Investigation of the rheological properties of devulcanized rubber-modified asphalt with different rubber devulcanization degrees and rubber contents

Abstract: Devulcanized rubber-modified asphalt (DRMA) possesses broad application potential due to its environmental friendliness and exceptional performance. However, the relationship between the rubber devulcanization degree, rubber content, and the modification effect of asphalt binder has not been clearly revealed. In this work, DRMA with different rubber devulcanization degrees and contents was prepared. The storage stability and rheological properties of several asphalt binders were evaluated, and the interaction mechanism between different devulcanized rubber (DVR) and asphalt was also detected using a laser scanning confocal microscope (LSCM). The segregation test results indicated that the storage stability of DRMA increased with the rubber devulcanization degree and decreased with the DVR content. The rheological test results demonstrated that under the same rubber devulcanization conditions, the elasticity ratio, rutting resistance, and fatigue resistance of DRMA of the ML40 (Mooney viscosity was 40 measured by large rotor) series was enhanced continuously, while the above properties of DRMA of the other series were enhanced and then weakened with the rubber devulcanization degree. Additionally, the DRMA of the ML60 series had a superior elasticity ratio and rutting resistance when the DVR content was the same. The low-temperature performance of DRMA increases with the rubber devulcanization degree and DVR content. The solubility test results and microstructure of DRMA showed that the rheological properties of DRMA were affected by the formation of the network structure and the mechanical properties of DVR.

Keywords: Crumb rubber, Devulcanization degree, Rubber content, Rubber-modified asphalt, Rheological properties

1. Introduction

Waste disposal is currently one of the most serious challenges that humans face. It has been estimated that over 1 billion tons of waste tires are produced worldwide annually due to the rapid development of the automotive industry, the management of which has always been a problem for mankind (Asaro et al., 2018; Farina et al., 2017). Due to the stable crosslinked three-dimensional network structure of vulcanized rubber, reprocessing by melting is impossible. The discarding of used tires will result in mosquito sickness and fire-related issues, and the exhaust emitted from used tires contains several harmful volatile organic compounds (VOCs)(Turer, 2012). Additionally, landfilled waste tires degrade soil quality by eradicating beneficial microbes in the soil(Khait, 2005). Therefore, the recycling and reclamation of scrap tires has become important.

Scrap tires can be ground at ambient temperature or in the glass transition region using liquid nitrogen in a cryogenic system to produce varying mesh sizes of crumb rubber (CR). Using crumb rubber for asphalt modification is a preferable way to reclaim waste tires. Researchers have carried out many studies on the rheology of crumb rubber modified asphalt(Marasteanu et al., 2017; Padmarekha et al., 2013; Šernas et al., 2023; Soenen et al., 2013). Due to its exceptional rutting resistance, low-temperature cracking resistance, durability, and skid resistance, rubber-modified asphalt (RMA) possesses broad application prospects (Lo Presti, 2013). However, due to the large difference in physical and chemical properties, such as density and solubility parameters, between rubber and asphalt, the compatibility between asphalt and rubber is inferior, resulting in the poor storage stability of RMA(Polacco et al., 2015; Wang et al., 2020). Moreover, the addition of CR will raise the viscosity of asphalt; thus, the construction temperature must be increased, which will consume more energy and emit harmful VOCs(Thives & Ghisi, 2017).

Researchers found that the rubber devulcanization process, which involves selectively breaking the crosslinked bonds of rubber based on bond energy, can effectively enhance the compatibility between asphalt and rubber(J. Li et al., 2021). Several devulcanization methods, including microwave, chemical, biological, and thermomechanical methods, have been developed(Asaro et al., 2018). The high-temperature dynamic devulcanization method is the most commonly used technique for rubber reclamation in China and India due to its high efficiency and convenience, while its high energy consumption and toxic air emissions cannot be overlooked. Although the microwave method can selectively break the C-S and S–S bonds by controlling the microwave exposure time and there is no environmental pollution during the regeneration process, the method has limitations, as it requires rubber composed of polar groups(Aoudia et al., 2017; Bockstal et al., 2019; Garcia et al., 2015). The biological method is still far from being used in industrial applications because the devulcanization process takes place only on the surface of the rubber, although it has the advantages of being a simple process, having low energy consumption, and allowing environmental protection. Recently, an emerging thermomechanical method called the twin-screw extrusion method has been applied, which can realize selective bond scission by setting extrusion conditions, such as screw diameter, barrel temperature, feeding rate, and screw speed(Yazdani et al., 2011). In addition, the twin-screw extrusion method has the advantages of low pollution and continuous production, making it suitable for industrial applications.

Currently, published studies focus on performance evaluation with different devulcanization methods. Kabir et al.(Kabir et al., 2021) compared the performance of microbial devulcanized rubber-modified asphalt with conventional rubber-modified asphalt and found that the microbial devulcanization process enhanced the storage stability and stress relaxation capacity of asphalt binder, while the viscosity decreased. Zhou et al.(Zhou et al., 2020) evaluated the rheological properties of microwave-activated crumb rubber-modified asphalt before and after aging and detected that the aging resistance was enhanced after microwave technology. Zhang(Zhang et al., 2019) prepared DRMA using the twin-screw extrusion method at different extrusion temperatures, and the rheological indices indicate that the rutting resistance of DRMA prepared at low extrusion temperatures increased with the DVR content, while that of DRMA prepared at high extrusion temperatures decreased with the DVR content. Overall, devulcanized rubber-modified asphalt possesses better cracking resistance and storage stability than rubber-modified asphalt (RMA), while the anti-rutting performance is worse(Fang et al., 2021; Kocak & Kutay, 2021; Li et al., 2019). However, the correlation between the modification effect of asphalt and the devulcanization degree and content of rubber has not been identified, which hinders the promotion and application of devulcanized rubber-modified asphalt.

Therefore, this study aims to investigate the effect of the rubber devulcanization degree and rubber content on the rheological properties and storage stability of asphalt binders. The rheological properties of different modified asphalts were evaluated through frequency sweep, multiple stress creep recovery (MSCR), and bending beam rheometer (BBR) tests, while the storage stability was evaluated through a segregation test. Solubility tests and laser scanning confocal microscopy were used to analyze the reaction mechanism by detecting the component change and chemical structure, respectively. The research results lay a foundation for the future application of devulcanized rubber-modified asphalt in pavement construction engineering.

2. Materials and Methods

2.1 Devulcanization degree characterization

Mooney viscosity is a widely used indicator in the rubber industry to characterize the average molecular weight and plasticity of rubber. Rubber devulcanization may be defined as the process of selectively breaking crosslinking bonds in rubber. As shown in Figure 1, the higher devulcanization degree is, the more seriously the internal cross-linked structure of the rubber will be destroyed. In this case, the mechanical properties of rubber will be weakened, and the average molecular weight of which will be decreased. Therefore, Mooney viscosity can be used to characterize the devulcanization degree indirectly.

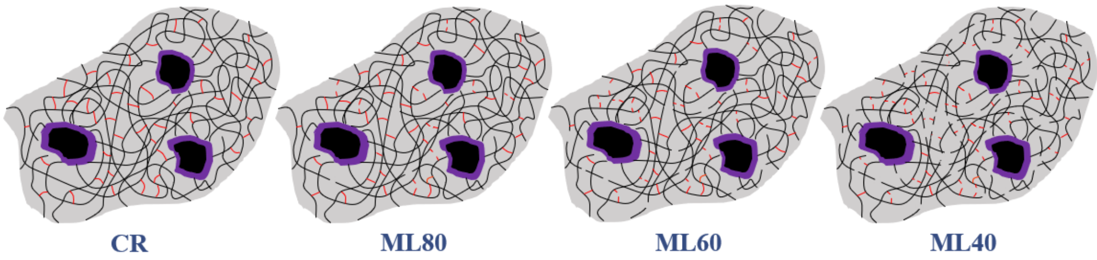
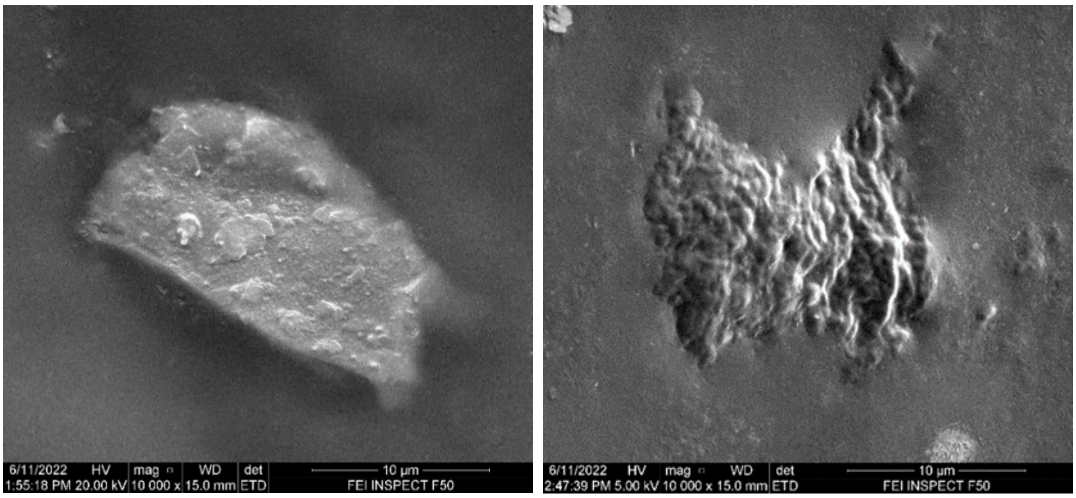
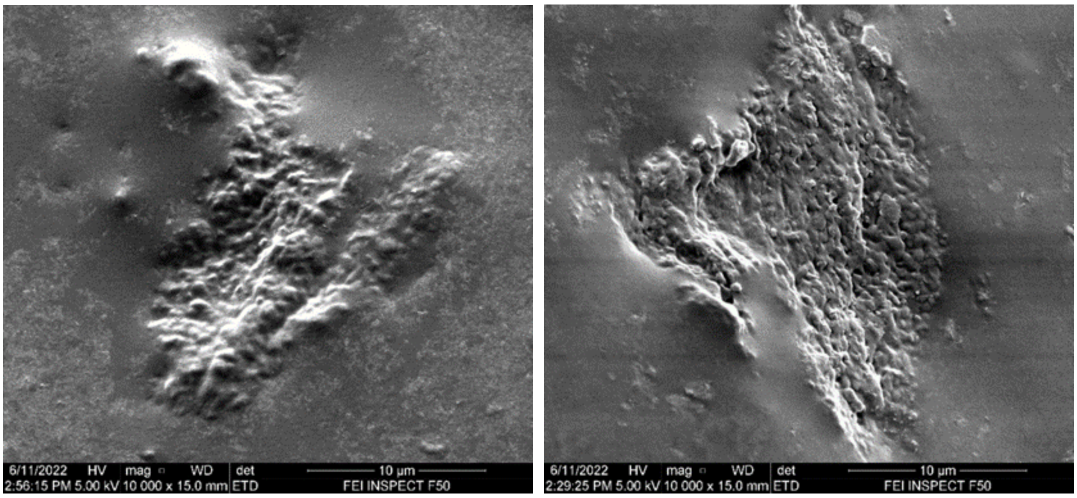


Figure 1 Internal structure of rubber particle with different devulcanization degrees

Considering that the twin-screw extrusion method can control the devulcanization degree of CR, the DVR of three devulcanization degrees were prepared by changing extrusion parameters including screw speed and screw temperature, and the Mooney viscosity value of which is ML40, ML60, ML80, respectively. The microstructure of rubber with different devulcanization degrees in asphalt is shown in Figure 2.



(a) CR (b) ML80



(c) ML60 (d) ML40

Figure 2 Microstructure of crumb rubber and devulcanized crumb rubber

2.2 Materials and preparation

Pen 70 asphalt was selected as the neat binder in this study, and its basic property indices are listed in Table 1. Crumb rubber (40 mesh) with different degrees of devulcanization was prepared by the twin-screw extrusion method. Firstly, the crumb rubber was put into the oven at 70°C for 1h, and then put into the twin screw extruder, the extrusion temperatures was 160°C, 200°C and 240°C, respectively, the screw speed was selected to be 600r/min and the feeding speed was 80r/min, and then the devulcanized crumb rubber with different devulcanization degrees were obtained by using granulator.

Table 1 Basic properties of matrix asphalt

Index	Unit	Test Result	Test Method
Penetration (25 °C, 100 g, 5 s)	0.1 mm	67.1	ASTM D5
Softening point (ring and ball method)	°C	48.2	ASTM D36
Ductility(15 °C, 5 cm/s)	cm	111.8	ASTM D113
PG grade	-	64-22	AASHTO M320
Change in mass after TFOT	%	0.1	ASTM D2872
Flashpoint (Cleveland open cup)	°C	288	ASTM D92

The dosages of devulcanized crumb rubber were 25%, 30%, 40%, and 50%. Due to the poor compatibility between crumb rubber and asphalt, only rubber-modified asphalt with 25% and 30% CR content was prepared. Sulfur was selected as the stabilizer in this study, and the content was 0.3% of the mass of the modifier. The preparation process of different modified asphalt is shown in Fig 3, and the nomenclature of modified asphalt is shown in Table 2.

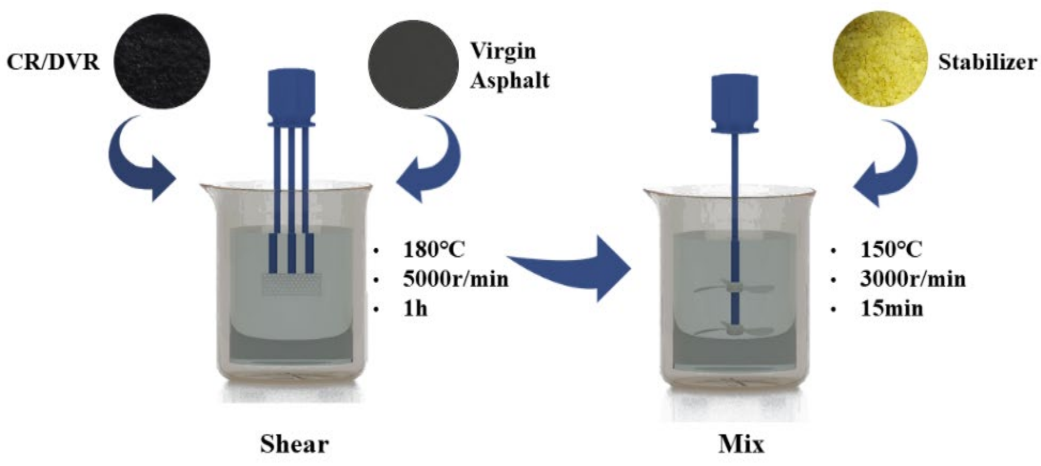


Figure 3 Diagram of the modified asphalt preparation process

Table 2 Nomenclature of different modified asphalts

Devulcanization degree \ Modifier Content	25%	30%	40%	50%
Vulcanized rubber	RMA25	RMA30	-	-
ML40	DRMA40-25	DRMA40-30	DRMA40-40	DRMA40-50
ML60	DRMA60-25	DRMA60-30	DRMA60-40	DRMA60-50
ML80	DRMA80-25	DRMA80-30	DRMA80-40	DRMA80-50

2.3 Testing methods

2.3.1 Storage stability test

The segregation phenomenon, caused by the large difference in physical and chemical properties between crumb rubber and asphalt, critically deteriorates the performance of polymer-modified asphalt. The storage stability was generally evaluated by a segregation test. It has been found that the multiple stress creep recovery test (MSCR) parameters are sensitive to the microstructural changes of polymer-modified asphalt, so the Stability Index (*SI)* was used to investigate the influence of the devulcanization degree and the modifier content on the storage stability of asphalt(Wang et al., 2020).

$$SI = \frac{R_{max} - R_{avg}}{R_{avg}} * 100\% \qquad (1)$$

where R_{max} is the larger value of the creep recovery rate between the top and bottom of the aluminum tube at the 3.2 kPa stress level, %; R_{avg} is the average value of the creep recovery rate between the top and bottom of the aluminum tube, %.

2.3.2 Frequency sweep test

Asphalt binder, as a typical viscoelastic material, exhibits different viscoelastic responses under different temperature and frequency conditions. In this study, dynamic modulus and phase angle master curves were constructed to explore the effect of crumb rubber devulcanization degree and content on asphalt rheological behavior. The frequency sweep test was conducted by a dynamic shear rheometer (DSR) device (Anton Paar, Austria). The test was conducted with a parallel-plate geometry (25 mm diameter and 1 mm gap) from 0.1 to 100 Hz at temperatures of 10, 20, 30, 45, and 60°C. The strain was controlled at 0.1%, and the frequency scan range was 0.1~100 Hz. The dynamic modulus and phase angle master curve were obtained based on time-temperature equivalence principle (WLF equation). The Christensen, Anderson, and Marasteanu (CAM) model and the double-logistic model were selected as fitting model of dynamic modulus and phase angle master curve, respectively.

2.3.3 Solubility test

The solubility test was designed to investigate the swelling process of different devulcanized rubber in asphalt, and the detailed steps can be found in the reference (D. Li et al., 2021). A certain weight of asphalt in molten state was first poured onto a 200-mesh sieve at 165°C for 20 minutes, during which time the liquid phase can flow through the sieve into the container below. Subsequently, the sieve and the swelling rubber particles above are immersed in a methylene chloride solution to separate the gel layer on the surface of the crumb rubber, and finally the weight of the crumb rubber was weighed for further analysis.

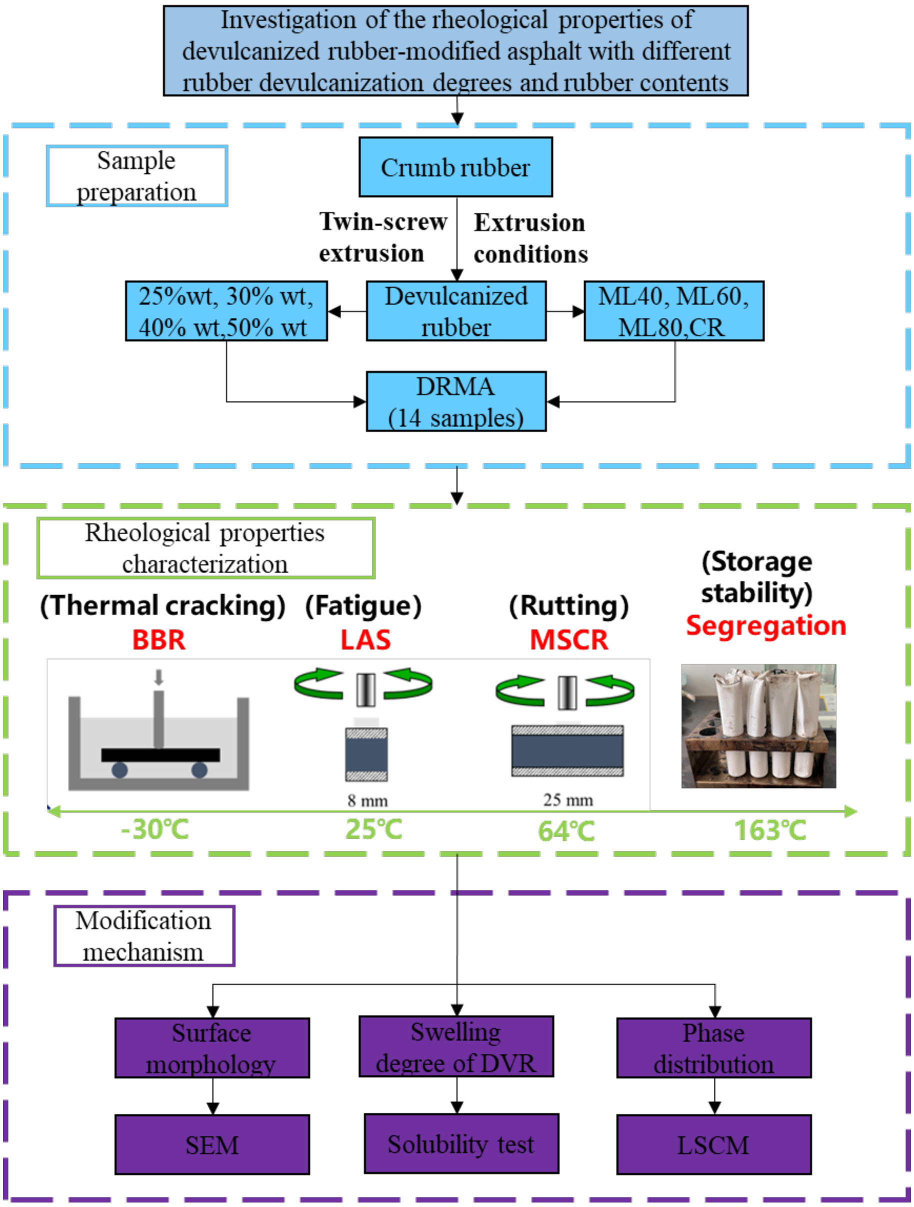


Figure 4 Organization and flowchart of the study

2.3.4 Multiple stress creep recovery test

The MSCR tests were performed using a DSR at 64 °C according to AASHTO T350-14. The creep recovery rate R and the nonrecoverable creep compliance J_{nr} were obtained to evaluate the ability of asphalt to resist permanent deformation under repeated loading.

2.3.5 Linear Amplitude Scanning Test

The Linear Amplitude Scanning (LAS) test has recently become accepted for accelerating the fatigue characterization of asphalt binders (AASHTO TP 101-12). First, the undamaged material parameter α was obtained by conducting a frequency sweep (0.2 to 30 Hz) at a strain level of 0.1%; After that, oscillatory shear was performed to characterize the damage process of different asphalt binders based on damage theory. The LAS tests were conducted at 25° C. The simplified viscoelastic continuum damage model (S-VECD) can be applied to characterize the damage and predict the fatigue life at any strain amplitude of interest.

2.3.6 Bending Beam Rheometer Test

The bending beam rheometer (BBR) test was conducted based on AASHTO T313. As the primary evaluation index obtained from the BBR test, the stiffness modulus (*S*) is used to characterize the deformation resistance while the creep rate (*m*) can be used to evaluate the stress relaxation ability and sensitivity of the stiffness of asphalt. A study found that a single *m* or *S* index cannot accurately evaluate the low-temperature performance of rubber-modified asphalt, the *k* index was established based on the physical meaning of the *m* and *S* indices(Fu et al., 2016).

$$k = \frac{Log_{10}(S)}{m} \qquad (2)$$

where *S* is the creep stiffness, MPa, *m* is the creep rate and s^{-1}.

In addition, the ΔT_c index, proposed in the American Airport Asphalt Pavement Plan (AAPTP 06-01) in 2011, was used to investigate the low-temperature cracking behavior of different modified asphalts(Anderson et al., 2011). The *S* and *m* indices at different temperatures were fitted under semilogarithmic and arithmetic coordinates, respectively, to obtain the continuous graded temperature, and the ΔT_c index can be calculated according to Formula 3(Yan et al., 2023).

$$\Delta T_c = T_{c,s} - T_{c,m} \quad (3)$$

where $T_{c,s}$ is the temperature when the creep stiffness of the binder is 300 MPa, ℃; $T_{c,m}$ is the temperature when the *m* value of binder is 0.3 s^{-1}.

2.3.7 Laser scanning confocal microscopy

The morphology of different rubber-modified asphalts was observed by using a Leica TCS SP8 (Leica, Germany). The heated binder was dropped on the slide, and the cover slide was covered to press the asphalt evenly. The polymer phase (green) and asphalt phase (black) were identified by laser scanning confocal microscopy.

3. Results and Discussion

3.1 Storage stability

The findings from the storage stability test, as illustrated in Figure 5, reveal a notable enhancement in the storage stability of devulcanized rubber modified asphalt when compared to conventional rubber-modified asphalt. With equivalent modifier content, it is observed that the stability index of devulcanized rubber modified asphalt is approximately one-third of that found in rubber modified asphalt. However, the storage stability of rubber modified asphalt experiences a considerable decline as the proportion of crumb rubber content increases. This decline can be attributed to the increased presence of undissolved crumb rubber, resulting in an elevated tendency for phase separation under the influence of gravity. Consequently, this leads to a marked divergence in the asphalt performance.

Moreover, under identical modifier content conditions, the storage stability of asphalt exhibits a hierarchical trend with regard to different devulcanization degrees, following the sequence of ML40 series > ML60 series > ML80 series > RMA series. This hierarchy is primarily influenced by the compatibility between crumb rubber and asphalt. Notably, a higher degree of devulcanization corresponds to an improved compatibility between crumb rubber and asphalt, thus yielding enhanced storage stability for the asphalt formulation.

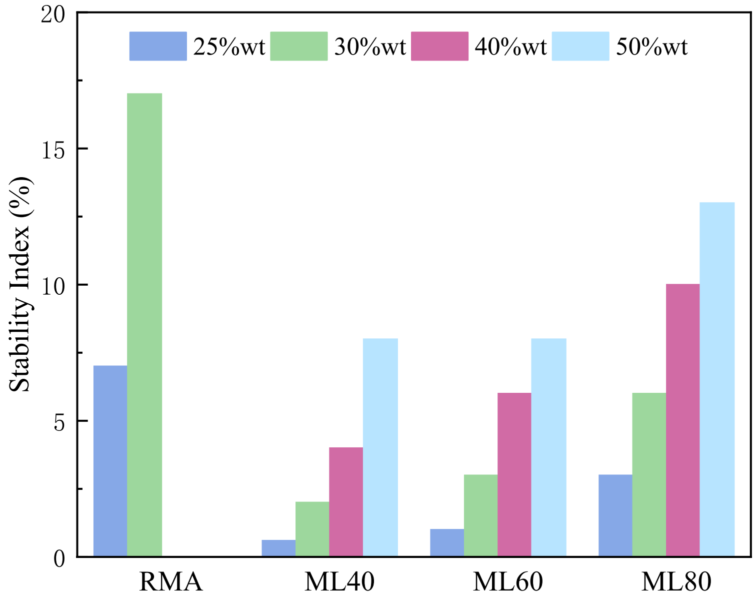


Figure 5 Separation test results of different asphalt

3.2 |G| and δ*

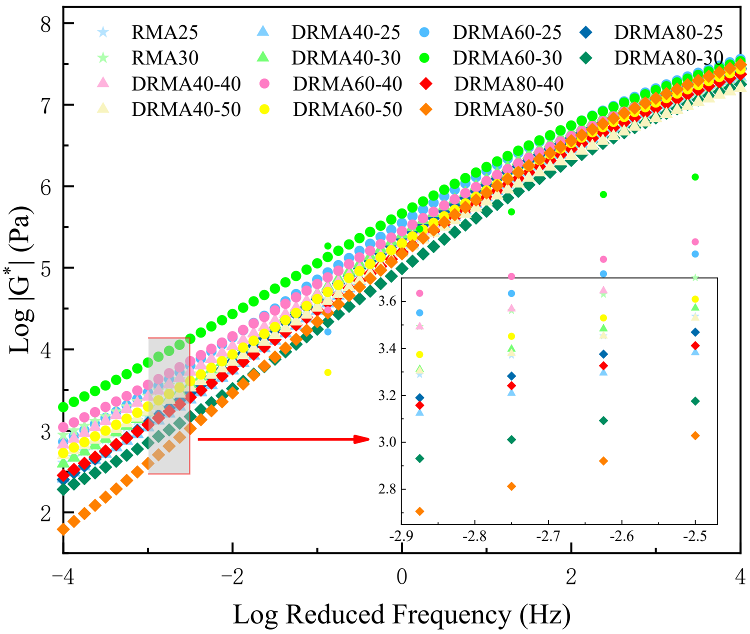


Figure 6 Complex modulus master curve

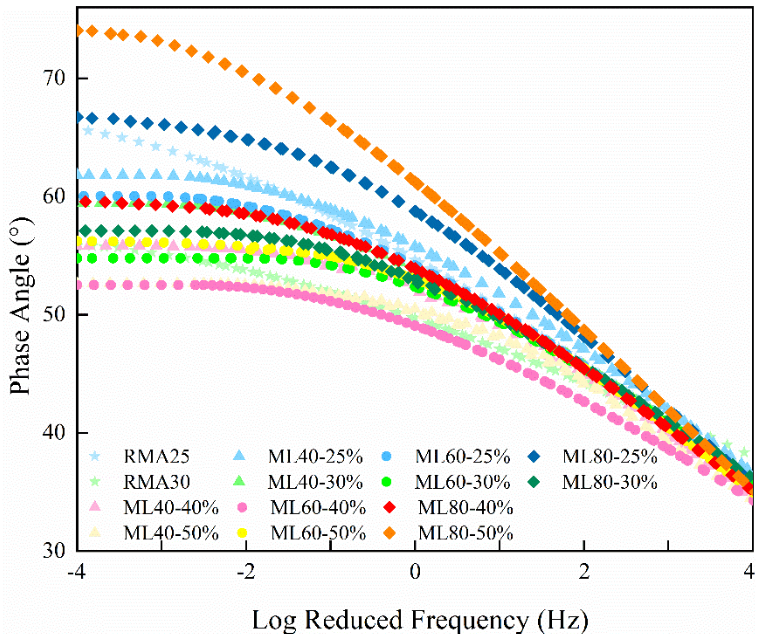
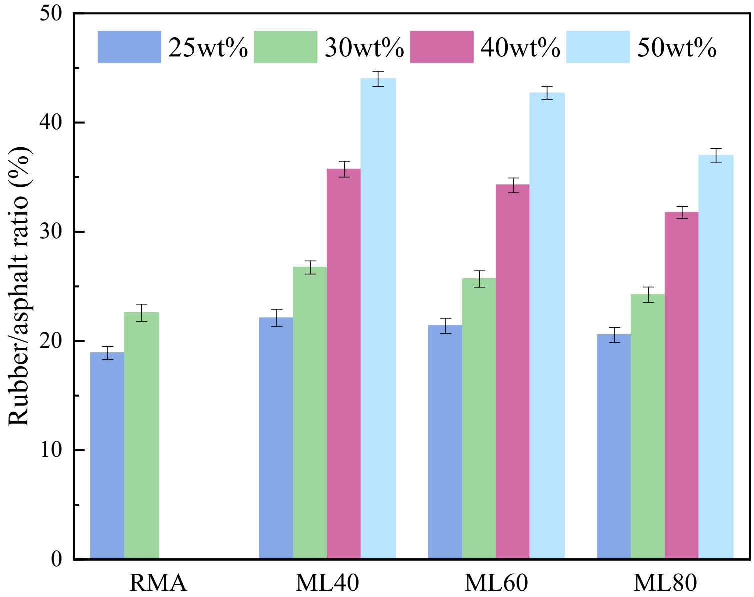


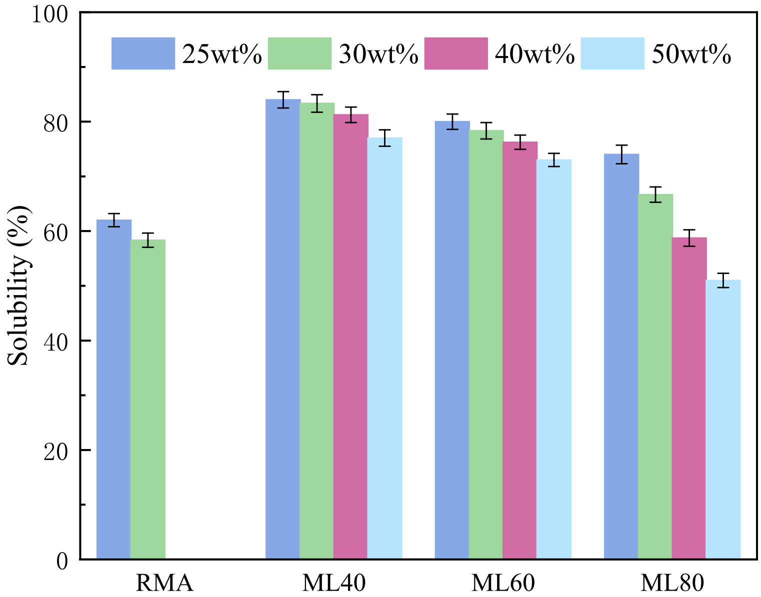
Figure 7 Phase angle master curve

Figure 6 and Figure 7, respectively demonstrate the complex modulus and phase angle of the asphalt master curve at 30 ℃. Considering that the elastic properties of asphalt are excellent enough at low temperature/high frequency, the high temperature/low-frequency region of the main curve is generally analyzed. Under the condition of the same devulcanization degree, the complex modulus of asphalt was strengthened first and then weakened with increasing CR/DVR content, while under the condition of the same CR/DVR content, the asphalt of the ML60 series possesses the most evident elastic characteristics. In light of this phenomenon, Wang proposed a micromechanical model of crumb rubber-modified asphalt and hypothesized that the complex modulus of rubber-modified asphalt is composed of the CR/DVR modulus and asphalt modulus according to a certain function and will be influenced by the effective volume fraction of CR/DVR (Wang et al., 2018; Wang et al., 2021). To validate this idea, a solubility test was conducted in this study. Solubility is defined as the mass ratio of dissolved CR/DVR to total CR/DVR, while the rubber/asphalt ratio is defined as the mass ratio of dissolved CR/DVR to asphalt. The results are shown in Figure 8. The effective volume fraction increased with increasing CR/DVR content, which enhanced the network structure within the asphalt, and thus, the complex modulus was enhanced first. However, the undissolved CR/DVR in asphalt increased continuously, which had a negative impact on the elastic characteristics of asphalt.

Moreover, it is noteworthy that despite the ML40 series displaying the highest effective volume fraction, the devulcanized rubber (DVR) with a Mooney viscosity of ML40 exhibited a notable deterioration in mechanical properties. This phenomenon translated into a reduction in the elastic properties of the modified asphalt. In contrast, the DVR with a Mooney viscosity of ML60 exhibited a favorable combination of a highly effective volume fraction and exceptional elastic properties. As a result, the asphalt formulations within the ML60 series demonstrated the most pronounced enhancements in elastic characteristics.



(a) Solubility

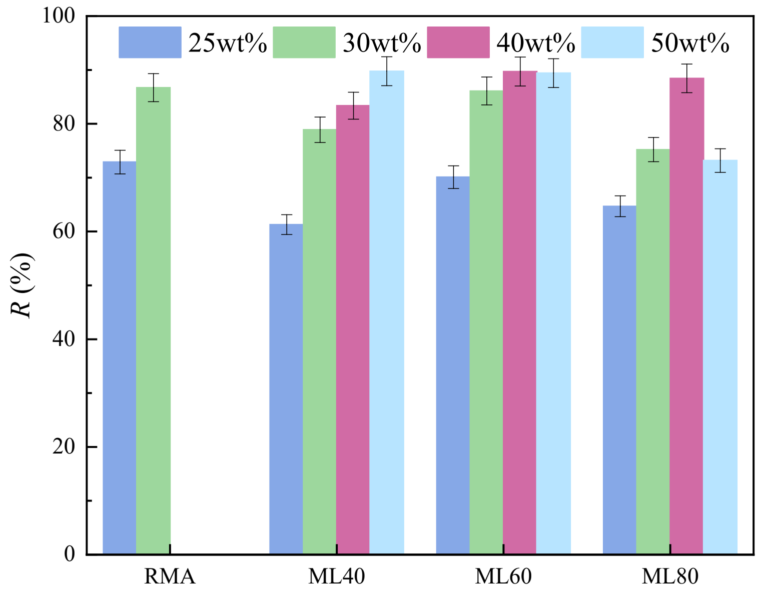


(b) Rubber/asphalt ratio

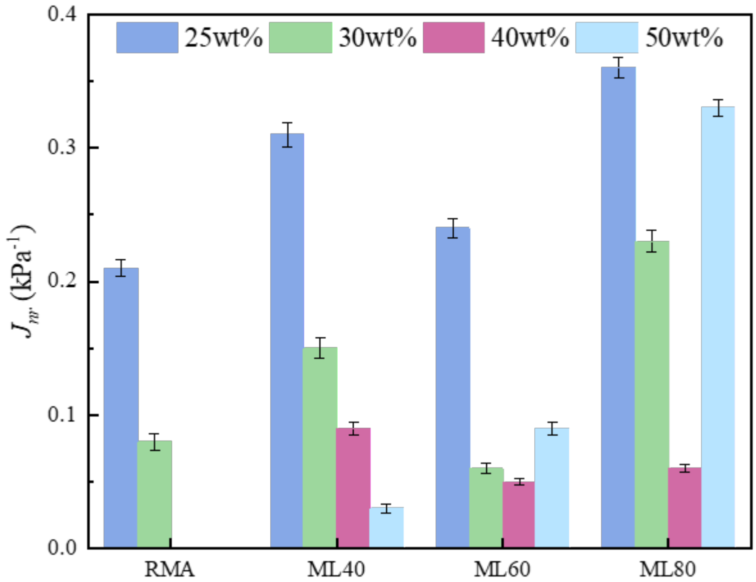
Figure 8 Solubility test results

3.3 Multiple stress creep recovery test results

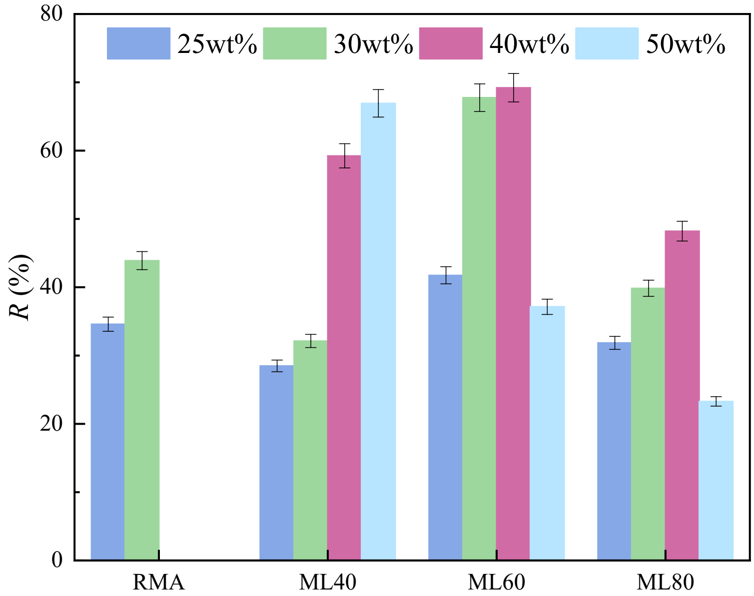
The multiple stress creep recovery (MSCR) test has been recently accepted to investigate rutting resistance due to its consideration of damage impact. As the two major parameters obtained from the MSCR test, the nonrecoverable creep compliance (J_{nr}) was used to evaluate the resistance to permanent deformation of asphalt binder under repeat loading, while the percent recovery (R) was applied to identify the presence of elastic response and stress dependence of different binders(Liu et al., 2021). Figure 9 demonstrates the MSCR test results of modified asphalt measured at different stress levels. Under the same devulcanization degree condition, the resistance to permanent deformation of asphalt under different stress levels tends to increase and then decrease with increasing modifier content, the reason for which was similar to those stated in the viscoelastic analysis section. Additionally, when the modifier content of different series of asphalt binders was the same, the traditional crumb rubber asphalt binder had the best resistance to permanent deformation under a strain level of 0.1 kPa, while the ML60 series of asphalt binders possessed the best resistance to permanent deformation under a strain level of 3.2 kPa, indicating that the ML60 series of asphalt binders was more suitable for application in heavy traffic sections.



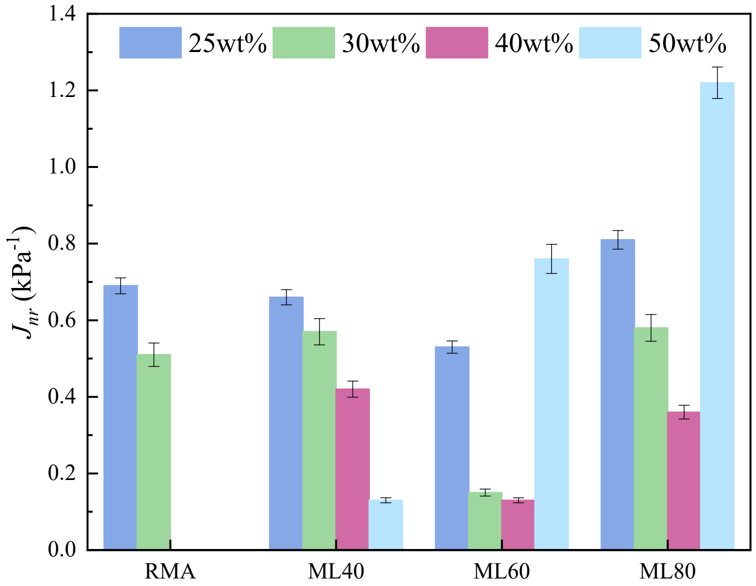
(a) ***R* measured at 0.1 kPa**



(b) ***J**$_{nr}$* **measured at 0.1 kPa**



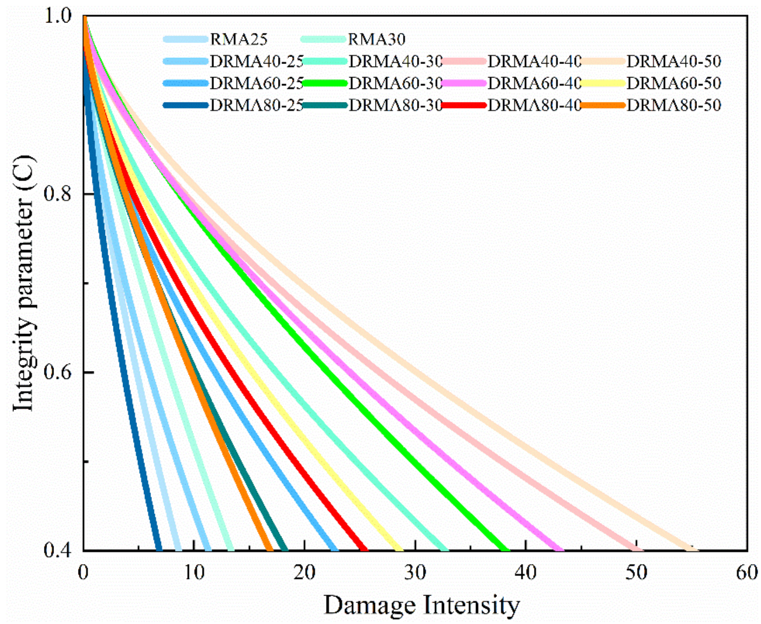
(c) ***R* measured at 3.2 kPa**



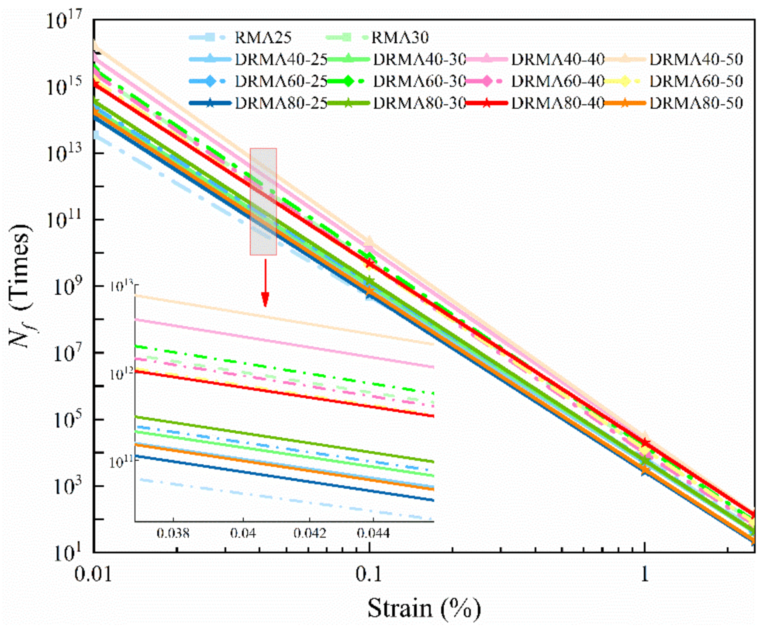
(d)J_{nr} measured at 3.2 kPa

Figure 9 MSCR test results

3.4 Linear amplitude scanning test results



(a) Integrity parameter VS. Damage intensity



(b) Number of cycles for loading to failure

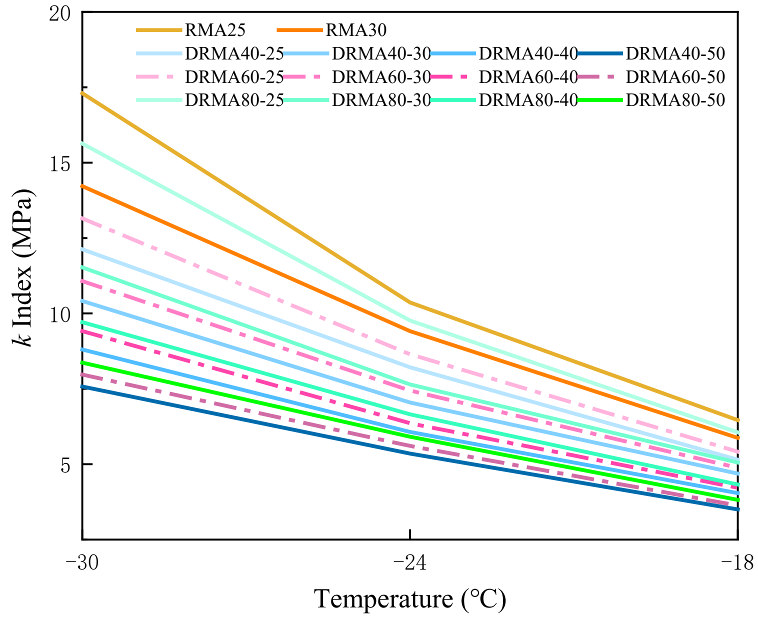
Figure 10 LAS test results of RMA and DRMA

As the major form of pavement damage, fatigue cracking has been a hot research topic in the field. The asphalt binder is the weakest part of the pavement, so it is necessary to evaluate the inherent fatigue properties of the asphalt binder. The simplified viscoelastic continuum damage (S-VECD) model has been successfully utilized to predict the damage evolution in asphalt mixtures for various traffic conditions(Safaei et al., 2016). The linear amplitude scanning (LAS) test was developed based on the S-VECD model in 2010 and has been formalized in AASHTO TP-101(Johnson, 2010).

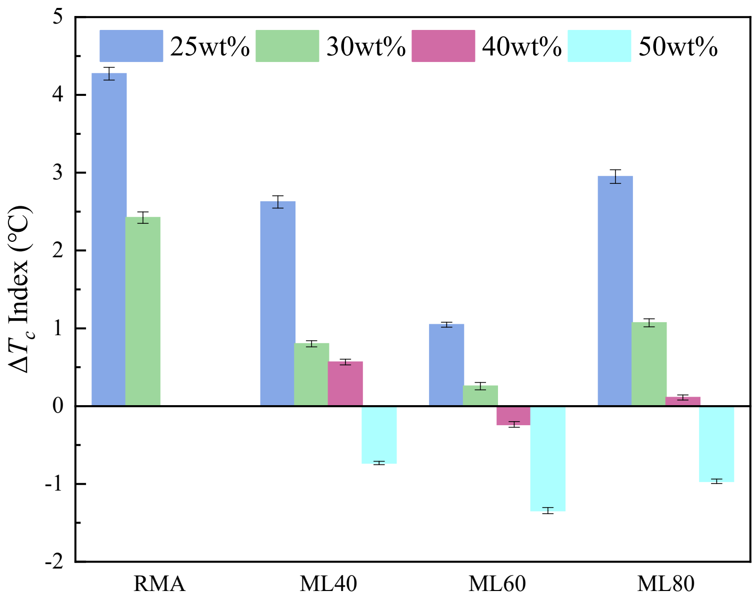
This study established C-D curves and N_f curves of different rubber-modified asphalts based on the S-VECD model. Figures 10(a) and 10(b) both indicate that when the devulcanization degree was the same, the fatigue performance of the ML40 series of DRMA was strengthened continuously, while the others tended to increase first in the dosage until a maximum value appeared and then decrease gradually, which is consistent with the MSCR conclusions. Additionally, under the same modifier content conditions, the asphalt binders of the ML60 series possess the best fatigue performance when the modifier content is less than 40 wt%, while the fatigue performance of asphalt binders of the ML40 series is the best when the DVR content exceeds 40 wt%. This phenomenon was generated by the synergistic effect of the content and effective volume fraction of CR/DVR. Overall, DRMA40-50 had the best fatigue performance of all subjects studied.

3.5 Bending beam rheometer test results

The *k* index of different asphalts under different temperature conditions is shown in Figure 11(a). It can be concluded that the low-temperature performance of asphalt was enhanced with the degree of devulcanization if the modifier content was the same, which is attributed to the stiffness reduction of the asphalt binder caused by the devulcanization process. In addition, the low-temperature performance was enhanced with increasing modifier content under the same devulcanization degree condition because the glass transition temperature of crumb rubber is lower than that of asphalt, which can reduce the glass transition temperature of the mixture continuously when the crumb rubber content increases(Rath et al., 2022).



(a) k index



(b) ΔT_c index

Figure 11 BBR test results of RMA and DRMA

The positive and negative values of the ΔT_c index reflect that the low-temperature cracking behavior of the asphalt binder is mainly controlled by creep stiffness or creep rate, and its absolute value indicates the degree to which the binder is *m*-controlled or *S*-controlled. Specifically, asphalt cracking is mainly controlled by creep stiffness when $\Delta T_c > 0$, and the asphalt binder still maintains a reasonable stress relaxation ability at T_c,

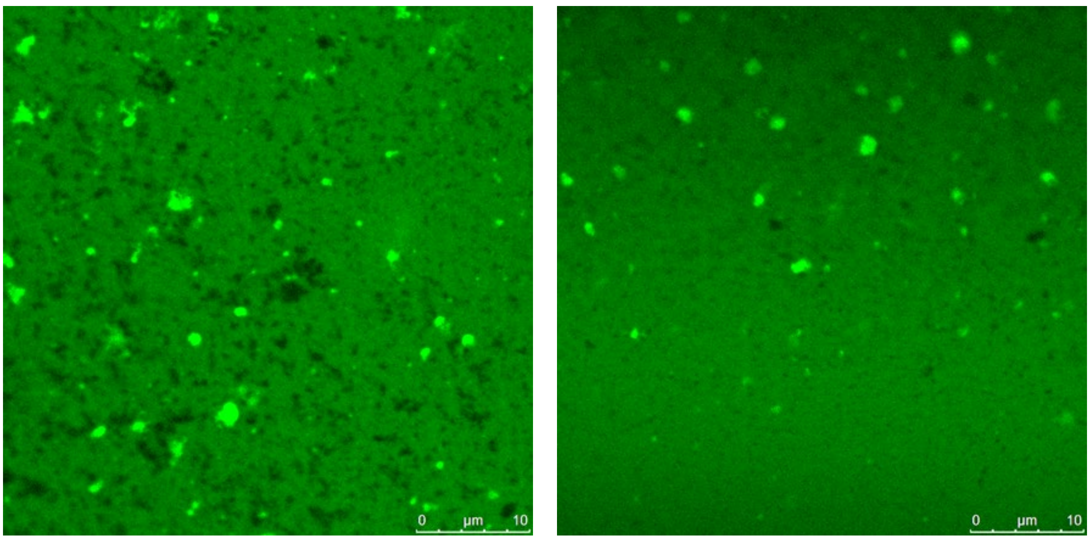
$_S$. In this case, pavement cracking is mainly caused by the hardening of the material itself and manifests as brittle fracture macroscopically.

Figure 11(b) demonstrates that the ΔT_c index of asphalt involved in this article changed from positive to negative with increasing modifier content, indicating that the asphalt cracking behavior is translated from *S*-controlled to *m*-controlled. The reason is that the increase in modifier content will reduce the creep stiffness, resulting in a lower $T_{c,\ S}$ temperature. In addition, the stress relaxation capacity of asphalt binder will be weakened due to the reduced viscosity ratio, which will lead to an increase in $T_{c,m}$ temperature. Moreover, the viscous behavior of asphalt at low temperatures will lead to a stress relaxation effect, which can release thermal stress effectively and thus reduce the risk of pavement cracking. As mentioned in the phase angle master curve, the ML60 series possesses the best elasticity characteristics; however, its viscosity ratio is the lowest, resulting in the worst stress relaxation capacity. Therefore, the absolute value of the ΔT_c index of the ML60 series is maximum, indicating that it is prone to fracture due to insufficient stress relaxation capacity.

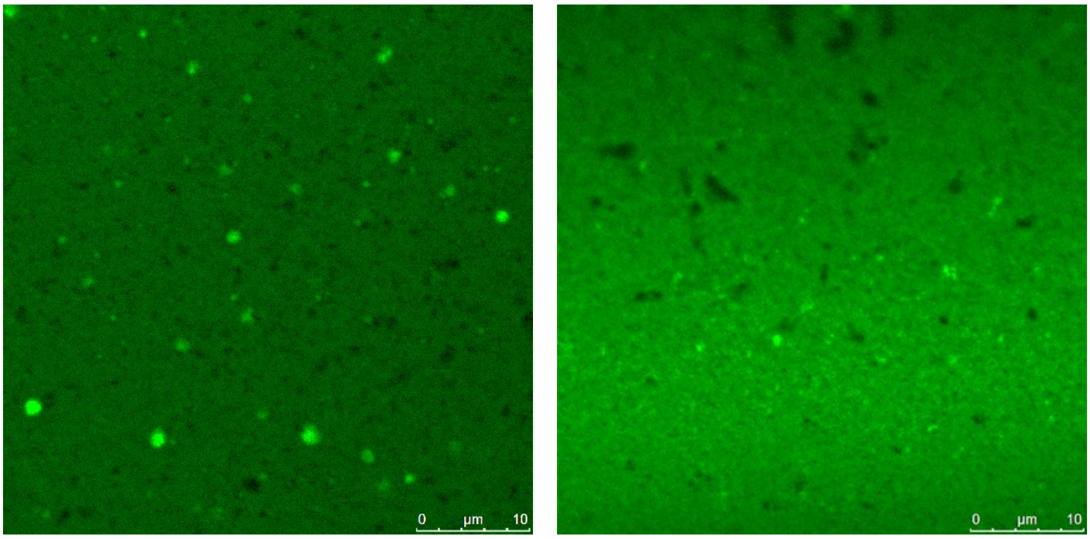
3.6 Modification mechanism analysis

Several studies have indicated that the interaction between crumb rubber and asphalt is mainly physical and has a slight chemical reaction(Fang et al., 2021). Therefore, the swelling process of rubber plays an important role in the performance modification of asphalt binders. The morphological characteristics of rubber-modified asphalt prepared by rubber with different degrees of devulcanization were examined by laser scanning confocal microscopy (LSCM). As shown in Figure 12, DRMA exhibited a well-dispersed punctate structure, which could be explained by the effective and efficient degradation of devulcanized crumb rubber in the blending process under thermal and mechanical energy; thus, the performance of rubber-modified asphalt was significantly improved compared with that of matrix asphalt.

In addition, as the devulcanization degree increases, the DVR is more evenly distributed within the asphalt matrix, and the undissolved particles are smaller and form a more homogeneous network structure, which is why the storage stability increased with the rubber devulcanization degree. However, the high temperature and fatigue properties of the asphalt binder were not improved due to the severe loss of mechanical properties of the devulcanized crumb rubber.



(a) RMA25 **(b) DRMA80-25**



(c) DRMA60-25 **(d) DRMA40-25**

Figure 12 Microstructure of asphalt binders with different devulcanization degrees under LSCM

4. Conclusions

This study prepared environmentally friendly devulcanized rubber-modified asphalt and investigated the effect of the rubber devulcanization degree and rubber content on the rheological properties and storage stability. The main conclusions are drawn as follows:

(1) The process of devulcanization demonstrates an effective means of mitigating the viscosity of rubber modified asphalt. However, this favorable reduction in viscosity is concomitant with a reduction in the mechanical properties of asphalt binders. Consequently, the pursuit of an optimal equilibrium between the construction workability and mechanical performance of rubber asphalt presents a significant and nuanced challenge for future researchers to address.

(2) The viscoelastic response of rubber modified asphalt to fluctuations in CR/DVR content and rubber devulcanization degree reveals a complex and multifaceted pattern. This intriguing complexity suggests a promising path for future research

aimed at gaining a more profound comprehension of the optimization of these elastic attributes. Notably, DRMA60-30 stands out due to its exemplary elastic properties, which are plausibly ascribed to a well-balanced and efficacious rubber volume fraction. Future investigations may delve into strategies for the precise adjustment of this equilibrium to achieve heightened performance levels.

(3) The rutting resistance of DRMA exhibits a distinctive non-linear correlation with modifier content, culminating in an apex prior to diminishing returns. This observation presents a significant avenue for prospective investigation, with a particular emphasis on delineating the optimal range of modifier content conducive to the maximization of rutting resistance.

(4) The fatigue resistance across various series displays a range of distinctive behaviors in response to variations in modifier content, unveiling compelling avenues for prospective exploration. This underscores the need for comprehensive inquiries into the underlying mechanisms governing fatigue performance, with the objective of elucidating strategies for augmenting fatigue resistance across different levels of modifier content. Asphalt binders featured in the ML60 and ML40 series hold particular promise, warranting a meticulous investigation into the feasibility of optimizing modifier content to enhance fatigue performance.

(5) The low-temperature performance of DRMA exhibits improvement with higher rubber devulcanization degree and increased rubber content. Concomitantly, the transition in the cracking behavior of DRMA shifts from a susceptibility to *S*-controlled cracking to *m*-controlled cracking as CR/DVR content rises. It is

noteworthy, however, that there are currently no standardized specifications delineating the criteria for the ΔTc index of 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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