

Research Article

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Study on adaptability of rheological index of nano-PUA-modified asphalt based on geometric parameters of parallel plate

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Abstract: To clarify the influence of geometric parameters of parallel plate on rheological properties of polyurea elastomer (PUA)-modified asphalt, nano-PUA powder was prepared, and nano-PUA powder modifier was modified by using high-speed shearing apparatus. The apparent viscosity of modified asphalt was evaluated by Brookfield viscosity. The rheological parameters of PUA-modified asphalt were determined by comparing the rheological test results of temperature scanning, frequency scanning, and multiple stress creep recover test using 8 and 25 mm parallel plates. Results indicated that the higher the content of nano-PUA modifier was, the better the high-temperature performance of asphalt would be. When using the 8 mm parallel plate, the high-temperature performance of modified asphalt was worse than that of matrix asphalt, and the PUA modifier would lead to a negative effect on the rheological property of asphalt. Regarding the 25 mm parallel plate, the high-temperature performance of modified asphalt was better than that of matrix asphalt, which was contrary to the results of 8 mm parallel plate. The rheological test results using 25 mm parallel plate were consistent with the results of Brookfield viscosity, indicating that 25 mm parallel plate was more suitable for evaluating the rheological performance of PUA-modified asphalt.

Keywords: asphalt, rheological properties, PUA, Brookfield viscosity, parallel plate

1 Introduction

With the rapid development of expressways, the performance requirements of pavement are increasing [1,2], and asphalt mixture is widely used in pavement construction because of its excellent flatness, low traffic noise, easy maintenance, and rapid construction [3–5]. However, the performance characteristics of asphalt pavement mainly depend on the rheological properties of asphalt pavement bonding materials [6,7]. The Strategic Highway Research Program recommends using dynamic shear rheometer (DSR) to determine the rheological properties of asphalt binders. According to AASHTO T315-12 [8], in the DSR test process, the specimens of 1 mm thickness, 25 mm diameter or 2 mm thickness, and 8 mm diameter were first formed between the parallel metal plates. In the test process, one parallel plate oscillates with respect to the other parallel plate under the preselected frequency and rotation deformation amplitude (strain control or torque amplitude stress control). The test conditions of a gap size of 8 mm plate and 2 mm rheometer were selected at low temperature (less than 20°C), whereas the test conditions of a gap size of 25 mm plate and 1 mm rheometer were selected at medium and high temperatures (20–90°C) [9]. However, in the actual asphalt mixture, the film thickness of the coating on the aggregate can vary from a few microns to several millimeters [10]. At the same time, due to the existence of modifier particles in the modified asphalt, it may also interfere with the test configuration. It is difficult to obtain accurate test results by following the superpave specification for evaluating the rheological properties of asphalt binders. Therefore, the size difference between standard test conditions and thin layer state in asphalt mixture has attracted some researchers' attention. Bahia evaluated the rheological properties of waste rubber adhesives, including rotational viscosity, modulus, phase angle, and low-temperature creep stiffness. Bahia *et al.* [11] increased the clearance height of DSR from 1 to 2 mm to minimize the influence of rubber particle size and evaluated the different

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rheological properties of waste rubber adhesives, including rotational viscosity, modulus, phase angle, and low-temperature creep stiffness. The results showed that the high-temperature performance of waste rubber adhesive depends on the size of crushed rubber materials particles, and the linear elastic limit provided by the geometric shape of 2 mm gap height test is similar to that of 1 mm gap height. In 2005, Putman and Thompson [12] increased the DSR clearance height from 1 to 2 mm, so as to accommodate large rubber particles in waste rubber adhesives during DSR test. Through the strain frequency scanning test, they reported that although the test geometry changed, the binder still maintained a linear viscoelastic region. Zhai and Bahia [13] noticed that the elastomer-modified asphalt binder is most sensitive to the change of gap size, whereas the oxidized asphalt is least sensitive to the change of gap size by testing different adhesives with a gap size from 10 μm to 1 mm. Teymourpour *et al.* [14] measured the high-temperature performance of waste rubber powder binder by adjusting the gap height of 1 mm to minimize the influence of the interaction between asphalt binder and rubber particles on performance grade grading results. The results showed that higher variability is observed at the height of 2 mm compared with the height of 3 mm gap. Therefore, it is recommended that the height of parallel plate gap is 3 mm, and the corrected stress level and test temperature of multiple stress creep recover (MSCR) test were proposed.

At present, scholars in China and abroad have carried out some research on the rheological gap height of asphalt, but most of them focused on evaluating the rheological properties of comparative asphalt by changing the gap height of parallel plates. However, in the study of asphalt rheological properties from different angles, a series of uninterrupted tests from low temperature to high temperature are needed. Under such conditions, both 8 and 25 mm parallel plates have to undergo a large temperature gradient change process, so it is inevitable that 8 mm parallel plates enter the high-temperature region or 25 mm parallel plates into the low-temperature region, and the data obtained are quite different [15].

Therefore, this study intends to take PUA-modified asphalt as the research object and characterize the apparent viscosity of modified asphalt at different temperatures based on Brookfield viscosity test. The temperature scanning, frequency scanning, and MSCR rheological test results of modified asphalt under 8 and 25 mm parallel plates were compared to determine the adaptability of rheological indexes of PUA-modified asphalt.

2 Materials and methodology

2.1 Materials

2.1.1 Asphalt

The road asphalt used in this study was 70# matrix asphalt, and its performance meets the technical requirements of “Technical Specification for Construction of Highway Asphalt Pavements” (JTG F40-2004) [16]. The technical parameters of matrix asphalt are shown in Table 1.

2.1.2 PUA

The nano-PUA materials contain acrylic functional groups and urethane bonds, whose cured adhesive has high wear resistance, adhesion, flexibility, high peel strength, excellent low-temperature resistance, and weather resistance. The materials used in this article belong to PUA, and its technical properties are presented in Table 2.

2.1.3 Preparing process of nano-PUA-modified asphalt

The preparing process of nano-PUA-modified asphalt is shown as follows:

1. The proper amount of PUA raw materials was placed into the hopper of preparing equipment. The H20/35 PUA high-pressure spraying machine (Graco Inc.) was used to prepare PUA film, and the technical parameters were adjusted. The thickness of the molded specimens was measured, and any five points of specimen must be within the range of $2\text{ mm} \pm 0.1\text{ mm}$.

2. The 2 mm thick PUA film sample was cut into particles with a side length of 4–5 mm using a paper cutter. In the cutting process, the cutting parameters were set accurately to ensure that the cutting surface was neat and smooth.

Table 1: Technical properties of asphalt

Technical properties	Value	Specification
Softening point ($^{\circ}\text{C}$)	50.4	>43
Penetration ([25 $^{\circ}\text{C}$, 100 g, 5 s]/0.1 mm)	71	60–80
Ductility (10 $^{\circ}\text{C}/\text{cm}$)	32	>15

Table 2: Technical properties of PUA

PUA species	Solid content (%)	Solid content (%)	Viscosity (cps)	Tensile strength (MPa)
PUA-100	32	81–85	≤800	28

3. The PUA particles were put into the storage bin of the grinding equipment, and the storage bin was frozen by liquid nitrogen. Meanwhile, the PUA particles and liquid nitrogen were mixed through a stirring device to confirm the full contact between PUA and liquid nitrogen. When cooled to the glass transition temperature, the PUA particles were sent to the grinder through the raw material conveyor for crushing.

4. The PUA powder with a particle size of 0.075 mm was screened out from the prepared PUA material, and 0.075 mm PUA material with matrix asphalt mass of 3, 6, and 9% was weighed. The 70# asphalt was heated to a molten state by oven, and the PUA powder was added to the molten asphalt three times. After the PUA powder was added, the asphalt was sheared and stirred with the high-speed shear apparatus, and the stirring process followed the principle of “low speed–high speed–low speed.” After shearing and mixing, the modified asphalt was placed at room temperature, and the preparation of PUA-modified asphalt was completed after swelling.

2.2 Methodology

2.2.1 Brookfield viscosity test

In this study, the Brookfield rotational viscometer (ASTM D 4402) [17] was used to analyze the influence of modifiers on the viscosity of asphalt at different temperatures. In this test, the rotor model was SC4-27, the rotation speed was 20 rad/min, and the testing temperatures were 95, 115, 135, 150, and 175°C.

2.2.2 Temperature scanning test

By means of dynamic rheological shear apparatus, the temperature scanning tests of matrix asphalt and PUA-modified asphalt at a single frequency and different temperatures were carried out. The curves of rutting factor $G^*/\sin \delta$, complex viscosity, and temperature were obtained. The test was started at 46°C and gradually increased to 82°C, with the test temperature interval of 6°C. The flow gap size of 8 mm parallel plate and 25 mm parallel plate was 2 and

1 mm, respectively. The test angular frequency was set to 10 rad/s, and control strain was set at 12%.

2.2.3 Frequency scanning test

DSR was used to conduct frequency scanning tests at different temperatures and frequencies for matrix asphalt and PUA-modified asphalt. Different complex modulus G^* , phase angle δ , and complex viscosity were obtained. The test temperature was set to 60°C. The frequency varied from 0.1 to 100 rad/s, and control strain was 1%.

2.2.4 MSCR

MSCR tests were carried out on matrix asphalt and PUA-modified asphalt at a temperature of 64°C and stress levels of 0.1 and 3.2 kPa, respectively. The average strain recovery rate (R) and unrecoverable creep compliance (J_{nr}) of matrix asphalt and modified asphalt were measured. The test temperature was started at 46°C, and the stress levels included 1.0 and 3.2 kPa, which would be repeated for 20 and 10 times, respectively. Every level included 10 cycles, which consisted of 1 s creep stage and 9 s unloading recovery stage per cycle that would last 300 s [18,19].

3 Results and discussion

3.1 Brookfield viscosity results of PUA-modified asphalt

The Brookfield viscosity results of different types of PUA-modified asphalt and matrix asphalt at 90, 115, 135, 150, and 175°C are presented in Figure 1. According to Figure 1, in different temperatures, the viscosity of PUA-modified asphalt was higher than that of matrix asphalt. At the same time, with the increase of PUA content, the viscosity of asphalt increased gradually, indicating that the addition of PUA modifier could increase the viscosity of asphalt and improve the high-temperature performance

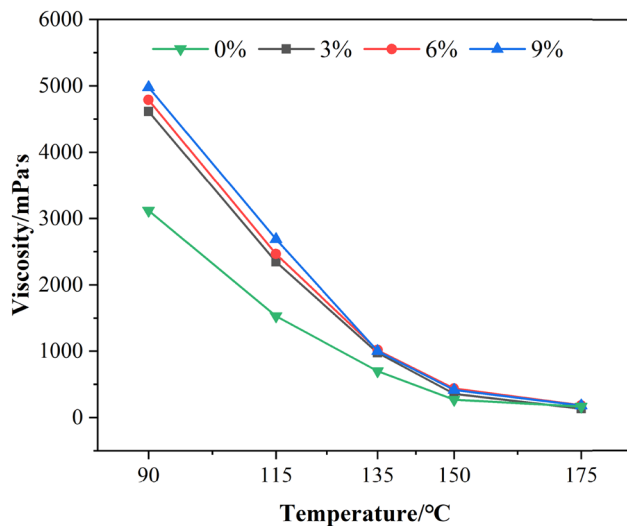


Figure 1: Brookfield viscosity test results.

of asphalt. Compared with 70# asphalt, the viscosity of 3, 6, and 9% PUA-modified asphalt increased by 48, 53, and 60% at 90°C and increased by 53, 61, and 76% at 115°C. When the testing temperature increased to 130°C, the apparent viscosity of modified asphalt and matrix asphalt was almost the same. Therefore, PUA had the best improvement in the apparent viscosity of asphalt at 115°C. That might be due to that the molecular bond between PUA and asphalt increased the interaction between asphalt molecules, thus increasing the apparent viscosity of asphalt [20–22]. When the temperature increased above 130°C, due to the high temperature, the fluidity of modified asphalt was better, and the effect of PUA on the viscosity of asphalt was not obvious.

3.2 Rheological properties of PUA-modified asphalt based on different size parallel plates

3.2.1 Correlation under temperature scanning test

Figure 2 depicts the temperature scanning test results of PUA-modified asphalt with different contents under different parallel plates. It could be seen from the figure that the complex shear modulus G^* and rutting factor $|G^*|/\sin \delta$ of modified asphalt decreased with the increase of temperature whether in 8 or 25 mm parallel plate and showed a trend of rapid decline first before flattening. From the analysis in Figure 2(a) and (e), it could be analyzed that under the action of 8 mm parallel plate, the G^* and $|G^*|/\sin \delta$ of modified asphalt with 9% content were

the largest and 3% was the smallest, whereas the distinction between 0 and 6% was low. The measured G^* was close to $|G^*|/\sin \delta$, and the curve was almost coincident. The results indicated that the high-temperature performance of modified asphalt with 9% content was the best, 3% was the worst, and there was no difference between 0 and 6% high-temperature performance, which contradicts the results of Section 3.1. By analyzing the corresponding phase angle, it could be found that the phase angle of modified asphalt increases first and then decreases with the increase of temperature, which reflected that the viscosity of modified asphalt decreased first and then increased during the heating process, which was also inconsistent with the results of Brookfield viscosity.

In contrast to the results under the action of 25 mm parallel plates, it could be observed from Figure 2(b) and (e) that both G^* and $|G^*|/\sin \delta$ of the modified asphalt were larger than those of the matrix asphalt, and the order from large to small was 9, 6, 3, and 0%. It showed that the addition of the modifier improved the high-temperature performance of the asphalt, and with the increase of the content of the modifier, the high-temperature performance of the asphalt continues to increase, which was consistent with the results of the Brookfield viscosity test. The phase angle diagram showed that the phase angle of each asphalt increased and that the viscosity of asphalt decreased with the increase of temperature, which was consistent with the results of Brookfield viscosity test. The above results displayed that the temperature scanning test under 8 mm parallel plate could not accurately reflect the high-temperature performance of PUA-modified asphalt; however, the temperature scanning test under 25 mm parallel plate could accurately reflect the high-temperature performance of modified asphalt with different contents.

3.2.2 Correlation under frequency scanning test

Figure 3 shows the frequency scanning test results of PUA-modified asphalt under different parallel plates. It could be seen from Figure 3(a) and (c) that under the action of 8 mm parallel plate, the complex modulus G^* of each asphalt increased with the increase of frequency, among which the complex modulus between each asphalt at low frequency (0.1–10 rad/s) was small and the difference was not obvious. At high frequency (10–100 rad/s), the difference of complex modulus between asphalts was obvious, among which the complex modulus G^* of matrix asphalt was the largest, followed by modified asphalt with

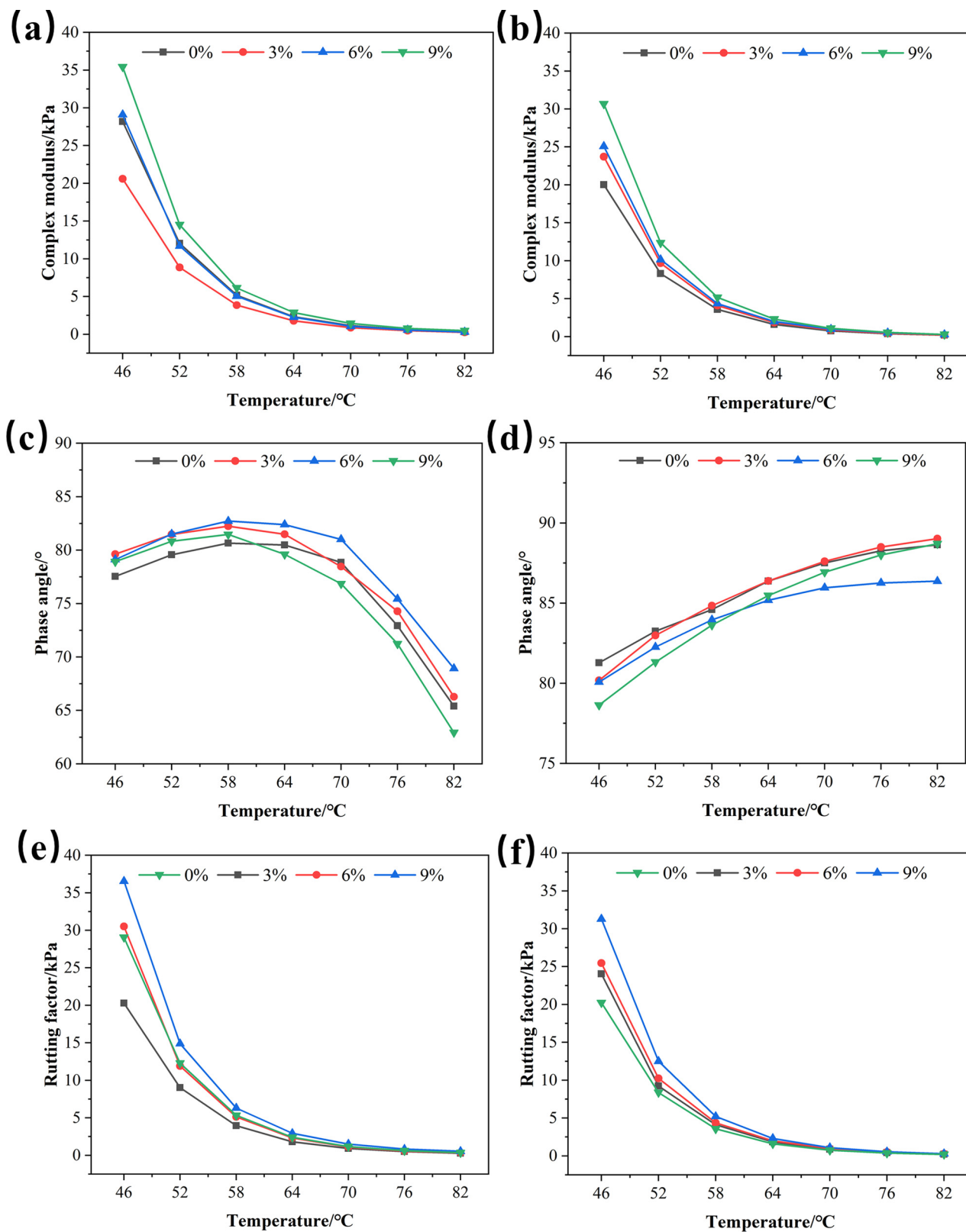


Figure 2: Temperature scanning results under different parallel plates: (a) 8 mm G^* , (b) 25 mm G^* , (c) 8 mm δ , (d) 25 mm δ , (e) 8 mm $|G^*|/\sin \delta$, and (f) 25 mm $|G^*|/\sin \delta$.

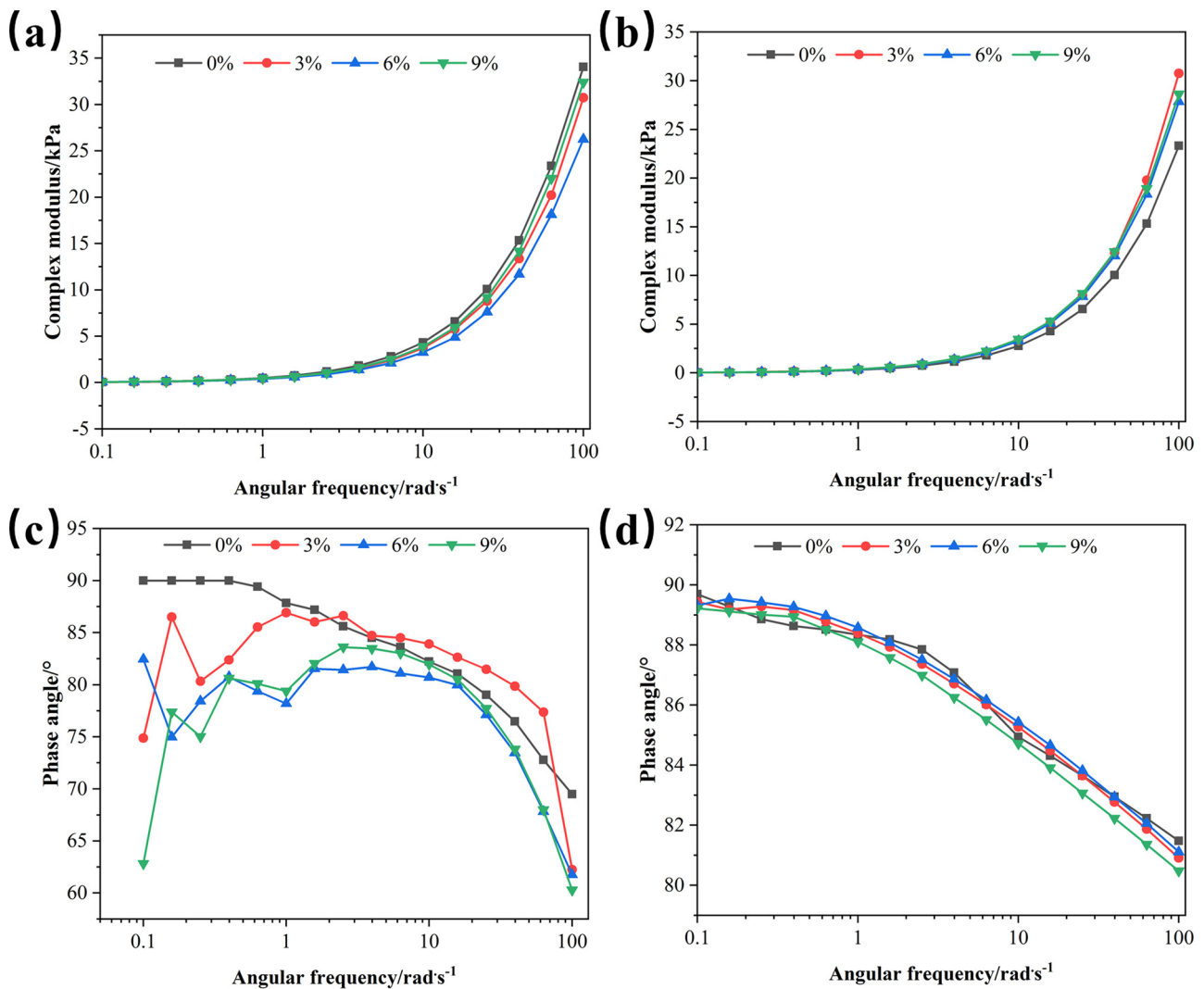


Figure 3: Frequency scanning results under different parallel plates: (a) 8 mm G^* , (b) 25 mm G^* , (c) 8 mm δ , and (d) 25 mm δ .

9% content, and the smallest was 6%. For the phase angle δ , the matrix asphalt showed a stable downward trend under the action of high and low frequencies. The phase angle δ of three modified asphalts with PUA modifiers fluctuated greatly under low frequency. When $\omega > 10$ rad/s, the δ of modified asphalt decreased rapidly with the increase of frequency. This result reflected that under the action of 8 mm parallel plate, the high-temperature stability of matrix asphalt was more stable than that of PUA modification, and PUA had a reverse effect on the modification of matrix asphalt.

Figure 3(b) and (d) shows the frequency scanning results of modified asphalt under 25 mm parallel plate. From the complex modulus results, it could be seen that the change trend of complex modulus G^* of four kinds of asphalt was similar, that is, G^* increased with the increase of frequency. Among them, the G^* of PUA-

modified asphalt was larger than that of base asphalt, indicating that PUA modifier could improve the high-temperature performance of asphalt. The phase angle diagram analysis showed that the δ of each asphalt decreased with the increase of frequency, and the decreasing trend of the three modified asphalts was consistent, and the matrix asphalt was slightly floating. This furthermore reflected that the high-temperature performance of PUA-modified asphalt was better than that of matrix asphalt under the frequency scanning at 60°C.

Compared with the frequency scanning results of 8 and 25 mm parallel plates, the phase angle curve of asphalt had obvious floating and irregular under 8 mm parallel plates, which was significantly different from the phase angle curve of conventional asphalt frequency scanning. From the perspective of complex modulus, matrix asphalt showed better high-temperature performance,

which all indicated that 8 mm parallel plate cannot evaluate the modification effect of PUA on asphalt. For the 25 mm parallel plate, the phase angle curve and the complex modulus curve were not abnormal. The modified asphalt with PUA had obvious discrimination compared with the matrix asphalt in phase angle and complex modulus, and the complex modulus of the three modified asphalts was larger than that of the matrix asphalt, indicating that PUA modifier could better improve the high-temperature performance of asphalt under the 25 mm parallel plate.

3.2.3 Correlation under MSCR test

Figure 4 demonstrates the MSCR testing results of PUA-modified asphalt and matrix asphalt under 8 mm and 25 mm parallel plates. Under the 8 mm parallel plate, the

accumulated strain of each asphalt increased gradually with stress loading, and there was no strain rebound during unloading. In contrast, cumulative strain of matrix asphalt was greater than that of modified asphalt under the 25 mm parallel plate. Under 0.1 kPa stress level, the peak strain of modified asphalt was slightly larger than the initial strain, and the strain had obvious rebound change. Under 3.2 kPa stress level, the peak strain of modified asphalt was much larger than the initial strain, and the asphalt shown a small strain rebound during unloading stage. Based on this, the recovery rate $R_{0.1}$, unrecoverable creep compliance $J_{nr0.1}$ in 0.1 kPa load cycle and the recovery rate $R_{3.2}$, unrecoverable creep compliance $J_{nr3.2}$ in 3.2 kPa load cycle were calculated as the study indices of MSCR. The calculated results of study indices are plotted in Figure 5.

Figure 5 shows the calculation results of irreversible creep compliance J_{nr} and creep recovery rate R of asphalt

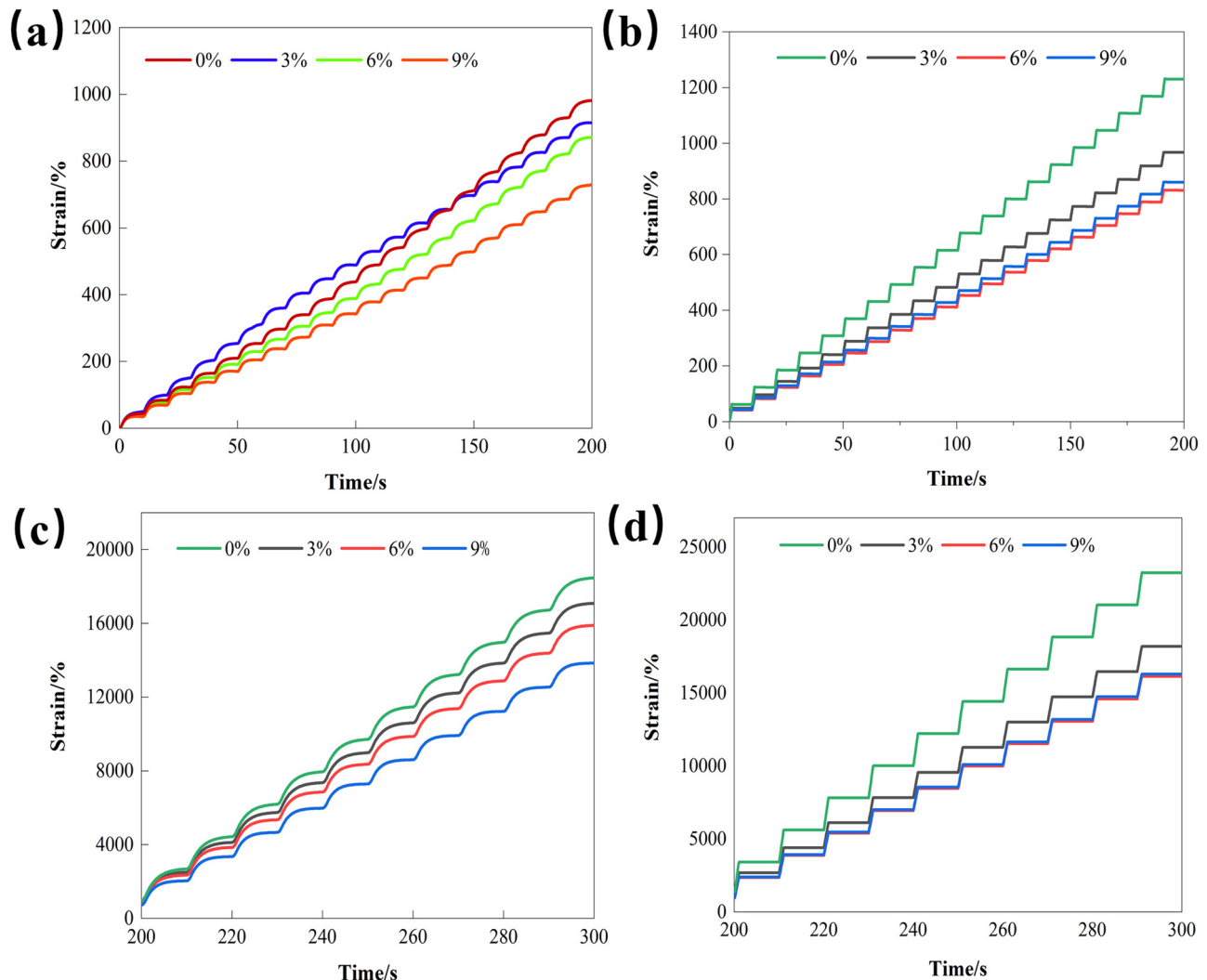


Figure 4: MSCR results of PUA-modified asphalt under different parallel plates: (a) 8 mm parallel plates/0–200 s, (b) 25 mm parallel plates/0–200 s, (c) 8 mm parallel plates/200–300 s, and (d) 25 mm parallel plates/200–300 s.

under two parallel plates. Under the 8 mm parallel plate, the unrecoverable creep compliance J_{nr} of each asphalt was close to about 1. J_{nr} contents of different modified asphalts were lower than that of matrix asphalt when using 25 mm flat. Under different stress levels, compared with matrix asphalt, with the increase of PUA content, J_{nr} decreased first and then increased. At the stress level of 0.1 kPa, the J_{nr} content of 3, 6, and 9% decreased by 21, 32, and 30% compared with the matrix asphalt, respectively. At the stress level of 3.2 kPa, the J_{nr} content of 3, 6, and 9% decreased by 21, 30, and 29% compared with the matrix asphalt, respectively. This showed that PUA modifier could increase the elastic properties of asphalt, and the modified effect was best when the dosage was 6%. Under the 8 mm parallel plate, the R values of different asphalts were all negative, and the values were almost the same. The negative R values might be because at 64°C using 8 mm plate, the

plate gap increased to 2 mm, the flow of asphalt becomes stronger, resulting in the measurement results were wrong. Therefore, in the MSCR test, 8 mm parallel plate could not be used to evaluate the modification effect of PUA on asphalt.

3.3 Correlation between rheological properties and Brookfield viscosity of modified asphalt with different size parallel plates

3.3.1 Correlation between temperature sweeping and Brookfield viscosity

Figure 6 shows the complex viscosity results of PUA-modified asphalt scanned at different parallel plates.

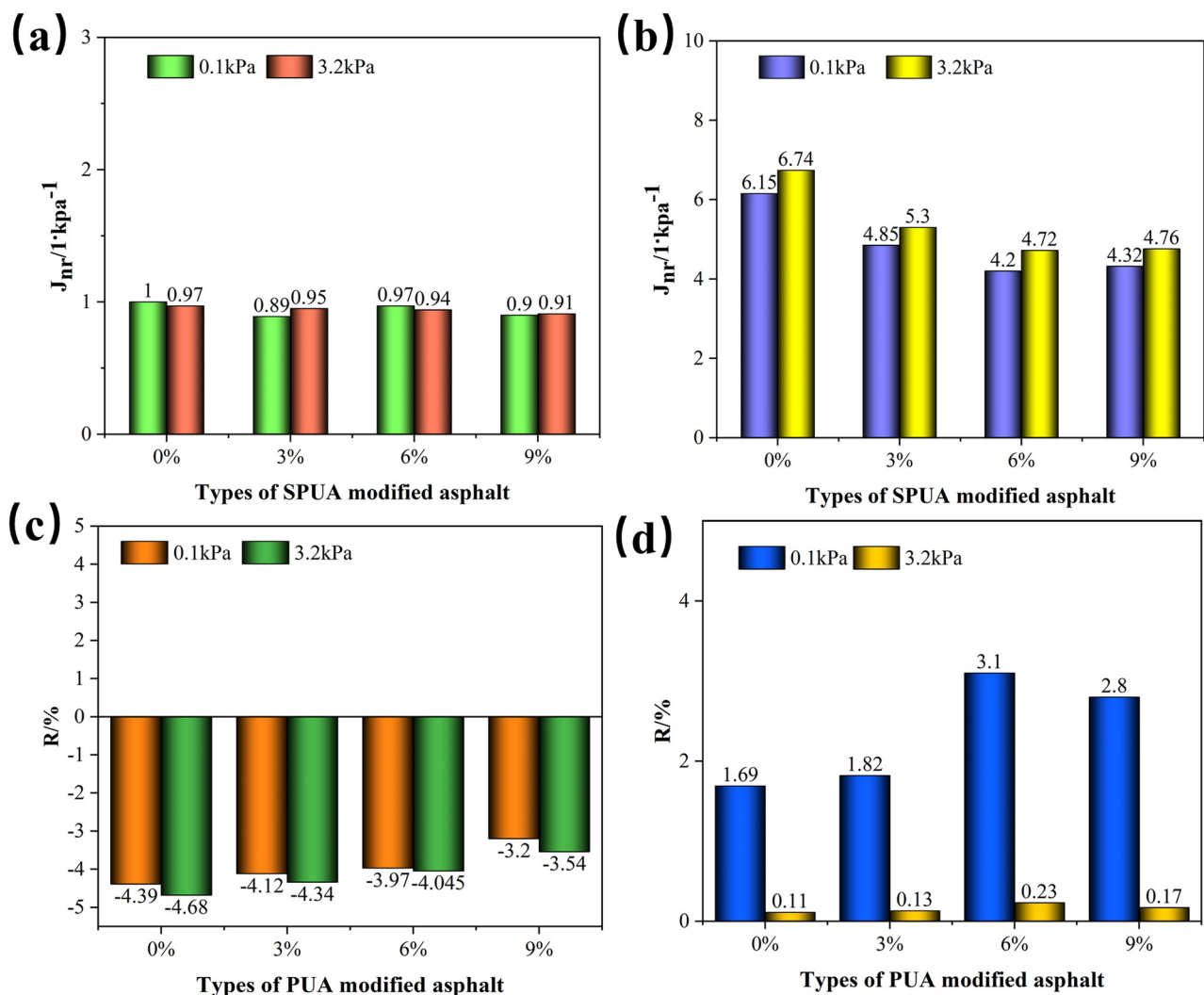


Figure 5: Unrecoverable creep compliance and creep recovery rate of asphalt under different parallel plates: (a) J_{nr} under 8 mm parallel plate, (b) J_{nr} under 25 mm parallel plate, (c) R under 8 mm parallel plate, and (d) R under 25 mm parallel plate.

The complex viscosity of modified asphalt under 8 and 25 mm parallel plates decreased gradually with the increase of temperature, and the trend was sharply decreased first and then tends to be gentle, which showed that the viscosity of modified asphalt under the two parallel plates decreased with the increase of temperature, and the overall trend was similar to the Brookfield viscosity. Further analysis of the chart showed that in the 8 mm parallel plate, the complex viscosity of the modified asphalt at the same temperature was in the order of $9\% > 6\% \approx 0\% > 3\%$, that is, the modified asphalt with 9% content had the largest viscosity in the temperature sweeping test, followed by 6 and 0%, and the modified asphalt with the minimum content of 3%. In contrast to the temperature scanning under 25 mm parallel plate, it could be known from Figure 6(b) that the complex viscosity of modified asphalt increased with the increase of modifier content at 46–82°C, which indicated that the addition of modifier can improve the viscosity of asphalt, and the viscosity of asphalt was better and the high-temperature performance was better with the increase of modifier content.

The results of Brookfield viscosity test in Section 3.1 showed that adding PUA modifier could increase the viscosity of asphalt and improve the high-temperature performance of asphalt, and the greater the content of PUA modifier, the better the viscosity of asphalt. Compared with the complex viscosity of temperature sweeping under 8 and 25 mm parallel plates, it was found that the complex viscosity law under 25 mm parallel plates was consistent with the Brookfield viscosity law, which reflected that PUA modifier could improve the high-temperature performance

of asphalt. The greater the content of modifier, the greater the viscosity of asphalt, and the better the high-temperature performance. In summary, 8 mm parallel plate could not evaluate the modification effect of PUA-modified asphalt in temperature sweeping test.

3.3.2 Correlation between frequency sweep and Brookfield viscosity

The complex viscosity results of PUA-modified asphalt under different parallel plates frequency scanning are shown in Figure 7. The figure shows that the complex viscosity of modified asphalt decreases with the increase in frequency under 8 and 25 mm parallel plates, indicating that increasing the loading frequency would reduce the viscosity of modified asphalt, thereby weakening the high temperature rutting resistance of modified asphalt. From Figure 7(a), it could be found that under the loading frequency of 0.1–1 rad/s, the complex viscosity of modified asphalt was relatively unstable, and there was a large floating. At the loading frequency of 1–100 rad/s, the complex viscosity of each asphalt decreases gradually, and at the same frequency, the complex viscosity of matrix asphalt was greater than that of modified asphalt, from large to small it was in the order of $0\% > 9\% > 3\% > 6\%$, indicating that under the frequency scanning test of 8 mm parallel plate, the viscosity of modified asphalt was lower than that of matrix asphalt, and PUA modifier had no improvement in the high-temperature performance of matrix asphalt. By analyzing the frequency scanning under the

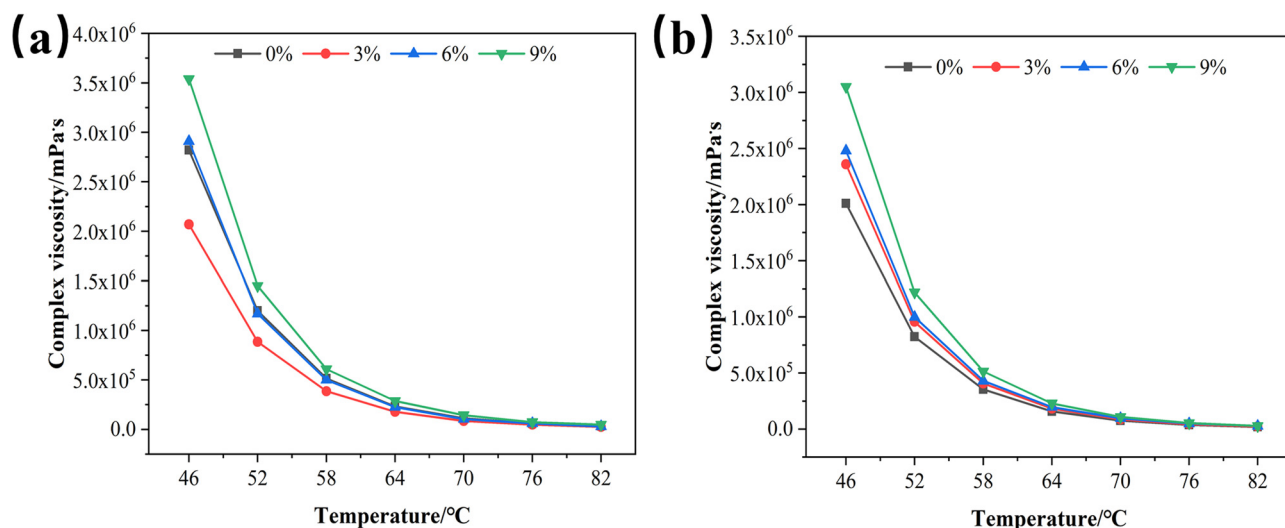


Figure 6: Complex viscosity of temperature sweeping under different parallel plates: (a) complex viscosity under 8 mm parallel plate and (b) complex viscosity under 25 mm parallel plate.

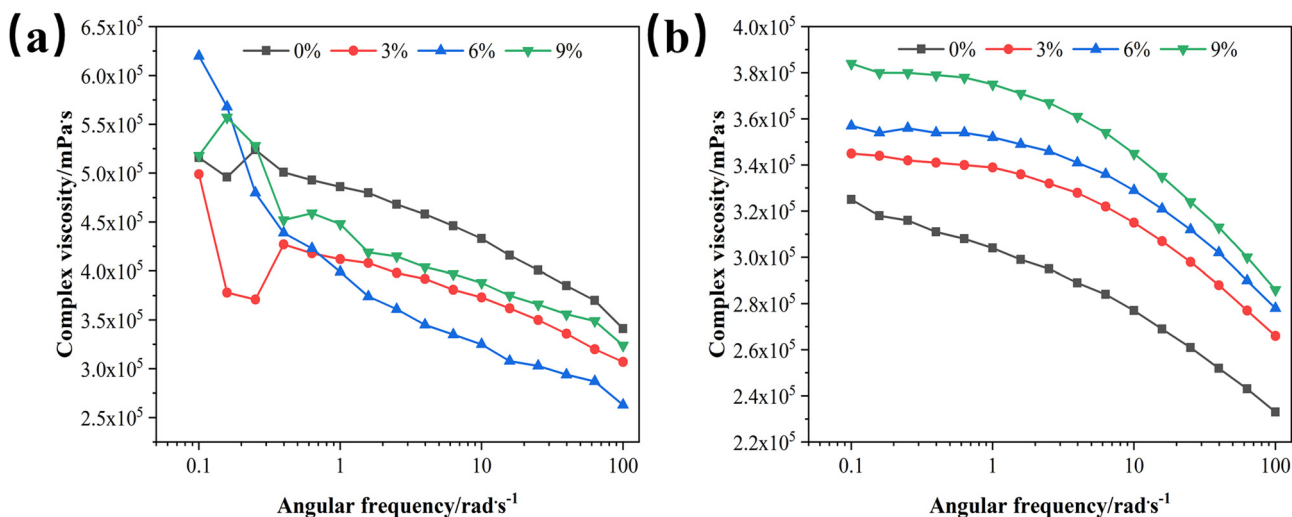


Figure 7: Complex viscosity of modified asphalt frequency scanning under different parallel plates: (a) complex viscosity under 8 mm parallel plate and (b) complex viscosity under 25 mm parallel plate.

25 mm parallel plate, it could be seen that the complex viscosity of each asphalt decreased with the increase of frequency, and the change trend of each curve was relatively stable. In particular, the decreasing trend of the three modified asphalts with PUA modifier was basically the same. In addition, at the same frequency, the complex viscosity of modified asphalt with PUA was much larger than that of matrix asphalt, which showed that the addition of PUA modifier could increase the viscosity of asphalt and improve the high-temperature performance of asphalt.

In summary, compared with the results of the Brookfield viscosity test, the frequency scanning results under the 8 mm parallel plate were inconsistent with the high-temperature performance of different asphalts reflected by the Brookfield viscosity results, whereas the frequency scanning results under the 25 mm parallel plate was consistent with Brookfield viscosity results. The high-temperature performance law between asphalts was consistent with the results of Brookfield viscosity, indicating that the modification effect of PUA modifier on asphalt could not be evaluated under the 8 mm parallel plate, and the 25 mm parallel plate was more suitable for evaluating the high-temperature performance of PUA-modified asphalt.

4 Conclusion

In this article, PUA-modified asphalt was taken as the research object. The high-temperature performance of

modified asphalt was evaluated by Brookfield viscosity. The rheological properties of modified asphalt were compared and analyzed by changing the size of parallel plates in DSR test, and the influence of different sizes of parallel plates on modified asphalt was clarified.

1. With the increase of PUA-modifier content, the Brookfield viscosity of asphalt increased gradually, and the viscosity increased continuously. The addition of modifier could effectively improve the high-temperature performance of asphalt.

2. Under the action of 8 mm parallel plate, the high-temperature performance of modified asphalt was lower than that of matrix asphalt, and the modifier had a negative effect on the modification of asphalt. Under the 25 mm parallel plate, the high-temperature performance of modified asphalt was higher than that of matrix asphalt. With the increase of PUA, the high-temperature performance of asphalt was better, and the modifier had the effect on the high temperature performance of asphalt.

3. Compared with the Brookfield viscosity test results, the rheological test results under 8 mm parallel plate were inconsistent with the Brookfield viscosity of different asphalts reflected by the results of Brookfield viscosity. The rheological test results under 25 mm parallel plate showed that the high-temperature performance law of each asphalt was consistent with the results of Brookfield viscosity, indicating that 25 mm parallel plate was more suitable for evaluating the high-temperature performance of PUA-modified asphalt.

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