscosity rejuvenator. The conventional properties of low-viscosity asphalt are as below: 25 °C penetration is 273dmm, softening point is 10 °C and viscosity is 2.305 Pa s at 60 °C.

Table 1
Conventional properties and chemical compounds of 70# base asphalt.

Items	Measured value	Test methods
Penetration(25 °C, 0.1 mm)	67	ASTM D5
Softening point(°C)	48.4	ASTM D36
Ductility(10 °C, cm)	85.2	ASTM D113
Ductility(15 °C, cm)	>150	
Viscosity(60 °C, Pa·s)	210	AASHTO T316
Saturates(S)/wt%	13.35	ASTM D4124
Aromatics(A)/wt%	17.35	
Resins(R)/wt%	39.70	
Asphaltenes(At)/wt%	29.60	

3.2. Preparation of aged asphalt and various rejuvenators

To obtain the aged asphalt, 70# base bitumen was aged by air blowing with a laboratory reaction vessel. The air-blowing test was conducted at 220–230 °C with an air flow of 2 l/min at atmospheric pressure (Zhang et al., 2018). In these tests, the oxidation aging time of virgin asphalt in the air-blowing unit was adapted to observed change of penetration value. The aged asphalt was obtained when a 10dmm penetration was reached, which was based on the actual penetration value of aged binder from reclaimed asphalt pavement.

The SBS-modified asphalt rejuvenator (referred to SBSMA) was prepared by a high shear mixer. The 200# base asphalt was heated to 140 °C and 6 wt% SBS was mixed laxly into the asphalt. Then the blend was mixed about 60min under 5000 rpm, at 175 °C. Finally, in order to obtain the stable SBS modified asphalt with polymer network structure, 0.12 wt% sulfur was added into the blend, which continued to be mixed by a mixer under 1000 rpm rotation speed for 2 h.

Similarly, CR-modified asphalt rejuvenator (referred to CRMA) was prepared using the following procedure. The 200# base asphalt was heated to 140 °C and 20 wt% crumb rubber was added into the low-viscosity asphalt. The blend was heated to 180 °C and mixed under 1000 rpm speed for 3 h to insure both the swelling as well as dispersion of crumb rubber particles in asphalt.

Table 2 displays the conventional properties of aged asphalt, 200# base asphalt, SBSMA and CRMA rejuvenators (see Figure 1), including 60 °C viscosity, 25 °C penetration, softening point and 5 °C ductility. Clearly, aged asphalt possesses the highest viscosity and softening point, but its low-temperature performance is worse. The 200# base asphalt has low-value viscosity and great low-temperature ductility. The physical properties of SBS-modified asphalt (SBSMA) and CR-modified asphalt (CRMA) rejuvenators are also shown in Table 2. The penetration and softening point of these two modified asphalt rejuvenators are similar, but SBS-modified asphalt rejuvenator has lower viscosity and larger ductility than CR-modified asphalt rejuvenator.

3.3. Preparation of the rejuvenated asphalts

According to the previous studies (Ding et al., 2016a,b), the diffusion of large molecules was the critical step that controlled the diffusion rate between virgin and aged asphalt binder, besides adding rejuvenator into aged asphalt could significantly accelerate the diffusion of the whole model. Meanwhile, Ding et al., 2016a,b) also compared the blending efficiency of plant produced asphalt paving mixtures containing high RAP and found that warm mix showed the highest blending efficiency.

In order to have better compatibility, the aged asphalt and polymer-modified asphalt rejuvenators were blended by using a mixer for 30min under the rotation speed of 1000 r/min. The mixing temperature was set at 140 °C to prevent the rejuvenators from aging and keep the high blending efficiency between rejuvenator and aged asphalt (Zhang et al., 2018; Ding et al., 2016a,b). The concentration ratio of polymer-modified asphalt rejuvenator and aged asphalt was 2:8, 3:7, 4:6, 5:5 and 6:4, respectively. To evaluate the impact of polymer on the performance of recycled asphalt, 200# asphalt binder with low viscosity was selected as rejuvenator solely to recycle the aged asphalt, and the concentration ratio of 200# asphalt and aged asphalt was 3:7. The aged and rejuvenated binders utilized in this study are illustrated in Table 3.

4. Experiments and methods

4.1. Rotational viscometer (RV) test

To assess the impact of polymer-modified asphalt rejuvenator on the anti-flow and workability for recycled asphalt, the viscosity measurement was performed. The experiment was conducted by using Brookfield Rotational Viscometer. The experimental temperature and shear rate were 135 °C and 20r/min, respectively.

4.2. Dynamic shear rheometer (DSR) test

In this study, rheological methods, including temperature sweep test, frequency sweep test, multiple stress creep and recovery (MSCR) test and steady-state flow test were conducted by using a strain-controlled dynamic shear rheometer (DSR) TA-HR1. Meanwhile, all DSR measurements were conducted on three replicates of samples to obtain reliable results.

Asphalt was tested by using the temperature sweep tests at 10 rad/s and increasing temperature from 48 to 78 °C with the increment of 6 °C. Besides, 60 °C frequency sweep test was also conducted with the frequency increasing from 10^{-1} rad/s to 10^2 rad/s. In addition, MSCR test was executed on the RTFO-aged asphalt samples with two stress levels of 0.1 kPa and 3.2 kPa at 60 °C. Furthermore, steady-state flow test at 60 °C was performed to measure the viscous flow behaviors of polymer-modified recycled asphalt. The shear rate region was from 10^{-3} rad s^{-1} to 10^2 rad s^{-1}.

4.3. Bending beam rheometer (BBR) test

The BBR test was performed to explore the low-temperature cracking resistance performance of polymer-modified recycled asphalts based on the two parameters: creep stiffness (S) and m-value at the temperature of −18 °C and −24 °C (Ren et al., 2018).

4.4. Short-term and long-term aging tests

Rolling thin film oven tests (RTFOT) and Pressure aging vessel tests (PAV) was conducted to simulate the short-term and long-term aging of asphalt binder, respectively. In the RTFOT process, 35 g of recycled asphalt was added to the rotary thin film oven at 163 °C. The rate of oven-hot air and the vertical rotation speed of holder were set at 4000 ml/min and 15 r/min for 85min. In the PAV test, 50 g of RTFOT sample was added in the plates and the experimental temperature was 90 °C and the air pressure was 2.1 MPa. The PAV sample could be obtained after 20 h (Dong et al., 2017).

Table 2
Conventional properties of aged asphalt and rejuvenators.

Items	Viscosity (60 °C, Pa·s)	Penetration (25 °C, 0.1 mm)	Softening point (°C)	Ductility (5 °C, cm)
Aged asphalt	32359	10	84.1	0.1
200# base asphalt	2.305	273	10.1	>100
CRMA	684	221	53.0	44.6
SBSMA	333	241	51.0	89.2

Table 3
Sample range matrix.

Binder types	Asphalt binders
Aged asphalt	Air-blowing oxidation aged 70# asphalt
BA3-7	30 wt% 200# asphalt +70 wt% aged asphalt
SBS2-8	20 wt% SBS modified asphalt rejuvenator +80 wt% aged asphalt
SBS3-7	30 wt% SBS modified asphalt rejuvenator +70 wt% aged asphalt
SBS4-6	40 wt% SBS modified asphalt rejuvenator +60 wt% aged asphalt
SBS5-5	50 wt% SBS modified asphalt rejuvenator +50 wt% aged asphalt
SBS6-4	60 wt% SBS modified asphalt rejuvenator +40 wt% aged asphalt
CR2-8	20 wt% CR modified asphalt rejuvenator +80 wt% aged asphalt
CR3-7	30 wt% CR modified asphalt rejuvenator +70 wt% aged asphalt
CR4-6	40 wt% CR modified asphalt rejuvenator +60 wt% aged asphalt
CR5-5	50 wt% CR modified asphalt rejuvenator +50 wt% aged asphalt
CR6-4	60 wt% CR modified asphalt rejuvenator +40 wt% aged asphalt

5. Results and discussion

5.1. Conventional properties

In this study, these conventional properties, including penetration, softening point, ductility as well as 135 °C viscosity, were obtained to evaluate the regeneration effect of aged asphalt using polymer-modified asphalt rejuvenator. Fig. 2 shows the conventional properties of base, aged and recycled asphalts. It is clear that aging process remarkably decrease the penetration value as well as increase both softening point and viscosity of base asphalt. Aged asphalt has the highest softening point and viscosity, meanwhile, it has the lowest penetration and ductility value. That is to say, aged asphalt has brilliant high-temperature property but worse low-temperature anti-cracking ability and construction workability. Fortunately, these penetration, ductility and viscosity of aged asphalt can be restored by adding low-viscosity asphalt. Compared to aged asphalt, the penetration and ductility of BA3-7 recycled asphalt increases by 30dmm and 1.4 cm, while the 135 °C viscosity decreases by 8.3 Pa s. However, the softening point of aged asphalt decreases from 84.1 °C to 60.4 °C after adding low-viscosity asphalt. It can be concluded that low-viscosity asphalt can improve the penetration and ductility of aged asphalt, but it would weaken high-temperature properties. Meanwhile, the influence of low-viscosity asphalt on enhancing the low-temperature properties of aged asphalt is limited, that is why SBS and CR are selected to further modify the recycled asphalt.

From Fig. 2, the softening point, 5 °C ductility and viscosity for recycled asphalt can be improved by adding SBS and CR, while the penetration decreases. It is indicated that SBS and CR can improve both high and low-temperature performance of recycled asphalt simultaneously. With the concentration ratio increasing, the penetration and ductility of recycled asphalt both enhance gradually, while the softening point and 135 °C viscosity both decrease in proportion. Compared with base asphalt, polymer recycled asphalts all have greater softening point, ductility and softening point, which shows that polymer recycled asphalts possess better high and low-temperature properties than base asphalt. When concentration ratio is 5:5, the softening point of SBS and CR modified recycled asphalt is 64.7 °C and 62.4 °C, while the ductility is 27.1 cm and 7.2 cm, respectively. According to our previous study (Ren et al., 2018; Qian et al., 2018), the original SBS modified asphalt with 3 wt % SBS dosage was prepared, the softening point and 5 °C ductility of which is 55 °C and 20 cm, respectively. Clearly, the conventional high and low-temperature properties of SBS5-5 recycled asphalt are superior to that of ordinary SBS modified asphalt. The above results mean that SBS and CR modified asphalt rejuvenator is good for strengthening the low-temperature properties and workability for aged bitumen dramatically. In terms of 135 °C viscosity, it is well known that the viscosity value should not exceed 3.5 Pa s to save energy used in asphalt pavement construction. It can be found that SBS3-7, SBS4-6, SBS5-5 and SBS6-4 all meet the requirement, while the viscosity of CR5-5 and CR6-4 are lower than 3.5 Pa s. Furthermore, compared to SBS-modified recycled asphalt, CR-modified recycled asphalt has lower penetration and ductility while having higher softening point and viscosity. Clearly, SBS-modified recycled asphalt is good at the low-temperature properties and construction workability, while CR-modified recycled asphalt possesses the better deformation resistance. In consideration of balancing both conventional high and low-temperature performance of recycled asphalt, SBS5-5 and CR6-4 recycled asphalts are recommended to be used in the recycling of aged asphalt.

5.2. Temperature sensitivity

The temperature sensitivity could reflect the application range of asphalt pavement effectively. And the relationship between complex modulus G* and temperature was selected to estimate

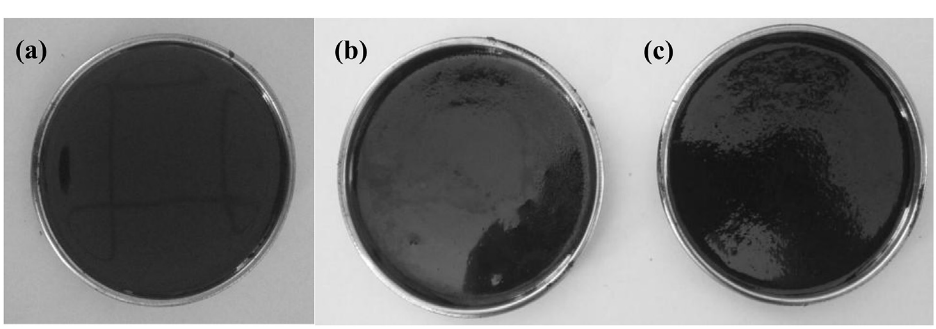


Fig. 1. Apparant morphology photographs of 200# base asphalt(a), SBS modified asphalt rejuvenator(b) and CR modified asphalt rejuvenator(c).

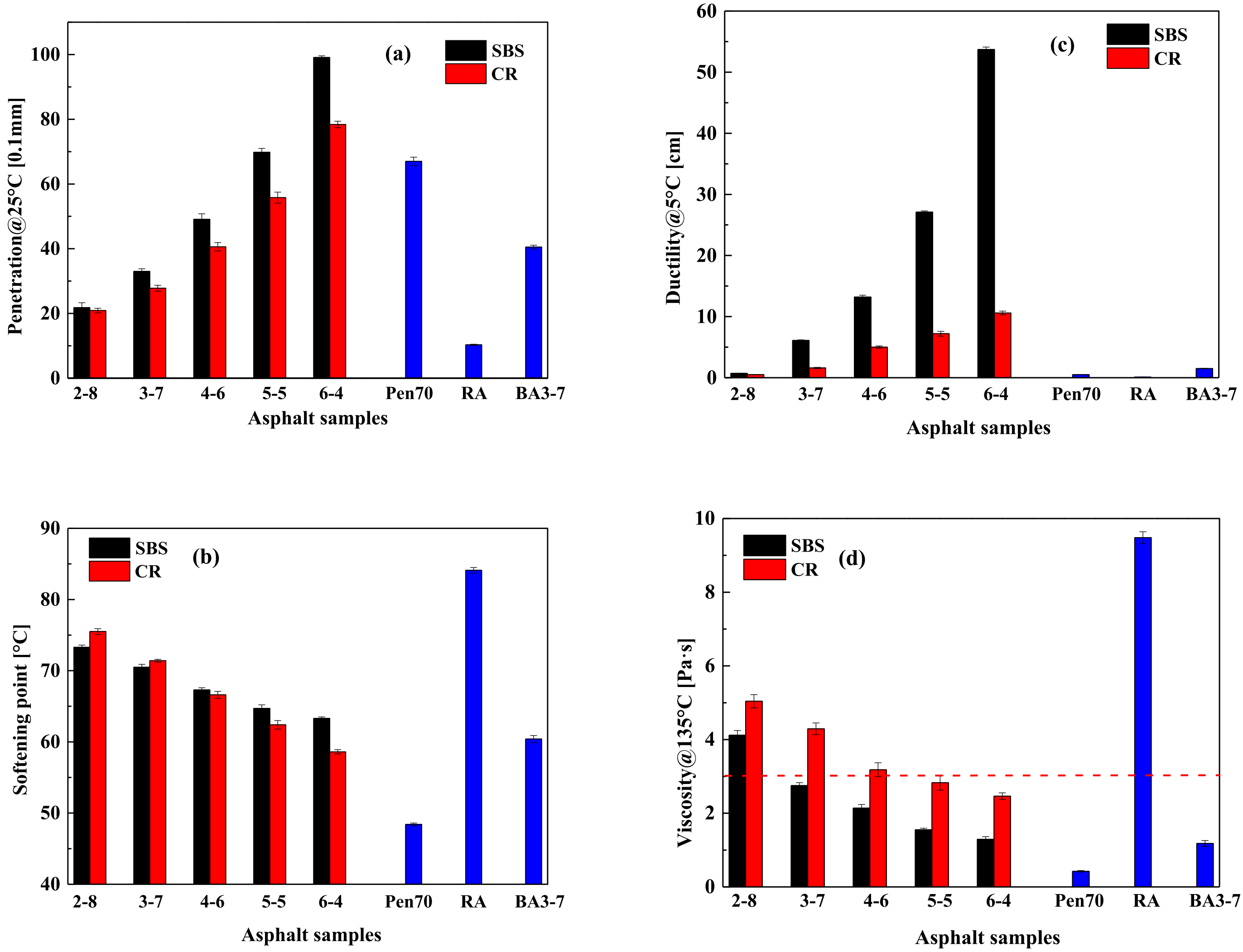


Fig. 2. Conventional properties of base, aged and recycled asphalt.

temperature sensitivity of samples, which was displayed in Fig. 3. The G* value decreases as the increase of temperature as well as there is a good linear relationship between modulus and temperature.

From Fig. 3, it can be seen that the aged asphalt has the highest G* value than others. Besides, adding low-viscosity asphalt and polymer modified low-viscosity asphalt rejuvenators have adverse effects on the modulus of recycled asphalt. Moreover, the absolute value of equation slope of BA3-7 is larger than aged asphalt, which indicates that low-viscosity asphalt has a bad influence on temperature sensitivity. However, SBS3-7 and CR3-7 both have lower absolute values of equation slope than the BA3-7, indicating SBS and CR both can weaken the temperature dependence of performance for recycled asphalt. With the concentration ratio raising, recycled asphalts have more excellent temperature sensitivity resistance performance. When the concentration ratio is more than 4:6, the temperature sensitivity resistance of recycled asphalt is superior to that of aged asphalt, indicating more polymer-modified low-viscosity asphalt rejuvenator content could further improve the performance stability of recycled asphalt. Furthermore, SBS and CR have different effects on the temperature susceptibility of recycled asphalt. It can be seen from Fig. 3 that with the same concentration ratio of polymer-modified low-viscosity asphalt rejuvenator and aged asphalt, all CR modified recycled asphalts have the lower absolute value of equation slope than that of SBS modified recycled asphalts, which suggests that CR-modified asphalt rejuvenator has more benefits to the temperature sensitivity resistance performance of recycled asphalts.

5.3. Rheological behaviors

5.3.1. Frequency sweep test

Characterization in rheological properties of asphalt is an efficient method to estimate the recycling influence of rejuvenator on the viscoelastic behavior for aged asphalt. The master curves for aged and recycled asphalts are plotted in Fig. 4. The G* value of asphalt increases with the increasing of frequency, which means that high frequency has the benefit of preventing asphalt roads from deformation. To further investigate the frequency sensitivity of aged and recycled asphalt, a linear regression model is used and these equations are shown in Fig. 4. It is obvious that the complex modulus of asphalt has a great linear relationship with loading frequency. The aged asphalt has low-frequency sensitivity and the addition of low-viscosity asphalt increases the frequency sensitivity of aged asphalt dramatically. Meanwhile, the addition of SBS and CR can weaken the frequency sensitivity of recycled asphalt. With the concentration ratio increasing, frequency sensitivity of recycled asphalt becomes higher. Compared to SBS-modified recycled

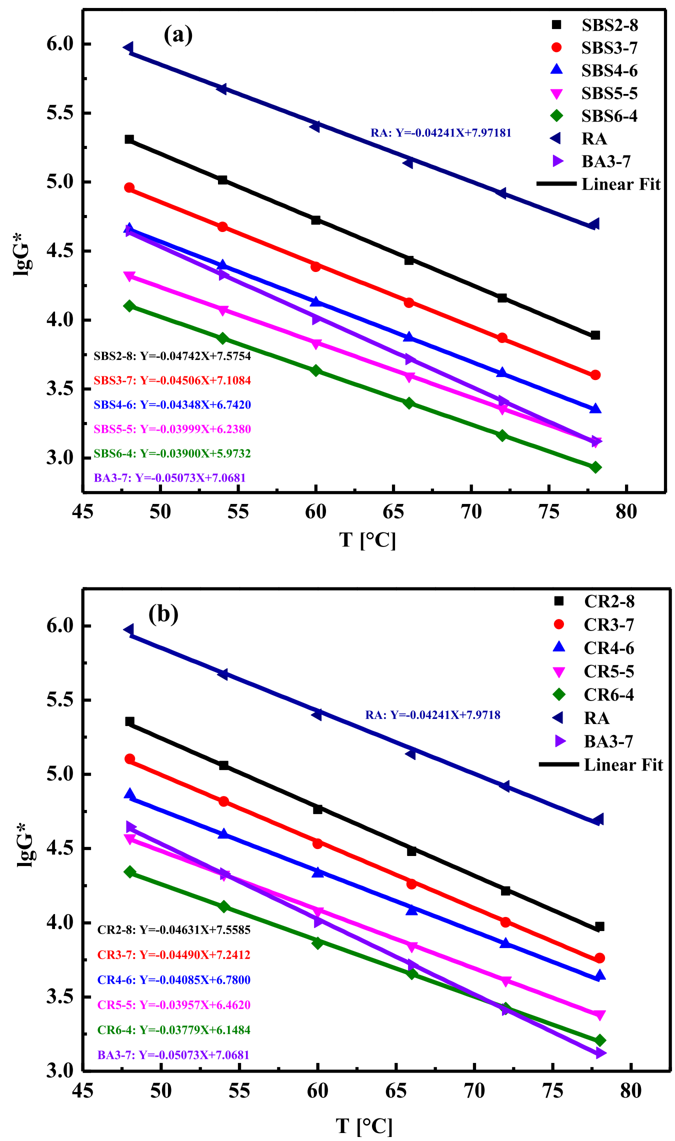


Fig. 3. Relationship between temperature and complex modulus of SBS or CR modified recycled asphalt.

asphalt, CR-modified recycled asphalt has lower slope value and better frequency sensitivity. Furthermore, aged asphalt has the highest complex modulus in all asphalt samples, which dues to the loss of light compounds and increasing stiffness. The addition of low-viscosity asphalt decreases the G* value of aged asphalt, which can be improved by adding SBS and CR. With the increasing of polymer-modified low-viscosity asphalt content, the complex modulus of polymer-modified recycled asphalt declines owing to the increase of low-viscosity asphalt content.

The phase angle δ is used to investigate the influence of rejuvenator on the viscoelastic property of aged asphalt. The phase angle δ of aged and recycled asphalt at 60 °C are obtained and shown in the Fig. 5. It can be found that aged asphalt has the lowest phase angle value, which is due to the loss of light components and viscous property. After adding low-viscosity asphalt, the δ value of aged asphalt increases dramatically, showing that low-viscosity asphalt can recover the viscous property of aged asphalt. However, asphalt binder with balanced viscoelastic behavior is popular in pavement construction, and BA3-7 recycled asphalt is insufficient in the elastic property. Thus, SBS and CR are added in recycled asphalt to improve and balance its viscoelastic performance. It is clear that adding SBS and CR can decrease the δ value of recycled asphalt. With the concentration content of SBS or CR modified low-viscosity asphalt increasing, the phase angle of recycled asphalt increases gradually due to the increasing of low-viscosity asphalt content. However, the existence of SBS and CR decelerates the increasing trend and has a great influence on enhancing elastic properties of recycled asphalt. Furthermore, compared to SBS-modified recycled asphalt, CR-modified recycled asphalt has lower phase angle, indicating CR-modified recycled asphalt has better elastic property.

5.3.2. Temperature sweep test

In order to assess the viscoelastic behaviors of aged and recycled asphalt, temperature sweep test was conducted from 48 to 78 °C with the increment of 6 °C (Ren et al., 2018). Fig. 6 displays both storage modulus G′ and loss modulus G″ of aged and recycled asphalt. The G′ value always exhibits lower value than G″ of all asphalt samples, showing the main rheological property of aged and recycled asphalt are dominated by viscous behavior. It can be noted that the G′ value drops to more extent significantly than G″ with temperature increasing, which is consistent to the typical viscoelastic behaviors of asphalt binder. From Fig. 6, aged asphalt has the highest G′ and G″ value, which are enhanced obviously by adding low-viscosity asphalt. It is indicated that the addition of low-viscosity asphalt weakens the viscoelastic properties of aged asphalt. Fortunately, adding SBS and CR can enhance both G′ and G″ value of recycled asphalt, which means that SBS and CR can strengthen the viscoelastic behaviors of recycled asphalt. Furthermore, rheological behaviors of recycled asphalt depend on the concentration ratio of SBS or CR modified low-viscosity asphalt rejuvenators and aged asphalt. With the concentration ratio increasing, both storage modulus and loss modulus of recycled asphalts decrease gradually.

In addition, the rutting index G*/sinδ of aged and recycled asphalt at varying temperatures from 48 °C to 78 °C is plotted in Fig. 7. It is clear that the rutting factor decreases with the increase of temperature and there is a great linear relationship between rutting factor and temperature. As the temperature increasing, asphalt sample becomes soft and its viscosity decreases, which leads to the weakening of rutting resistance performance (Zhang et al., 2018). The aged asphalt has the highest rutting factor and best anti-rutting ability, which is connected to the loss of light compounds and the increase of stiffness. After adding low-viscosity asphalt, the rutting factor declines remarkably owing to the decreasing of viscosity, indicating the low-viscosity asphalt has passive influence on improving high-temperature properties of aged asphalt. Fortunately, the rutting factor of recycled asphalt can be increased by adding SBS and CR, which shows SBS and CR can strengthen the anti-rutting of recycled asphalt. With the increase of concentration ratio of SBS or CR modified low-viscosity asphalt rejuvenator and aged asphalt, the rutting factor of recycled asphalt declines signally owing to the increase of low-viscosity asphalt content. Besides, it can be noted clearly that the rutting factor of CR-modified recycled asphalt is larger than that of SBS-modified recycled asphalt. That is to say, CR-modified recycled asphalt has better rutting resistance properties at high temperature.

Furthermore, the failure temperature of base, aged and recycled asphalt, which is a certain temperature when the rutting factor is equal to 1.0 kPa, is plotted in Fig. 8. After aging, the failure temperature of base asphalt increases from 68.12 °C to 112.9 °C, showing the remarkable improvement of rutting resistance for aged asphalt. Besides, it can be found that the addition of low-viscosity asphalt decreases the failure temperature of aged asphalt by 32.8 °C, which indicates that the low-viscosity asphalt

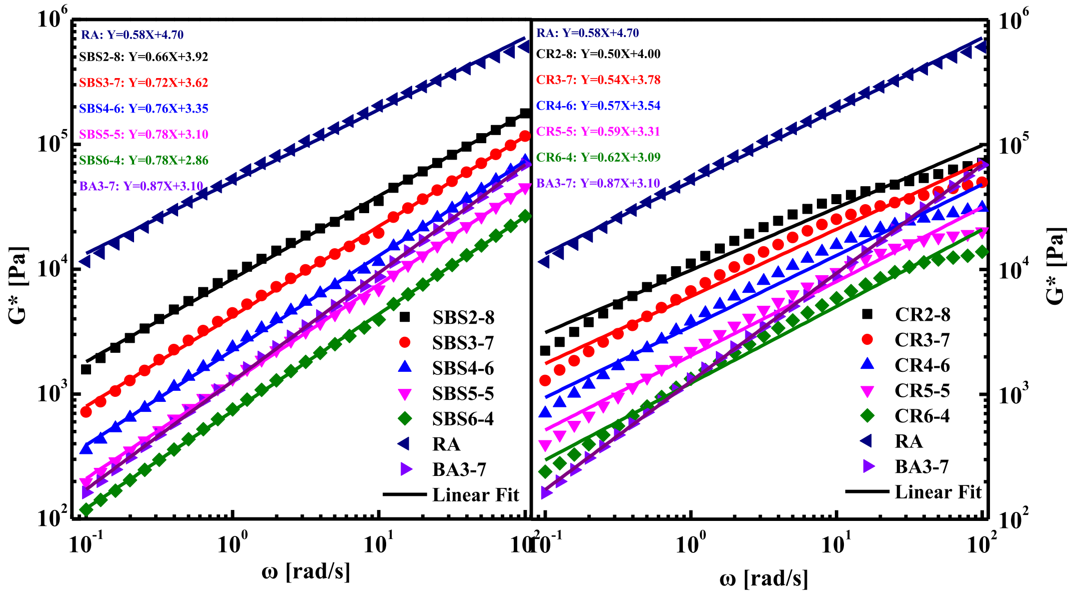


Fig. 4. Master curves of SBS and crumb rubber modified recycled asphalt.

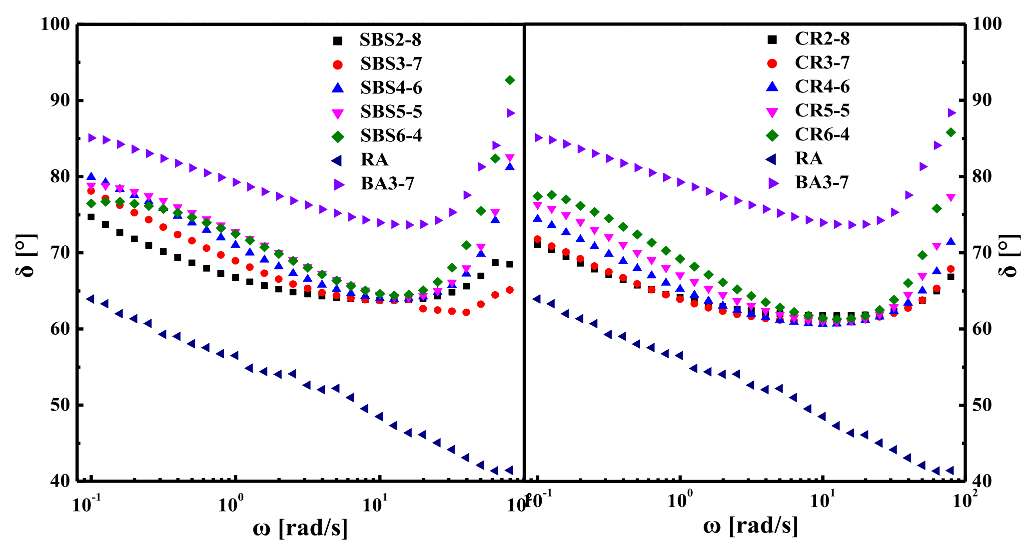


Fig. 5. The phase angle of SBS and crumb rubber modified recycled asphalt.

has bad influence on the rutting resistance of aged asphalt. Thus, the rejuvenator content should be controlled to ensure the high-temperature performance of recycled asphalt. Fortunately, failure temperature of recycled asphalt can be increased by 11.12 °C and 14.63 °C by adding SBS and CR, which means that SBS and CR can improve the high-temperature anti-rutting property of recycled asphalt. Importantly, the failure temperature values of recycled asphalts are all higher than base asphalt, indicating that the high-temperature property of recycled asphalt is superior to base asphalt. Meanwhile, as the concentration ratio of SBS or CR modified low-viscosity asphalt and aged asphalt increasing, the failure temperature of recycled asphalt decreases gradually. Therefore, the concentration ratio should be considered and selected discreetly to prevent the recycled asphalt from rutting deformation. Besides, CR-modified recycled asphalt has higher failure temperature than that of SBS-modified recycled asphalt, indicating that CR-modified recycled asphalt has an advantage in high-temperature rutting resistance ability. Interestingly, all obtained SBS or CR modified recycled asphalts have satisfied failure temperature more than 80 °C, except for the failure temperature of SBS6-4 recycled asphalt is 76.57 °C. Obviously, the failure temperature of obtained recycled asphalts in this study can meet the PG requirement for polymer modified asphalt and can be used into road construction. Only considering the high-temperature properties of recycled asphalt, the lower concentration ratio of rejuvenator and aged asphalt should be selected and used in recycling of aged asphalts. However, the optimal rejuvenator content should be determined when all properties of recycled asphalt binders are considered.

5.4. Creep and recovery behavior

In the MSCR tests, two parameters (recovery percent R% and non-recoverable compliance Jnr) are obtained to assess the effects of SBS and CR modified low-viscosity recycled asphalt rejuvenator

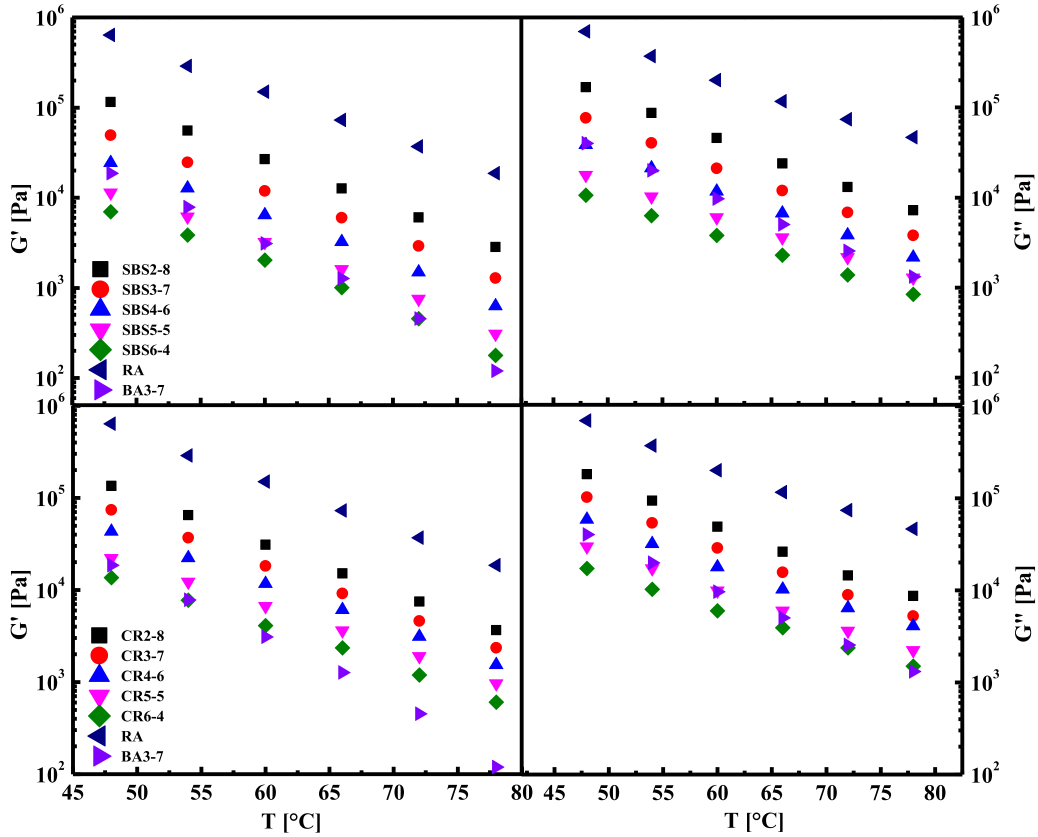


Fig. 6. Storage modulus (G′) and loss modulus (G″) of aged and recycled asphalt.

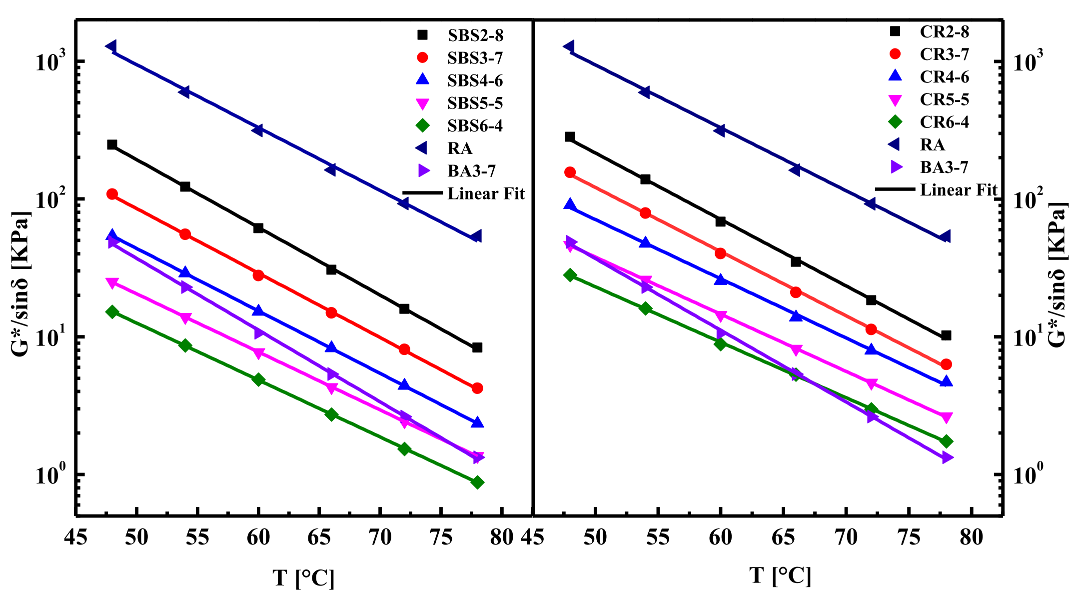


Fig. 7. G*/sinδ values of SBS and crumb rubber modified recycled asphalt.

on the creep recovery and viscoelastic properties of aged asphalt. Asphalt with higher R% and lower Jnr would have more elastic component and be adapt at high-temperature permanent deformation resistance. In this study, aged and recycled asphalt were all subjected to multiple shear loading and unloading cycle of 1s and 9s separately. Ten cycles of loading were carried out at the stress level of 0.1 kPa and 3.2 kPa (Saboo and Kumar, 2015).

Figs. 9 and 10 show the R% and Jnr value of aged and recycled asphalt, respectively. It is as expected that aged asphalt has the lowest Jnr value and highest R% value, indicating that aged asphalt has more elastic compounds and possesses the excellent rutting and permanent deformation resistance performance. The result is consistent to the rutting factor and failure temperature that aged asphalt has brilliant high-temperature properties. As the loading

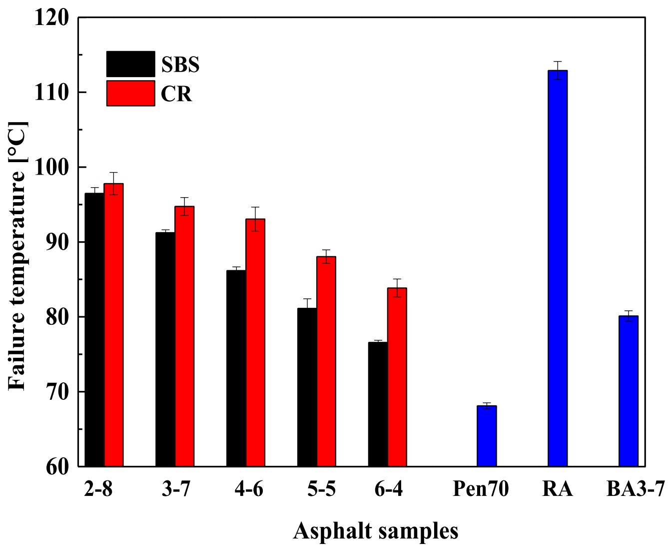


Fig. 8. Failure temperature of SBS and crumb rubber modified recycled asphalt.

stress increasing, the R% declines and Jnr of asphalt increases dramatically, which further explains the vehicle overloading has disadvantageous influence on the pavement properties of asphalt roads. Meanwhile, the addition of low-viscosity asphalt can decrease the R% and increase the Jnr value of aged asphalt remarkably. For example, at the loading stress of 3.2 kPa, the R% value of aged asphalt decreases by 59.27% and the Jnr value increases by 0.7 kPa^{-1}, which means that low-viscosity asphalt weakens the elastic recovery and permanent deformation resistance properties of aged asphalt.

In term of the effect of SBS and CR on the creep and recovery behavior of recycled asphalt, it is observed that SBS and CR modified recycled asphalt has higher R% value and lower Jnr value than that of BA3-7 recycled asphalt, which illustrates the favorable influence of SBS and CR on improving the elastic properties and high-temperature performance of recycled asphalt. Furthermore, the concentration ratio of rejuvenator and aged asphalt has crucial influence on the R% and Jnr values of recycled asphalt. With the increasing of concentration ratio, the R% value of recycled asphalt decreases and the Jnr value increases gradually. It is indicated that although both SBS and CR can enhance the elastic properties of

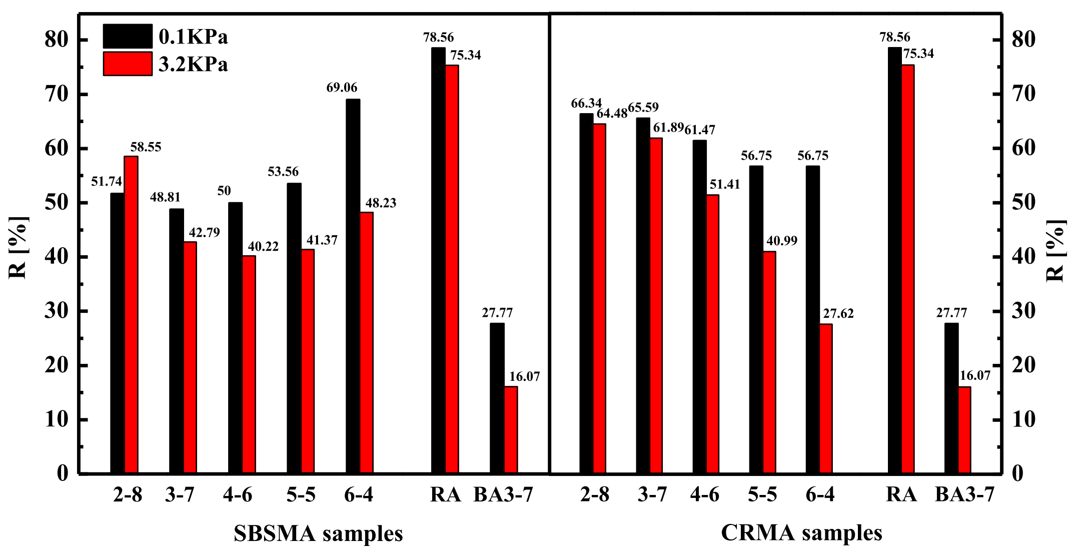


Fig. 9. Average recovery percent R% values of SBS and CR modified recycled asphalt.

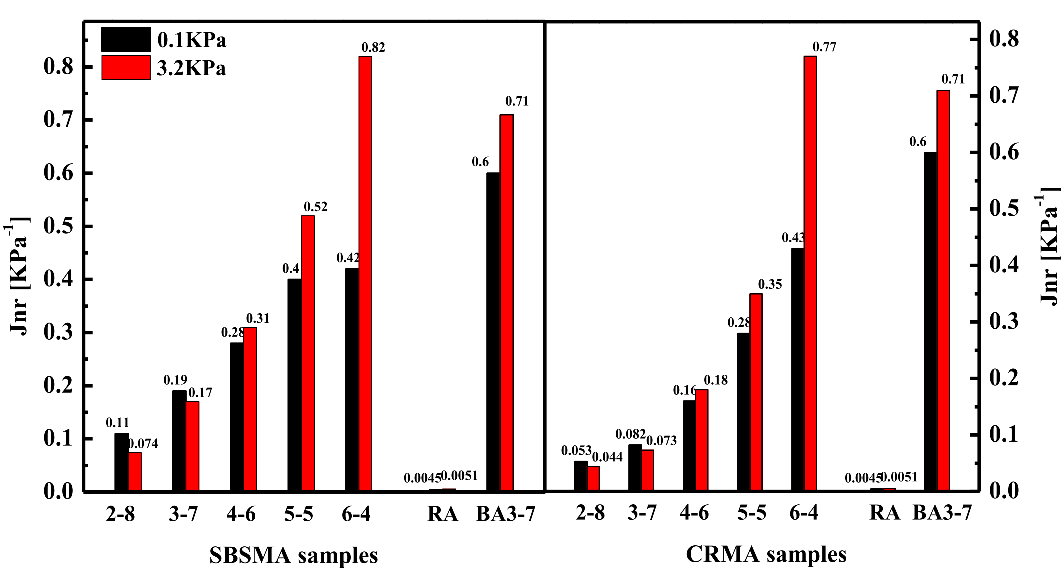


Fig. 10. Average Jnr values of SBS and CR modified recycled asphalt.

recycled asphalt, the influence of low-viscosity asphalt on the creep and recovery behavior mainly dominates. However, when the concentration ratio increases to 5:5 and 6:4, the R% value of SBS modified recycled asphalt starts to increase but the Jnr value still decreases. That may be explained that SBS mainly contributes to the improvement of the elastic property of recycled asphalt, while the low-viscosity asphalt has a great effect on the enhancement of viscous compounds. Furthermore, SBS and CR have different effects on the elastic recovery of recycled asphalt. It can be found that most of all SBS modified recycled asphalts have lower R% value than that of the CR modified recycled asphalt, while the former has higher Jnr value than the latter. That is to say that CR-modified recycled asphalt has better elastic recovery and high-temperature performance than SBS-modified recycled asphalt.

5.5. Steady state flow behavior

In order to further evaluate the viscous flow behavior and high-temperature properties of aged and recycled asphalt, steady-state flow tests were conducted through frequency sweep test at 60 °C using DSR with the shear rates increasing from 10^{-3} to 10^2 s^{-1}. The flow curves of aged and recycled asphalts are plotted in Fig. 11. At a wide range of low shear rates, the viscosities of aged and recycled asphalts all remain constant without the effects of shear rate, which is related to the typical Newtonian behavior of asphalt binders. On the other hand, the viscosity of aged and recycled asphalt shows a prominent dependence on the shear rate, especially when the shear rate exceeds $10^{-1}s^{-1}$. At the high shear rate range, the viscosity of asphalt decreases dramatically, which shows an apparent shear-thinning behavior.

In general, flow curves of aged and recycled asphalts show Newtonian behaviors within low shear rates range, while shear-thinning behavior is obvious at high shear rates range, which further verifies the viscoelastic behavior of bitumen. It is clear that Newtonian behavior range of aged asphalt is smaller than others because of the loss of light compounds. Meanwhile, the addition of low-viscosity asphalt can expand the Newtonian behavior region of aged asphalt. The higher content light components in low-viscosity asphalt may be one main contributor, which compensates the viscous part of aged asphalt (Zhang et al., 2018). Moreover, SBS or CR intensifies the shear-thinning behavior of recycled asphalt, indicating the more complicated entanglement between asphalt and polymers.

The distinctions of flow curves for aged and recycled asphalts can be described and characterized by using the Carreau model, in which s means the slope of shear-thinning behavior range and $\dot{\gamma}_c$ represents the essential shear rate related to the turning point of the shear-thinning region. Importantly, η_0 corresponds to the critical viscosity with the shear rates approaching to zero, which also calls zero shear viscosity (ZSV) and is an effective indicator to estimate the deformation resistance of asphalt binder. These Carreau model parameters of aged and recycled asphalts are displayed in Table 4.

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

In terms of zero shear viscosity (ZSV@60 °C) of aged and recycled asphalt, aged asphalt has the highest ZSV value of 217682 Pa s, which has a positive effect on the high-temperature properties but adverse influence on the workability of asphalt road construction. It is clear that the addition of low-viscosity asphalt can remarkably decrease the zero shear viscosity because of the compensation of light compounds. When 30 wt% low-viscosity asphalt is added, the zero shear viscosity of aged bitumen decreases to 1726 Pa s. Compared with BA3-7 recycled asphalt, SBS and CR modified recycled asphalt has lager ZSV and grater high-temperature

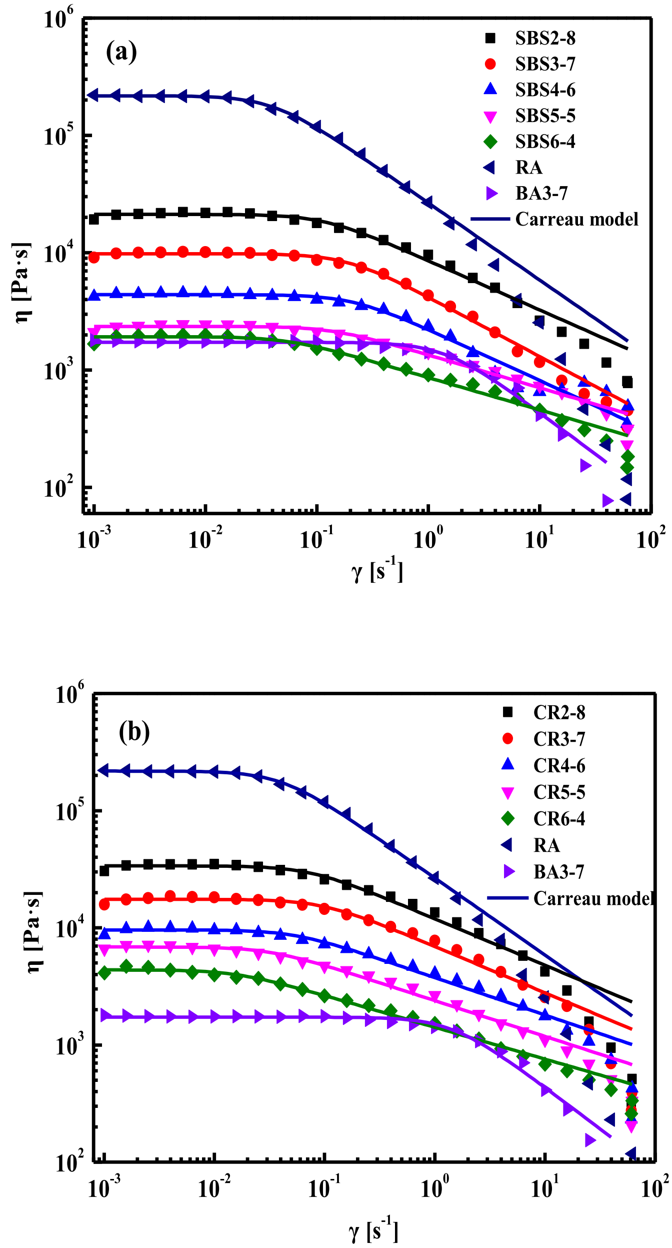


Fig. 11. Flow curves of SBS and CR modified recycled asphalt.

Table 4
The results calculated from Carreau model at 60 °C of aged and recycled asphalts.

	Asphalt binders						
	RA	BA3-7	SBS2-8	SBS3-7	SBS4-6	SBS5-5	SBS6-4
$\eta_0 \times 10^{-3}$(Pa·s)	217.682	1.726	21.239	9.816	4.399	2.360	1.926
$\dot{\gamma}_c(s^{-1})$	0.329	0.355	0.210	0.254	0.218	0.140	0.138
s	0.0410	1.439	0.115	0.188	0.209	0.137	0.055
R^2	0.999	0.988	0.991	0.995	0.990	0.985	0.986
	RA	BA3-7	CR2-8	CR3-7	CR4-6	CR5-5	CR6-4
$\eta_0 \times 10^{-3}$(Pa·s)	217.682	1.726	33.760	17.496	9.596	6.859	4.367
$\dot{\gamma}_c(s^{-1})$	0.329	0.355	0.198	0.197	0.159	0.153	0.136
s	0.0410	1.439	0.0727	0.0959	0.0528	0.0316	0.0157
R^2	0.999	0.988	0.989	0.989	0.988	0.990	0.991

properties, which is in line with the results of rotational viscosity and failure temperature. Besides, the ZSV value of polymer-modified recycled asphalt decreases as the increase of concentration ratio between SBS or CR modified low-viscosity asphalt rejuvenator and aged asphalt. It can be concluded that low-viscosity asphalt can impair the zero-shear viscosity and high-temperature properties of aged asphalt dramatically, which can be further improved by adding SBS and CR. Thus, polymer-modified recycled asphalt not only can recover the viscosity and workability but also can enhance the high-temperature properties of recycled asphalt to some extent. Furthermore, it is clear that all CR-modified recycled asphalts have higher ZSV value than SBS-modified recycled asphalts, indicating that the former has better high-temperature performance than the latter.

5.6. Low temperature performance

The low temperature cracking resistance of aged and recycled asphalt was investigated by BBR tests. The PAV aged samples of old and recycled asphalt were conducted in this test at −18 and −24 °C, respectively. The creep stiffness and m-value were obtained and used to evaluate the low-temperature performance of asphalt binder (Ren et al., 2018). Asphalt sample with lower stiffness and higher m-value has more excellent anti-cracking potential. The stiffness S and m-value of aged and recycled asphalts are displayed in Figs. 12 and 13.

Fig. 12 shows the S and m-value of aged, low-viscosity asphalt recycled and SBS-modified recycled asphalt. It is found that aged asphalt has the largest stiffness and lowest m-value in all tested asphalt samples, which means that aged asphalt is easily to happen the thermal cracking disease. After adding low-viscosity asphalt, the stiffness of aged asphalt decreases and the m-value increases dramatically, which indicates that low-viscosity asphalt can restore and even improve the low-temperature performance of aged asphalt. Compared to BA3-7 recycled asphalt, SBS-modified recycled asphalt is 161 MPa lower on S value and 0.027 higher on m-value at −24 °C, while 76 MPa lower on creeping stiffness and 0.011

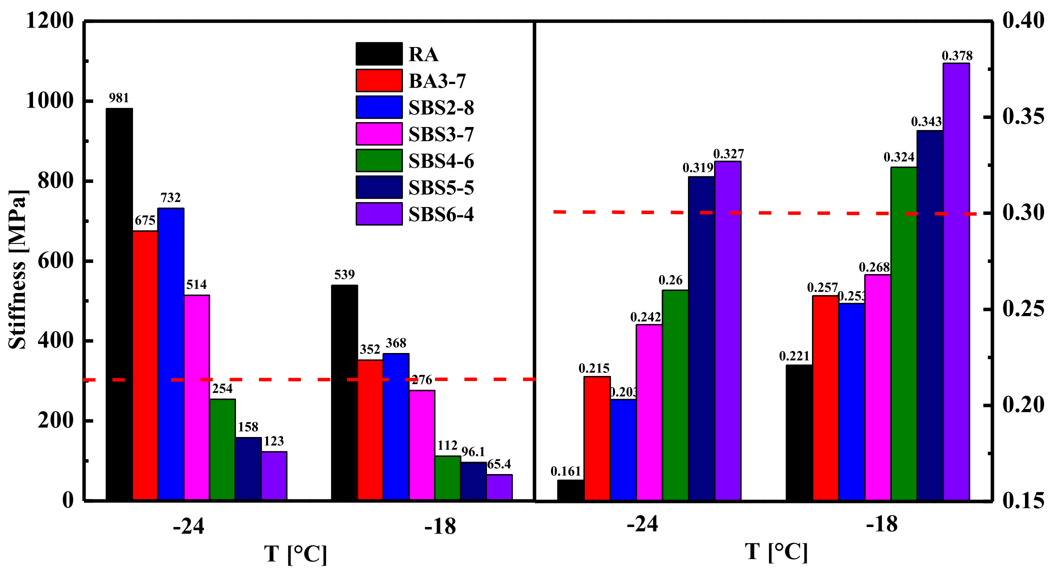


Fig. 12. Stiffness and m-value of SBS modified recycled asphalt.

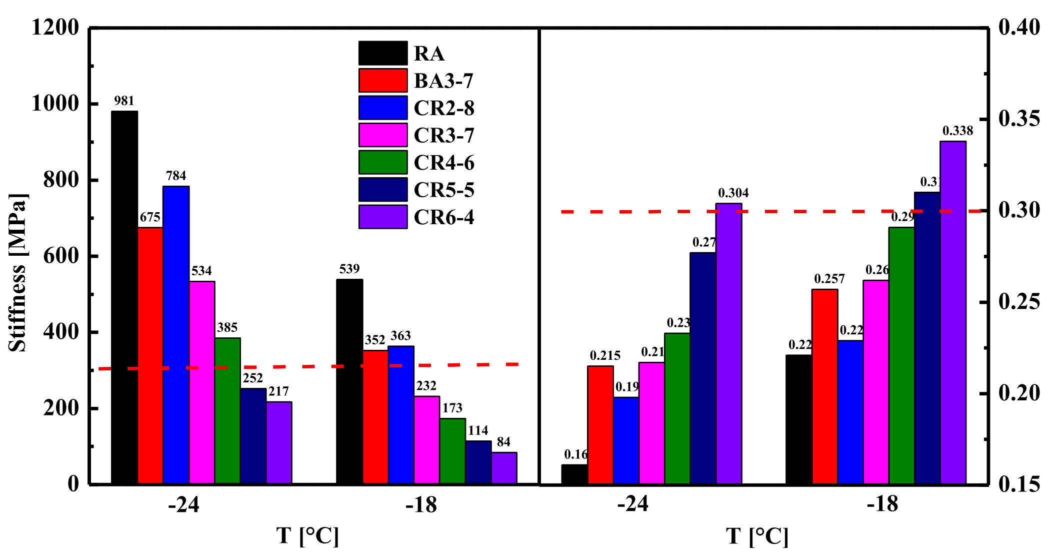


Fig. 13. Stiffness and m-value of crumb rubber modified recycled asphalt.

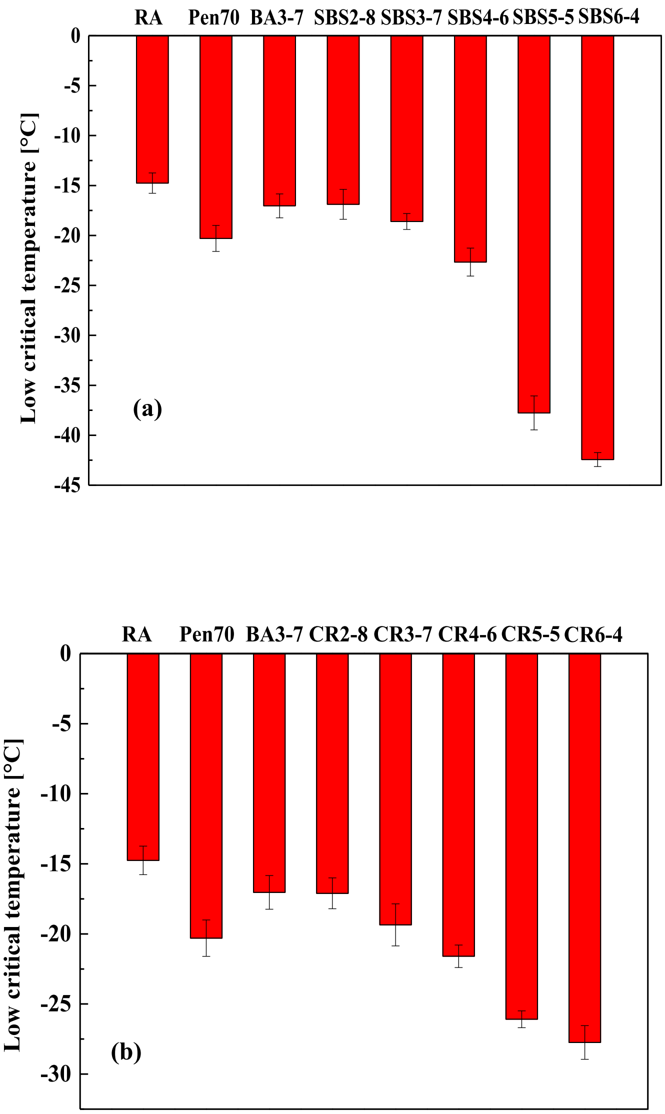


Fig. 14. The low critical temperature of SBS and CR modified recycled asphalt.

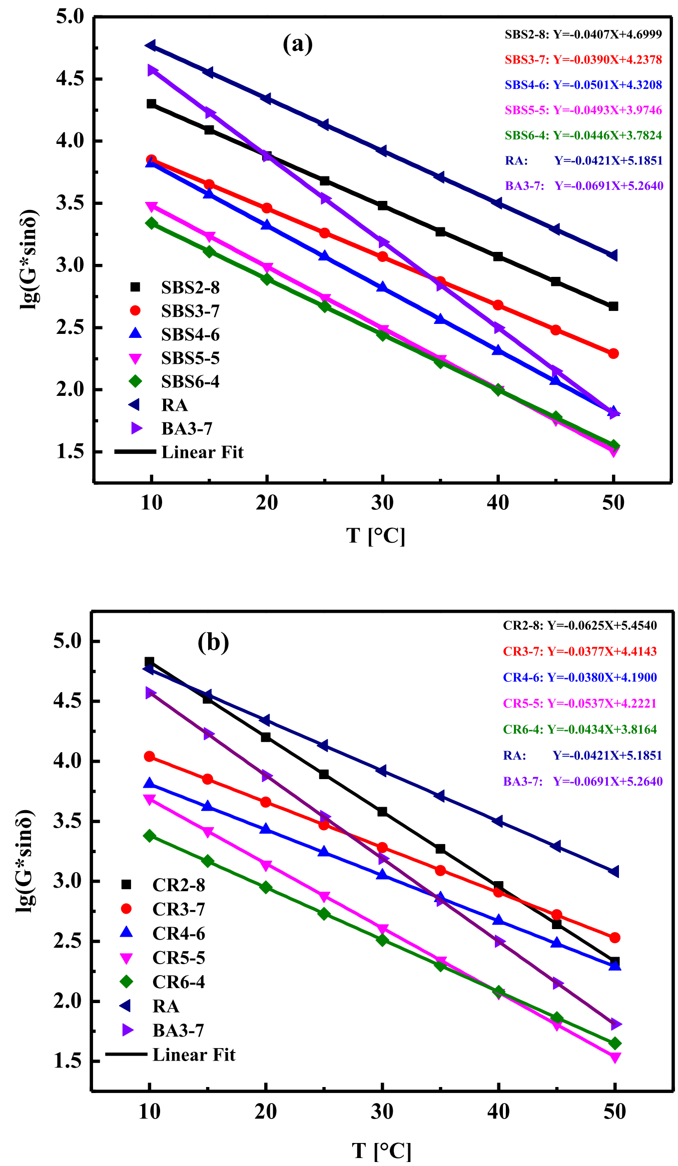


Fig. 15. The relationship between temperature and fatigue factors of SBS and CR modified recycled asphalt.

higher on m-value at −18 °C, respectively. It is indicated that SBS can further enhance the anti-cracking ability for recycled asphalt. In addition, SBS-modified recycled asphalt with a higher concentration ratio of SBS-modified asphalt rejuvenator and aged asphalt has lower creep stiffness and bigger m-value, which means that SBS-modified low-viscosity asphalt content has a positive impact on the low-temperature properties of recycled asphalt.

Fig. 13 presents the stiffness and m-value of CR modified recycled asphalt at −18 and −24 °C. It is obvious that CR can markedly reduce the creep stiffness and increase the m-value of recycled asphalt. Meanwhile, with the CR modified low-viscosity asphalt content increases, the stiffness of recycled asphalt becomes lower and the m-value boosts. That is to say, CR modified asphalt can improve the low-temperature cracking resistance of recycled asphalt signally. According to AASHTO T313-04, the maximum stiffness and minimum m-value meeting the low-temperature asphalt grade should less than 300 MPa and more than 0.3, respectively (Dong et al., 2017). At −18 °C, SBS4-6, SBS5-5, SBS6-4, CR 5-5 and CR6-4 can meet the low-temperature asphalt grade requirement, while SBS5-5, SBS6-4 and CR6-4 all meet the requirement.

The low critical temperature of base, aged and recycled asphalt is shown in Fig. 14, which can be obtained using the Superpave™ specification. It can be found that the low critical temperature of base and aged asphalt is −20.3 °C and −14.76 °C respectively, which means that aging process has obviously adverse effect on the low-temperature cracking resistance of asphalt. The low critical temperature of aged asphalt decreases by 2.2 °C as the 30 wt% low-viscosity asphalt is added. However, the low critical temperature of BA3-7 recycled asphalt is still higher than that of base asphalt, showing that the former has insufficient anti-cracking ability. Meanwhile, the addition of SBS and CR can decrease the low critical temperature of recycled asphalt. The recycled asphalt with higher SBS or CR modified asphalt rejuvenator content has lower low critical temperature, which indicates that SBS and CR modified low-viscosity asphalt rejuvenators have great benefits on the thermal cracking resistance performance of recycled asphalt. When the concentration ratio is larger than 4–6, the low critical temperatures of polymer modified recycled asphalts are all lower than that of base asphalt. Moreover, the decreasing trend of low critical temperature of polymer-modified recycled asphalt becomes more intense when the concentration ratio of rejuvenator and aged asphalt is larger than 5:5. For example, the low critical temperature of SBS5-5 and SBS6-4 recycled asphalt is lower of 23.0 °C and 27.6 °C than aged asphalt, respectively. Similarly, the low critical temperature of CR5-5 and CR6-4 recycled asphalt is lower of 11.2 °C and 12.9 °C than that of aged asphalt, which can fully meet the low-temperature performance requirement of polymer-modified asphalt. Furthermore, the improvement effects of SBS-modified low-viscosity asphalt rejuvenator on the cracking resistance is more obvious than CR-modified asphalt rejuvenator.

5.7. Fatigue resistance performance

The fatigue resistance of asphalt can be characterized by the fatigue factor $G^*\sin\delta$. From Fig. 15, fatigue factor of asphalt decreases as the increase of testing temperature. Meanwhile, aged asphalt has the highest $G^*\sin\delta$ value and terrible fatigue resistance performance. However, the addition of low-viscosity asphalt can reduce the $G^*\sin\delta$ value, indicating that low-viscosity asphalt has positive effect on improving the anti-fatigue ability of aged asphalt. Compared to BA3-7 recycled asphalt, SBS and CR modified recycled asphalts have lower $G^*\sin\delta$ values, which means that SBS and CR have great effects on the fatigue resistance performance of recycled asphalt. Furthermore, $G^*\sin\delta$ value of polymer-modified recycled asphalt decreases as the increasing of concentration ratio of polymer-modified low-viscosity asphalt rejuvenator and aged asphalt. That is to say, it is effective and meaningful to use polymer-modified low-viscosity asphalt to recycle the aged asphalt, which has satisfactory anti-fatigue property.

To assess the fatigue resistance of aged and recycled asphalts quantificationally, the fatigue temperature was used, which was calculated when the fatigue factor is 5000 kPa (Dong et al., 2017). The fatigue temperature of aged and recycled asphalt is shown in Fig. 16 and it is well known that asphalt binder with smaller fatigue temperature has better anti-fatigue ability. It can be found that the fatigue temperature of base asphalt increases from 20.15 °C to 35.28 °C, indicating aging process weakens the anti-fatigue ability of base asphalt dramatically. As shown in Fig. 16, the fatigue temperature of aged asphalt decreases by 35.8% when added low-viscosity asphalt, which indicates that low-viscosity asphalt can enhance the fatigue resistance of aged asphalt. However, the fatigue temperature of low-asphalt recycled asphalt is still higher than base asphalt and has bigger fatigue cracking confrontation than base asphalt. Meanwhile, fatigue temperatures of all SBS or CR modified recycled asphalts are lower than BA 3−7 recycled asphalt, which shows that SBS and CR have great effects on improving the anti-fatigue ability of recycled asphalt. Meanwhile, fatigue temperature of recycled asphalt decreases as the concentration ratio of polymer-modified asphalt rejuvenator and aged asphalt increases. When the concentration is larger than 3−7, the fatigue temperature values of polymer recycled asphalts are all lower than that of base asphalt. Therefore, SBS or CR modified low-viscosity asphalt rejuvenators can restore and strengthen the fatigue resistance performance of recycled asphalt. Furthermore, when the concentration ratio of rejuvenator and aged asphalt is same, the fatigue temperature of SBS-modified recycled asphalt is lower than that of CR-modified recycled asphalt, which means that SBS-modified recycled asphalt has better fatigue resistance ability.

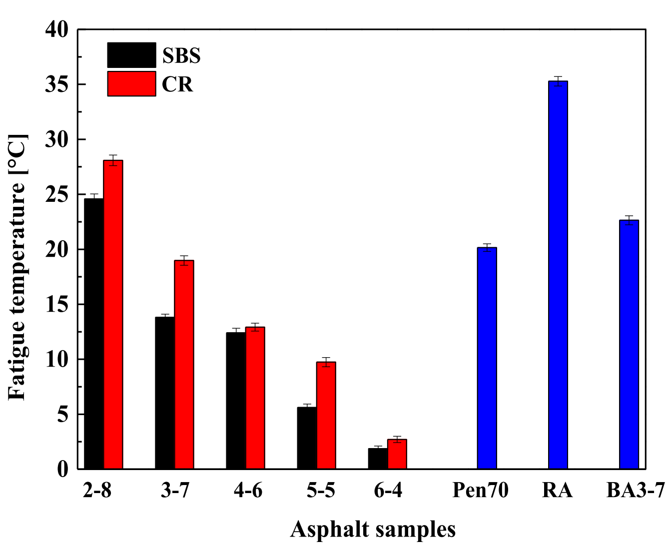


Fig. 16. The fatigue temperature of SBS and CR modified recycled asphalt.

5.8. Anti-aging properties

In this study, both short-term and long-term aging resistance properties of aged and recycled asphalt were investigated by RTFOT and PAV tests. Frequency sweep tests and steady-state flow tests were conducted on all asphalt samples. The complex modulus G^* and zero shear viscosity (ZSV) are selected to assess the anti-aging performance of aged and recycled asphalt.

*5.8.1. Complex modulus index AI@G**

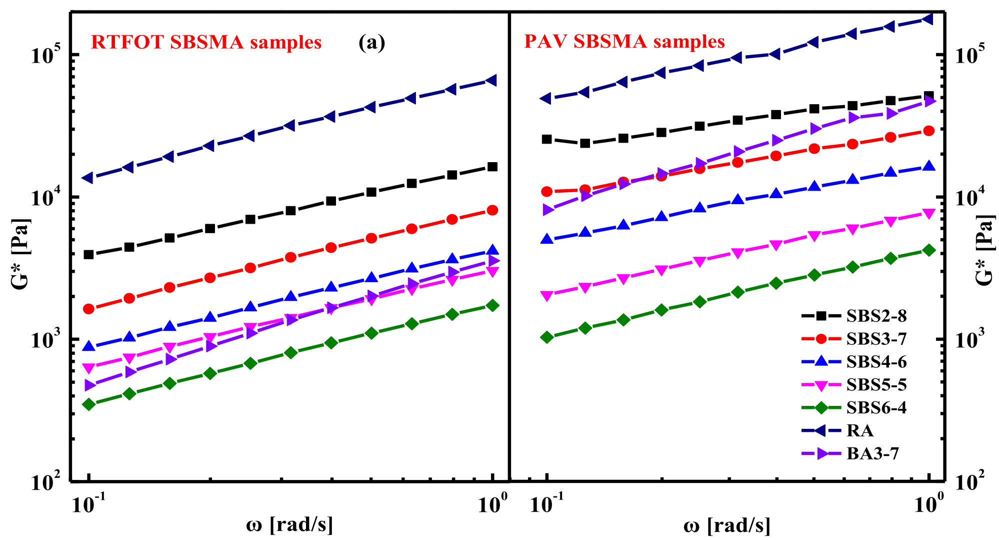
Fig. 17 shows the G^* values of RTFOT-aged and PAV-aged SBS or CR modified recycled asphalts. Both RTFOT and PAV aging process make the recycled asphalt have higher complex modulus, which is attributed to the loss of light compounds. With the aging degree deepening, the G^* of asphalt increases, indicating aging degree has positive impact on the deformation resistance of asphalt. Meanwhile, the G^* values of unaged and aged recycled asphalts are shown in Table 5. It is clear that reclaimed asphalt has the highest complex modulus due to the high content of heavy chemical components. The addition of low-viscosity asphalt decreases the complex modulus of reclaimed asphalt dramatically from 21790 Pa to 382 Pa, which can be improved by adding SBS and CR. Furthermore, aging degree has a great effect on the complex modulus of aged and recycled asphalt. With the aging degree deepening, G^* of asphalt increases signally. Obviously, the change degree of G^* value before and after aging can be used to evaluate the aging resistance properties of asphalt.

The G^* values of unaged, RTFOT aged and PAV aged asphalts are referred as G^*-Original, G^*-RTFOT, and G^*-PAV. Thus, the short-term and long-term aging index AI@G^*can be calculated using equations (2) and (3), respectively. The asphalt with lower aging index (AI) value has better anti-aging performance.

$$\text{RAI@G}* = \frac{G* - RTFOT}{G* - Original} \tag{2}$$

$$\text{PAI@G}* = \frac{G* - PAV}{G* - Original} \tag{3}$$

Fig. 18 shows the aging index AI@G^* of aged and recycled asphalt. It is obvious that AI value of reclaimed asphalt is the lowest regardless of short-term or long-term aging, indicating that reclaimed asphalt has the best anti-aging performance. The addition of low-viscosity asphalt increases the aging index, especially after PAV aging, which increases from 3.84 to 50.26. It is indicated that the low-viscosity asphalt rejuvenator could weaken the aging



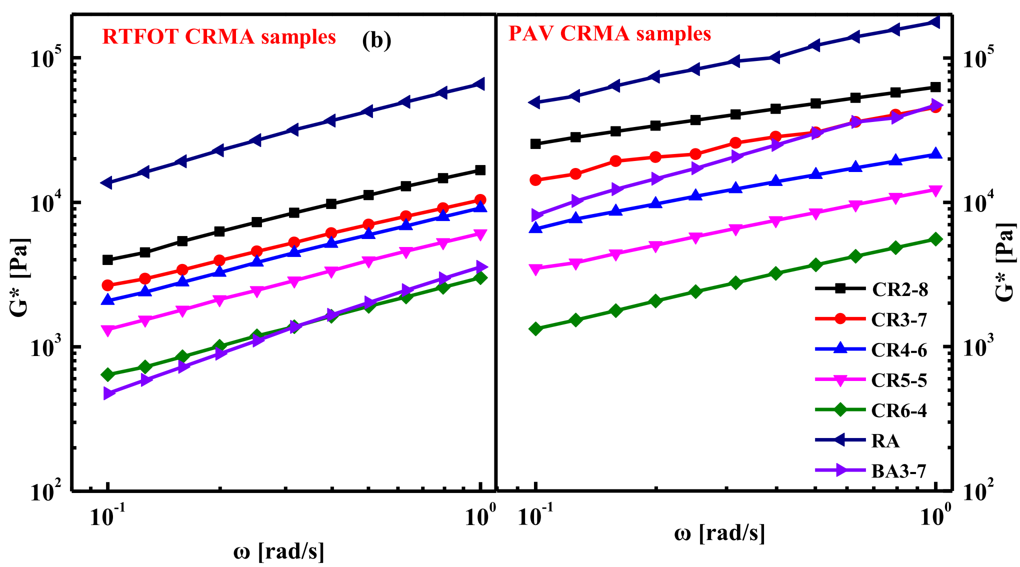


Fig. 17. The complex modulus of RTFOT and PAV aged reclaimed and recycled asphalt.

Table 5
The complex modulus of unaged, RTOFT and PAV aged recycled asphalts.

Sample codes	G*-Original(Pa)	G*-RTFOT(Pa)	G*-PAV(Pa)
SBS2-8	3340	6946	25400
SBS3-7	1545	3175	15780
SBS4-6	756	1671	8265
SBS5-5	428	1226	3567
SBS6-4	247	678	1828
RA	21790	26870	83690
BA3-7	382	1103	19200
CR2-8	4440	6661	37040
CR3-7	2617	4574	21520
CR4-6	1425	3828	11010
CR5-5	813	2459	5787
CR6-4	473	1189	2408

resistance ability of reclaimed asphalt. Fortunately, adding SBS and CR can decrease the aging index of recycled asphalt. For example, SBS and CR can decline the PAI@G* value from 50.26 to 10.21 and 8.22, respectively. Therefore, SBS and CR can improve the short-term and long-term aging resistance performance of recycled asphalt. It can be noted that SBS and CR modified recycled asphalts have the similar aging index after RTFOT aging, but CR modified recycled asphalt has lower AI value than that of SBS modified recycled asphalt after PAV aging, which indicates that CR modified recycled asphalt has better long-term aging resistance properties. With the increase of concentration ratio, the short-term and long-term aging resistance abilities of SBS-modified recycled asphalt are weakened first and then enhanced. The short-term anti-aging property of SBS5-5 asphalt is the worst and the long-term aging

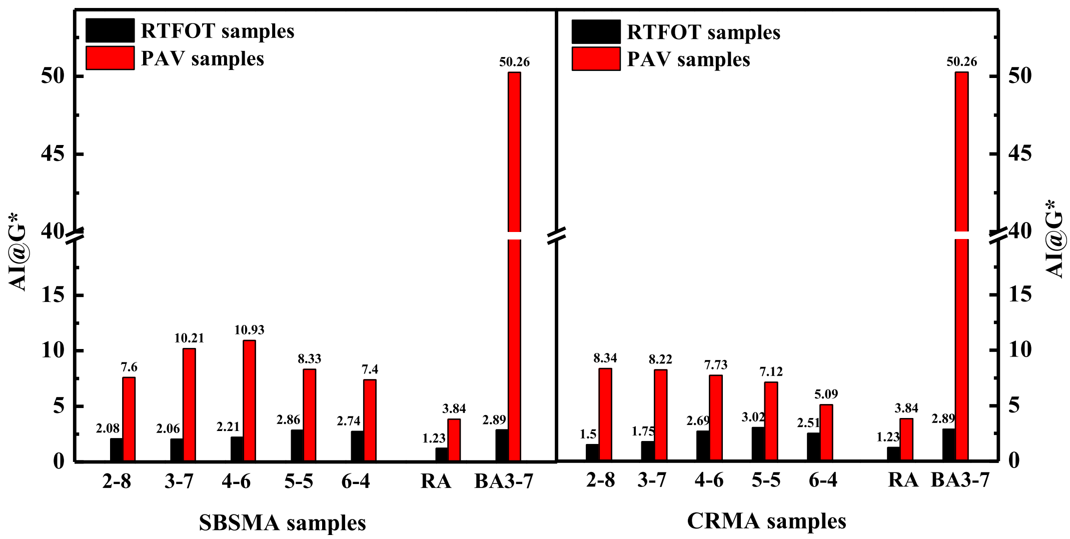


Fig. 18. The aging index AI @G* of unaged, RTOFT and PAV aged recycled asphalt.

resistance of SBS6-4 is the best. In terms of CR-modified recycled asphalt, the short-term anti-aging performance is weakened first and then improved, while the long-term aging resistance is improved with the increase of concentration ratio. Similarly, the short-term anti-aging property of CR5-5 asphalt is the worst and the long-term aging resistance of CR6-4 is the best.

5.8.2. Zero shear viscosity index AI@ZSV

The zero shear viscosity (ZSV) change of unaged and aged asphalt was also tested to evaluate the short-term and long-term anti-aging properties of recycled asphalt. Fig. 19 shows the flow curves of unaged, RTOFT and PAV aged recycled asphalt. It is clear that the shear viscosity of aged asphalt is highest, which is attributed to the loss of light compounds. The addition of low-viscosity asphalt decreases the shear viscosity of reclaimed asphalt, which can be enhanced by adding SBS and CR. Moreover, it is clear that the shear viscosity of recycled asphalts increases remarkably after RTFOT and PAV aging. The zero-shear viscosity (ZSV) of unaged, RTFOT-aged and PAV-aged asphalts were obtained using the Carreau model, which is shown in Equation (1). The aging index (AI@ZSV) is used to investigate the anti-aging properties of recycled asphalts, which can be obtained using equations (4) and (5):

$$\mathrm{RAI@ZSV} = \frac{ZSV - RTFOT}{ZSV - Original} \tag{4}$$

$$\mathrm{PAI@ZSV} = \frac{ZSV - PAV}{ZSV - Original} \tag{5}$$

Obviously, asphalt binder with lower AI@ZSV value would have better aging resistance performance. Table 6 illustrates the ZSV values of unaged, RTFOT-aged and PAV-aged recycled asphalts, which increases dramatically after aging, especially after PAV aging. Fig. 20 presents the aging index AI@ZSV of unaged, RTOFT and PAV aged recycled asphalts. It is clear that the changing trend of AI@ZSV of unaged and aged recycled asphalts is similar to the AI@G*, which can further verify the validity and accuracy of the experiment and conclusion. The reclaimed asphalt has the lowest AI value and best anti-aging properties. Moreover, low-viscosity asphalt has an adverse effect on the aging resistance ability of reclaimed asphalt, which can be enhanced by adding SBS and CR. It can be concluded that SBS and CR modified recycled asphalt rejuvenator not only can restore and improve the viscoelastic properties of reclaimed asphalt but also can maintain and enhance the short-term and long-term aging resistance performance of recycled asphalt.

6. Summaries and conclusions

This research investigated the possibility of using polymers (CR and SBS) modified low-viscosity asphalt as rejuvenators to recycle the aged asphalt. The conventional properties, rheological behaviors and anti-aging performance of polymer modified recycled asphalt were evaluated by RV, DSR and BBR. Moreover, the effects of concentration ratio between SBS or CR modified low-viscosity asphalt rejuvenator and aged asphalt on the high-temperature anti-rutting, low-temperature cracking resistance, fatigue and aging resistance abilities of recycled asphalt were studied. According to the results of this study, the following conclusions are drawn:

1) Adding low-viscosity asphalt can restore viscous properties, low-temperature cracking resistance and anti-fatigue performance of aged asphalt, but it would weaken high-temperature anti-rutting, temperature sensitivity, permanent deformation resistance of aged asphalt.
2) The addition of SBS and CR is good for improving the high-temperature rutting resistance, temperature sensitivity, viscoelastic properties, elastic recovery, low-temperature cracking resistance, anti-fatigue and anti-aging performance of recycled asphalt dramatically, which are enhanced with the increasing of concentration ratio of SBS and CR modified low-viscosity asphalt rejuvenator and aged asphalt.
3) SBS modified recycled asphalt is good at the low-temperature cracking resistance properties, construction workability and anti-fatigue performance, while CR modified recycled asphalt possesses better high-temperature anti-rutting performance, temperature sensitivity, elastic recovery properties and permanent deformation resistance.
4) Steady-state flow tests present that the addition of low-viscosity asphalt can expand the Newtonian behavior region of aged

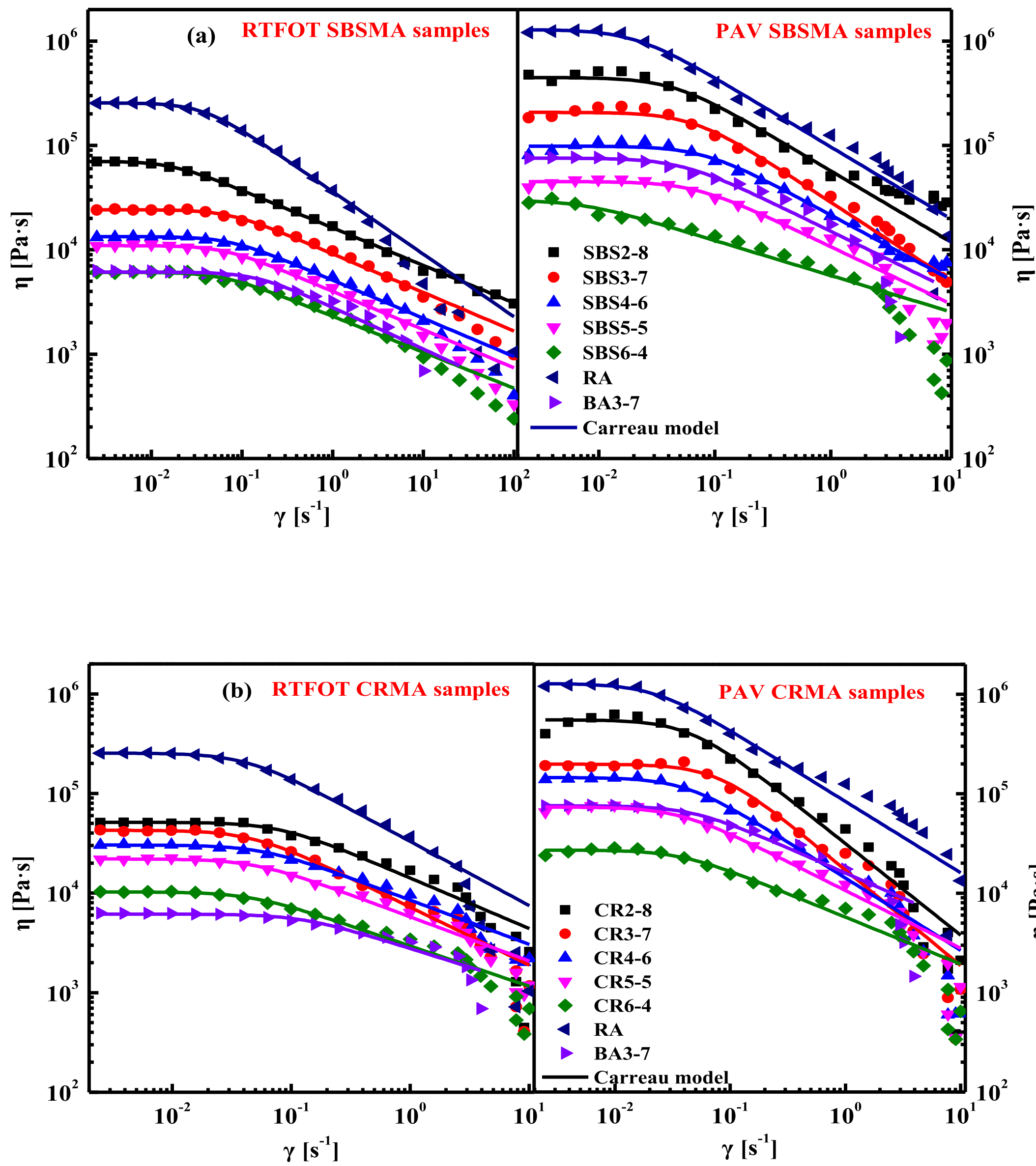


Fig. 19. Flow curves of unaged, RTOFT and PAV aged recycled asphalt.

Table 6
The zero shear viscosity of unaged, RTOFT and PAV aged recycled asphalt.

Sample codes	η_0-original(Pa·s)	η_0-RTFOT(Pa·s)	η_0-PAV(Pa·s)
SBS2-8	21239	70450	446807
SBS3-7	9816	24197	207258
SBS4-6	4399	13355	98328
SBS5-5	2360	10962	44988
SBS6-4	1926	6078	29805
RA	217682	254159	1286860
BA3-7	1726	6057	75456
CR2-8	33760	51395	553973
CR3-7	17496	42671	183148
CR4-6	9596	30338	97539
CR5-5	6859	21994	71484
CR6-4	4367	10266	27104

asphalt, while adding SBS or CR intensifies the shear-thinning behavior of recycled asphalt. Besides, the low-viscosity asphalt can remarkably decrease the zero shear viscosity of aged asphalt, which can be further improved by adding SBS and CR.

5) The reclaimed asphalt has the best anti-aging performance than all recycled asphalts and the low-viscosity asphalt rejuvenator has bad influence on the aging resistance ability of reclaimed asphalt. In addition, SBS and CR can improve the short-term and long-term aging resistance performance of recycled asphalt. CR-modified recycled asphalt has better long-term aging resistance ability.
6) Some obtained SBS and CR modified recycled asphalts have better overall pavement performance, such as SBS5-5 and CR6-4. Therefore, it is meaningful and feasible to recycle the aged base asphalt to be polymer-modified asphalt.

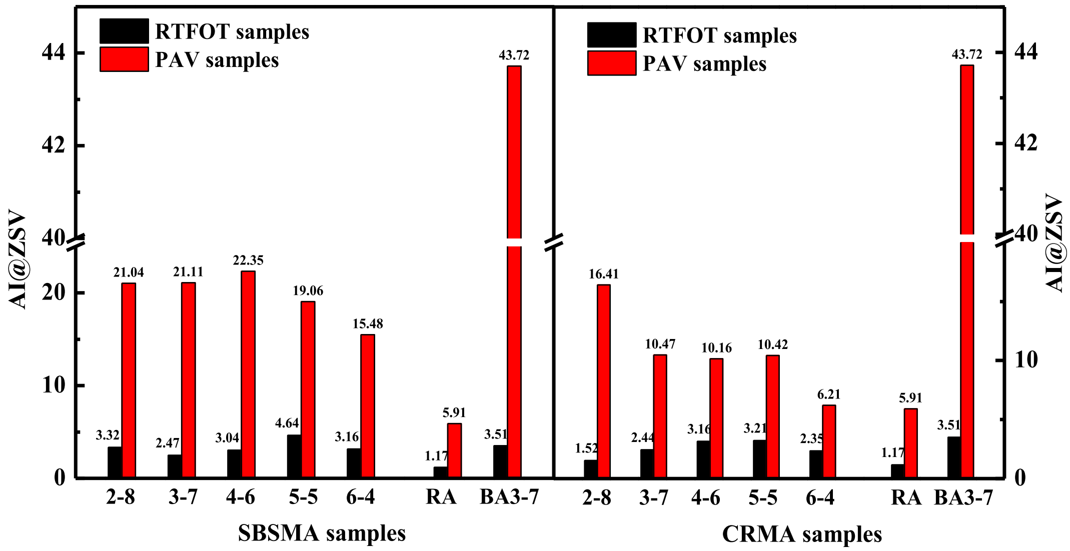


Fig. 20. The aging index AI@ZSV of unaged, RTOFT and PAV aged recycled asphalt.

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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