

Article

Modification Mechanism and Technical Performance of Recycled PE-Modified Asphalt

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Abstract: Waste plastic pollution is a serious issue. In order to adhere to the concept of green development and rationally dispose of polyethylene waste plastic products, polyethylene (PE)-modified asphalt was prepared using recycled polyethylene (RPE) and low-density polyethylene (LDPE) as raw materials. The chemical structures of the RPE- and LDPE-modified asphalt were studied using a Fourier transform infrared spectrometer (FTIR), and the dispersion of RPE was studied using a fluorescence microscope (FM). Subsequently, the modification mechanism of the PE-modified asphalt was revealed. The physical properties and high- and low-temperature rheological characteristics of the PE-modified asphalt were examined using physical property tests, a dynamic shear rheometer (DSR), and a bending beam rheometer (BBR). The creep performance of the PE-modified asphalt was analyzed using multiple-stress creep recovery (MSCR). In addition, a laboratory-made inexpensive inorganic stabilizer was added to enhance the storability of the PE-modified asphalt. The results show that PE and asphalt are similarly compatible and form an S-C bond with an inorganic stabilizer. The resulting product's storage stability is enhanced via the cross linking between the PE and asphalt and the subsequent formation of a network structure. The segregation softening point increased from 2 °C to 45 °C with the increase in PE content, and the increase in RPE was more obvious than that of LDPE. The high-temperature failure of the 2–6% RPE-modified asphalt can reach 70 °C, while that of the 8% RPE-modified asphalt can reach 76 °C. Low-temperature performance was reduced slightly: the 8% PE-doping low-temperature failure temperature was −14.7 °C. The low-temperature performance was somewhat reduced, but it was still within a PG rating.

Keywords: recycled PE; modified asphalt; modification mechanism; physical property; rheological property; work performance



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1. Introduction

High-temperature rutting and low-temperature cracking are probably the most common hazards that occur when asphalt is used as a binder for the construction of roads. Consequently, various polymer modifiers have been used to enhance the capabilities of asphalt and thus reduce the incidence of damage [1–4]. Large quantities of plastic products are discarded annually. However, the disposal of waste plastics is extremely challenging. Recycled polymers serving as asphalt binder modifiers have broad application prospects [5–8]. By applying polymers to the modification of asphalt, the asphalt's properties are enhanced while the contribution to environmental pollution is reduced [9].

The main waste polymer products are polyethylene (PE) [3], polyvinyl chloride, polyethylene terephthalate, ethylene vinyl acetate copolymer [10], etc. Recycled polyethylene (RPE)-based plastics melt at about 150 °C [11], have better low-temperature properties [12,13], and are one of the most suitable waste plastics for use as asphalt modifiers [14]. Alghrafy et al. [15] investigated the influence of RPE on the rheology and fatigue properties

of modified asphalt and concluded that asphalt made from RPE has better resistance to rutting and fatigue cracking after hardening. Garg et al. [16] studied the rheological characteristics of PE-modified asphalt and confirmed that the incorporation of used PE improved the high-temperature rheological performance of the asphalt. Xin et al. [17] demonstrated that the inclusion of PE composites enhanced the mechanical performance of asphalt binders and caused the composite shear modulus to increase significantly. Desidery et al. [18] revealed that the addition of synthetic waxes to the RPE used for asphalt modification caused the resulting asphalt's rutting resistance factor and composite shear modulus to increase, resulting in excellent high- and low-temperature rheological properties. Mushtaq et al. [19] reported that the incorporation of RPE enhanced asphalt performance and provided better stability. Yao et al. [20] discovered that the modification of asphalt with rubber and PE improved the resulting asphalt's rutting resistance and low-temperature performance. PE is a linear polymer made from ethylene monomers via free radical polymerization [21]. It can be classified as high-density polyethylene [22], medium-density polyethylene [23], or low-density polyethylene (LDPE) based on its density. Among these types, LDPE has a low density and large molecular spacing due to the areas where the saturated aromatics in the asphalt readily penetrate into the molecular chain [24]. Compared to other types of PE, LDPE can be used to significantly enhance the rheological properties of asphalt while granting it excellent high-temperature performance [25–27], the latter of which is important for improving the high-temperature rutting resistance of asphalt pavement [28]. Yan et al. [29] showed that LDPE can enhance the high-temperature behavior of rubber-modified asphalt and improve the ability of asphalt to resist rutting. Liu et al. [30] noted that adding LDPE improved the rheological characteristics of asphalt at high temperatures and its cracking characteristics at low temperatures. Dalhat et al. [31] observed that treated LDPE-modified asphalt has excellent viscoelastic properties, rutting resistance, and cracking resistance. Although PE is beneficial for asphalt in terms of enhancing its high-temperature performance, the incorporation of large amount of PE is not possible, as increasing the amount of PE progressively worsens the storage stability of PE-modified asphalt [32], which greatly limits the widespread usage of PE-modified asphalt.

In recent years, domestic and foreign scholars have studied PE-modified asphalt. Fuentes-Audén et al. [33] found that low blends of used plastics could be used for paving, while high blends were suitable for use in housing. Fernandes et al. [34] increased the amount of waste plastic incorporated into asphalt, and it has been observed that this increase can improve the physical properties of the asphalt, including with respect to its softening point, elasticity, and viscosity. Kaemaka et al. [35] confirmed that increasing the modifier content had a negative impact on the compatibility between and low-temperature performance of the modifier and the asphalt. Furthermore, it has been pointed out that the compatibility of the modifier with the asphalt component is an important factor influencing the stability of modified asphalt during storage [36]. Modifiers are often incompatible with asphalt due to great differences in density, structure, and molecular weight. The addition of certain stabilizers, such as carbon black [37], nano-clay [38], and montmorillonite [39], to a modifier can improve the compatibility of the resulting asphalt [40], which, in turn, can improve the storage stability of the asphalt. Wang et al. [41] discovered that carbon black reduced the difference in density between SBS and asphalt, which increased the compatibility of SBS with asphalt. Yu et al. [42] and Ren et al. [43] found that nano-clay transformed into intercalated or exfoliated structures after interacting with asphalt components, which allowed for an enhancement in asphalt storage stability. Fang et al. [44] found that montmorillonite incorporation enhanced the compatibility of PE with asphalt, which improved the thermal stabilities of the modified asphalt. In addition, Liu et al. [45] used reactive waste binder particles to enhance the compatibility of PE with asphalt binders, thereby enhancing the storability of the PE-modified asphalt. Kong et al. [46] found that waste lubricant byproducts were beneficial to improving the compatibility of recycled binder powder with asphalt and enhancing the storage stability of binder-powder-modified asphalt. Sienkiewicz et al. [47] found that the addition of compounds that enable

physical and chemical interactions between the modifier and asphalt in modified asphalt can enhance the stability of modified asphalt. The optimal amount of admixture, the mechanism behind the modification of asphalt with LDPE, and storage stability issues need to be studied in more depth.

In this study, LDPE and RPE were blended into asphalt using a wet process to produce modified asphalt made using PE. The chemical structures of LDPE and RPE were studied through infrared spectroscopy, and the PE distribution state of the asphalt was analyzed using FM, revealing the modification mechanism of PE-modified asphalt. Physical property tests, DSR tests, and BBR tests were conducted to investigate the influence of PE on the physical properties, rheological properties, and other technical properties of asphalt, respectively. By adding stabilizers, the storage stability test was used to analyze the working performance of the PE-modified asphalt and address the lack of readily usable PE-modified asphalt.

2. Materials and Experimental Methods

2.1. Asphalt Cementing Material

The type of asphalt used was 70[#] (whose penetration is between 60~80 mm) asphalt. Basic properties of this type of asphalt are displayed in Table 1.

Table 1. Technical index of 70[#] asphalt.

Performance	Units	Value	Experimental Method
5 °C Ductility	cm	48.6	T0605
15 °C Ductility	cm	>100	T0605
Softening point	°C	48.5	T0606
Penetration	0.1 mm	70.7	T0604

2.2. LDPE and RPE

The type of LDPE used was commercial LDPE. RPE was obtained by crushing waste plastic bags and plastic bottles made of LDPE with a particle size of 3–4 mm. Table 2 lists the RPE's technical specifications.

Table 2. Technical index of LDPE and RPE.

PE	Appearance	25 °C Density (g/cm ³)	Melting Temperature/(°C)	Ash Content (%)	Haze (%)
LDPE	White particle	0.928–0.939	135	8.7	-
RPE	White slice	0.918–0.925	121	-	4.4

2.3. Stabilizer

The amount of stabilizer added was 4‰ (by weight of asphalt). This stabilizer was added to improve the working characteristics of the PE-modified asphalt. Table 3 summarizes the technical specifications of the stabilizers.

Table 3. Technical indices of stabilizers.

Technical Indexes	Appearance	25 °C Density (g/cm ³)	Melting Point (°C)	Ignition Point (°C)	Boiling Point (°C)	Solubility	Ash Content (%)
Test results	Yellow powder	1.99	115	260	450	Insoluble water	0.002

2.4. Production of PE-Modified Asphalt

The recycled polyethylene plastic bottles and plastic bags were crushed using a crusher, thereby reducing the particle size of the bottles and bags to 3–4 mm. The modification

conditions were determined with reference to a vast body of experimental experience. A wet process was used to produce PE-modified asphalt. A total of 400 g of asphalt was heated to 140 °C in an oven to reach a fluid state and stirred with a high-speed shear mixer, while the speed was maintained at 5000 rpm. The temperature was kept at 185 °C, and the modifier concentrations were 0, 2%, 4%, 6%, and 8% (by weight of asphalt). High-speed shearing was performed for 1 h, and the stabilizer was added after the modifier was completely dissolved and stirred evenly. Then, high-speed shearing was conducted for 1 h, the mixture was cooled down to around room temperature.

2.5. Experimental Methods

2.5.1. FTIR Test

The PE was dissolved in CS₂, and the resulting PE-CS₂ solution was dropped onto a KBr wafer. The KBr wafer was placed under an incandescent lamp until it was completely volatilized. The scan count was set to 32 with a waveband scan range of 4000–500 cm⁻¹. In addition, PE-modified asphalt with the addition of laboratory-made inorganic additives and that without such additives was prepared as intended.

2.5.2. FM Test

In this test, 2 g of modified asphalt was deposited into a glass and placed into a 160 °C oven until modified flow was reached in the flat glass. After cooling to room temperature, the sample was placed onto a microscope slide. Then, the focal length of the microscope was coarsely and finely adjusted until it could be clearly observed. The magnification factor applied was 10×.

2.5.3. Physical Performance Test Method

A softening point test of PE-modified asphalt with and without laboratory-made inorganic additives was conducted according to the rules specified in JTGE20/T0606-2011, and the heating rate applied was 5 ± 0.5 °C/min. A penetration test of the PE-modified asphalt with laboratory-made inorganic additives was performed according to the rules outlined in JTGE20/T0604-2011. A standard test needle with a mass of 100 g was used. The penetration time was 5 s, and the temperature of the test was 25 °C. The PE-modified-asphalt-with-laboratory-made-inorganic-additives test was conducted according to the rules outlined in JTGE20/T0605-2011. The test was conducted at 5 °C.

2.5.4. DSR Test

The complex modulus and phase angle of the PE-modified asphalt were scanned using DSR, and the DSR test interval for PE-modified bitumen was between 52 °C and 88 °C. The diameter of the upper and lower plates was 25 mm. The gap was 1.0 mm. The heating rate of the sample was 2 °C/min, and the temperature accuracy was ±0.01 °C.

2.5.5. BBR Test

Test samples with a length of 127 ± 2.0 mm, a height of 6.35 ± 0.05 mm, and a width of 12.07 ± 0.05 mm were prepared. The load applied during the experiment was 980 ± 50 mN, and the deformation of the specimen was controlled in the range of 0.08–4 mm [48]. The respective performance characteristics of the RPE- and LDPE-modified asphalt were tested. The test temperatures were −12, −18, and −24 °C.

2.5.6. MSCR Test

Using DSR, 10 cycles of creep recovery tests were carried out at 64 °C under shear stress of 0.1 KPa and 3.2 KPa. The creep and recovery times were 1 s and 9 s, respectively. J_{nr} is the irrecoverable creep compliance, and J_{nr-diff} is the rate of change in irrecoverable creep compliance with stress. According to the collected strain, J_{nr} under different amounts

of stress and the change rate of J_{nr} with stress $J_{nr-diff}$ were calculated. The calculation method is as follows:

$$J_{nr} = \frac{9s \text{ continuous deformation after recovery} - \text{initial deformation}}{\text{shear stress}} \quad (1)$$

$$J_{nr-diff} = \frac{J_{nr(3.2KPa)} - J_{nr(0.1KPa)}}{J_{nr(3.2KPa)}} \quad (2)$$

2.5.7. Storage Stability Tests of Modified Asphalt

A storage stability test of the PE-modified asphalt with and without laboratory-made inorganic additives was conducted. The test adhered to the H/T0660-99 guidelines. An SA thin-walled cylindrical tube with a diameter of 2.54 mm and a height of 14 cm with an upper opening was used. After loading 50 g of PE-modified asphalt, the opening was closed, and the tube was placed vertically in an oven at 160 °C. After 48 h of heating at a constant temperature, the sample was taken out and quickly placed vertically in a refrigerator for 4 h. The PE-modified asphalt with and without laboratory-made inorganic additives was divided into three equal sections, and the difference between the softening points of the upper and lower sections was tested.

2.6. Technical Route

The experiment was conducted using the scientific method, and the process is described in Figure 1.

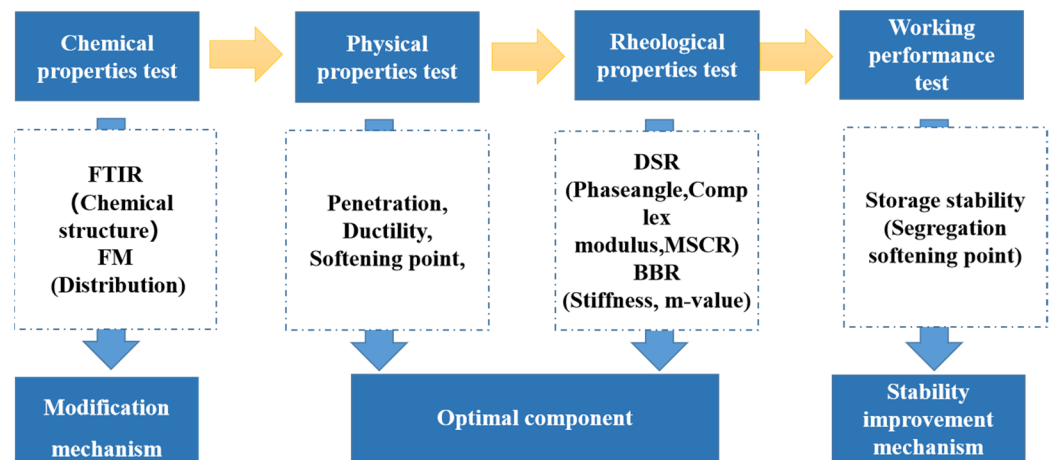


Figure 1. Technology road map.

3. Result and Discussions

3.1. Modification Mechanism of PE-Modified Asphalt

3.1.1. Chemical Structure Analysis of PE and Asphalt

Figure 2 presents the FTIR results regarding LDPE, RPE, and the asphalt they modified. In Figure 2, 2918 cm^{-1} is the asymmetric stretching vibration absorption peak of $-\text{CH}_2-$ in RPE and LDPE, 2850 cm^{-1} is the symmetric stretching vibration absorption peak of $-\text{CH}_2-$, and 1472 cm^{-1} is the bending vibration absorption peak of $-\text{CH}_2-$. The components of the two different types of PE are the same. The relative peak area of the asymmetric stretching vibration absorption peak of $-\text{CH}_2-$ at 2918 cm^{-1} decreased from 0.66 to 0.55 compared with that of the matrix asphalt, and the relative peak area of $-\text{CH}_2-$ at 2850 cm^{-1} also decreased from 0.35 to 0.31, while the relative peak area of the bending vibration absorption peak of $-\text{CH}_2-$ at 1472 cm^{-1} increased from 0.87 to 0.91, indicating that after the addition of PE, the aromatic components in PE and asphalt intercalate, interpenetrate, and adsorb, and the

asphalt and PE form an interpenetrating network, resulting in the change of $-CH_2-$ from exhibiting a stretching vibration to a bending vibration.

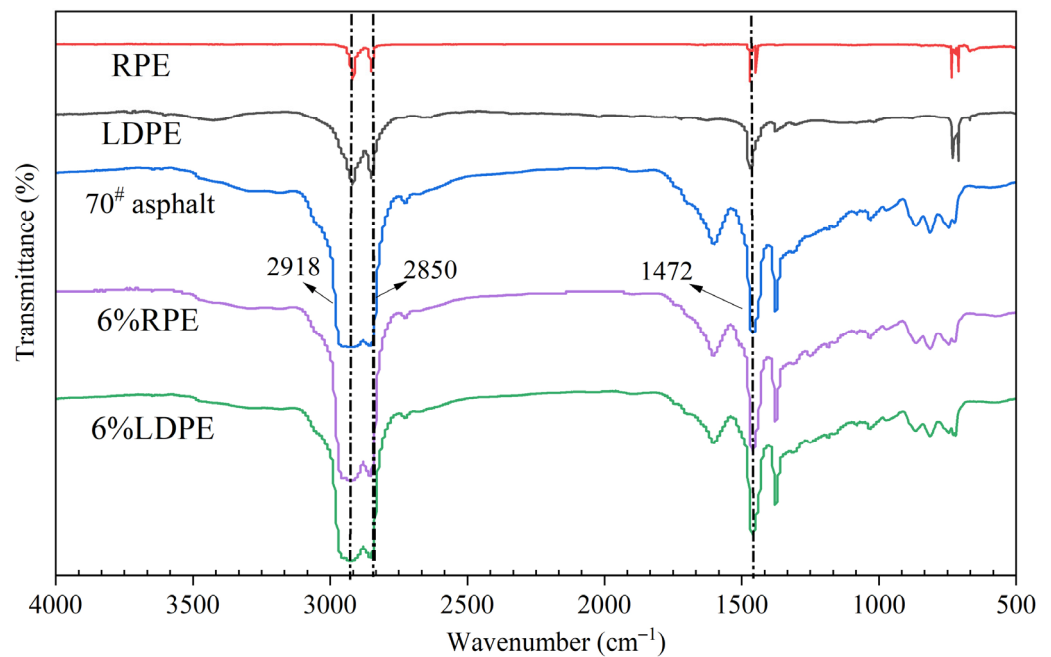


Figure 2. The FTIR of LDPE, RPE, and the asphalt they modified.

3.1.2. Distribution of RPE in Asphalt

Figure 3 presents fluorescence photos of the RPE-modified asphalt and an RPE distribution analysis diagram. It is evident from the figure that RPE-modified bitumen is a multi-phase dispersion system, RPE is dispersed in the asphalt phase, and the white regions in Figure 3e–h are a polymer-rich phase. As the RPE content rose, the number of white regions gradually increased, along with the fluorescence intensity, but the agglomeration of asphalt polymer [49,50] intensified. Under the same area (1 cm^2), the bright-yellow parts of Figure 3a–d accounted for 3.23%, 5.15%, 13.52%, and 23.42%, respectively. RPE is uniformly dispersed. RPE easily disperses because of its sheet shape, low density, high melt flow rate, and the good flexibility of its polymer chain. Its molecular spacing is large, and small molecules in asphalt easily penetrate its molecular network, thus forming a uniform system.

3.2. Effect of PE on Physical Properties of Asphalt

Figure 4 presents the test results regarding the PE-modified asphalt's physical properties. As shown in Figure 4, the softening point tends to increase as the LDPE and RPE content increases. Between the two, the improvement of the softening point of RPE is more significant than that of LDPE, reaching more than $70 \text{ }^\circ\text{C}$ at 6% content, and the increase is more than 40% greater than that of asphalt. There is a noticeable decrease in the ductility of the asphalt associated with the increase in modifier concentration. However, the ductility of the LDPE- and RPE-modified asphalt is better when their content is less than 6%. Penetration was inversely proportional to the LDPE and RPE content. A 21% reduction in penetration was achieved for the modified asphalt with 6% PE content. Since PE can achieve melt flow at high temperatures, it exhibits linear polymer properties at temperatures above $130 \text{ }^\circ\text{C}$. PE and the aromatic components in asphalt are mutually soluble and adsorbed via high-temperature shearing. With the gradual incorporation of PE, asphalt and plastic form an interpenetrating network [51], forming two continuous phases. The polymer chains are similarly soluble, intertwined, and cross-linked. As a result, the thermal stability of modified asphalt is improved, while the molecular fluidity of asphalt is lessened, which leads to the hardening of asphalt, a significant increase in viscosity and

softening points, and a reduction in penetration [52]. However, the incorporation of PE makes the asphalt more brittle at low temperatures. Especially under the action of tensile stress, some uneven parts of the asphalt's surface and interior produce fine holes, which gradually develop into fine lines. When extended, the molecular chain breaks [53]. The optimum content of PE is 6%.

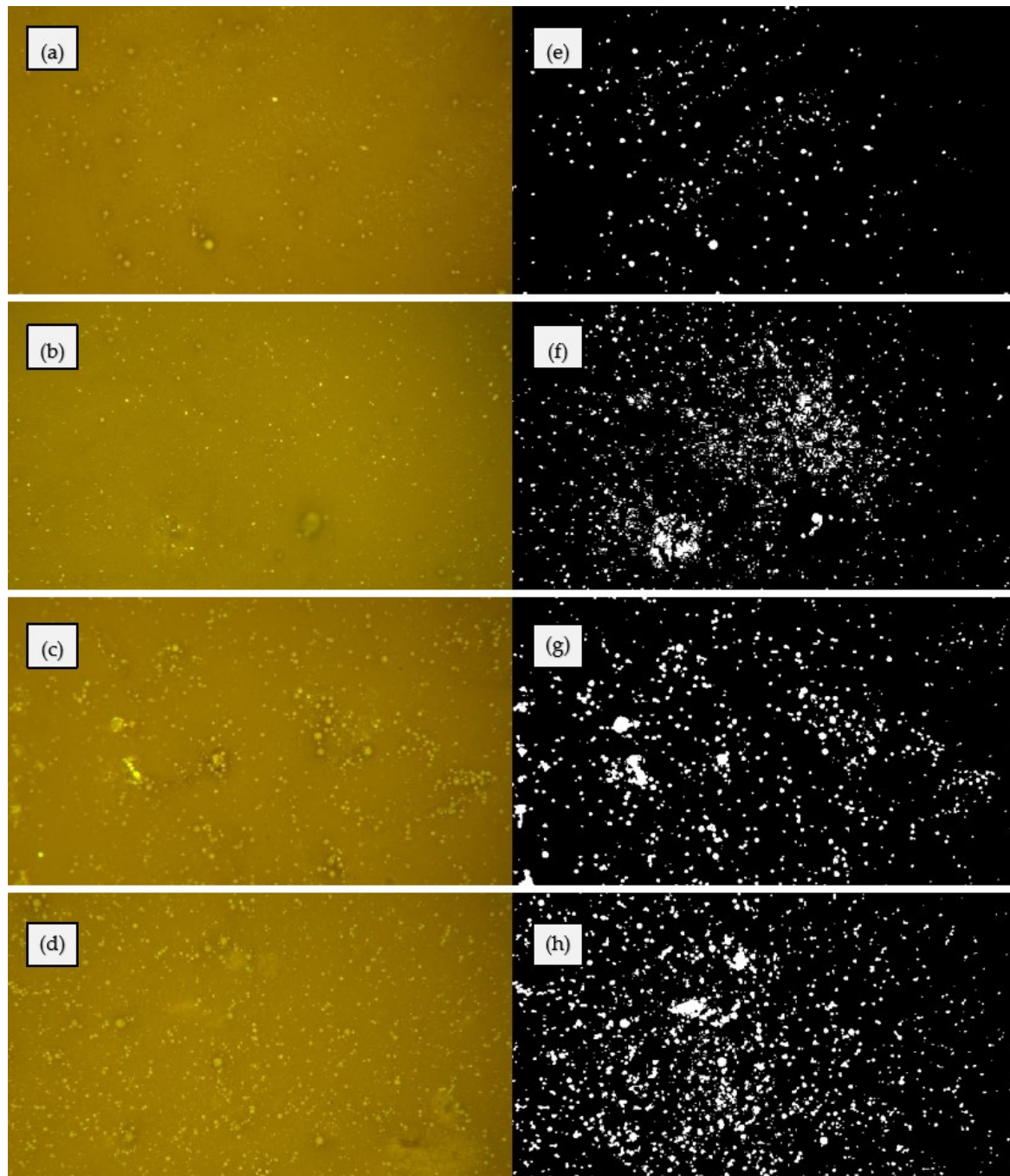


Figure 3. Fluorescence images of different amounts of RPE and quantitative analysis of RPE ((a) 2% RPE; (b) 4% RPE; (c) 6% RPE; (d) 8% RPE; (e) 2% RPE; (f) 4% RPE; (g) 6% RPE; (h) 8% RPE).

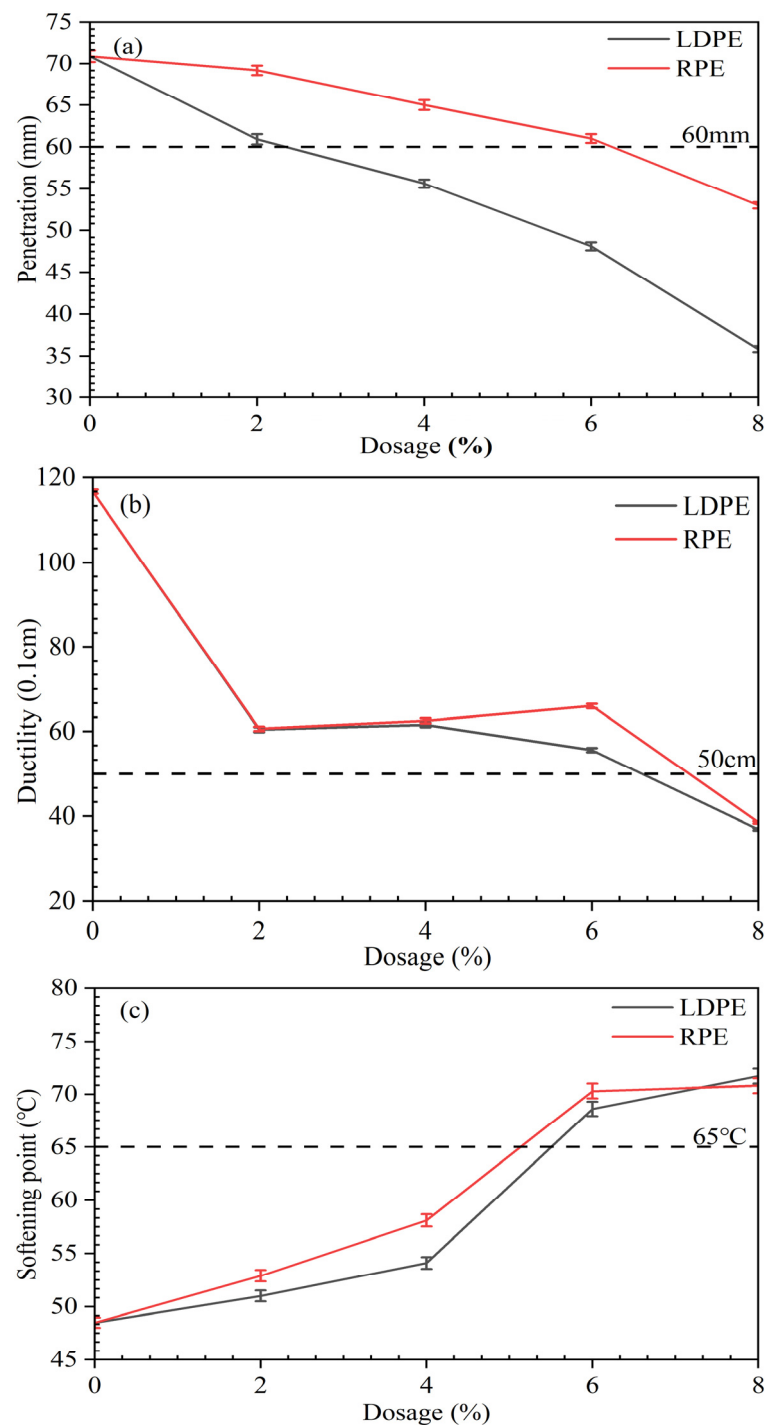


Figure 4. Test results regarding PE-modified asphalt's physical properties ((a) penetration; (b) ductility; (c) softening point).

3.3. Effect of PE on Rheological Properties of Asphalt

3.3.1. Effect of PE on High-Temperature Rheological Properties of Asphalt

Figures 5 and 6 present the test results regarding the phase angle (δ) and complex modulus (G^*) of the PE-modified asphalt with different shares of LDPE and RPE, respectively. In Figures 5 and 6, it can be observed that with the addition of LDPE and RPE, δ gradually decreases to a value smaller than the δ of asphalt. Thus, the elastic recovery ability of asphalt gradually worsens, and the asphalt is less capable of resisting rutting deformation. When the content is 6%, δ is optimal. The complex modulus of the modified asphalt increases with the increase in the PE dosage. When the content is 6%, G^* is optimal,

and the optimal content is associated with δ . The reason for this association is that the molecules in the asphalt can move more easily and are more prone to deformation. After adding LDPE and RPE, crosslinking occurs between molecules, the number of macromolecular substances increases, molecular movement becomes more difficult, resistance to deformation is enhanced, the complex modulus increases, and the phase angle decreases. The high-temperature failure temperature was calculated using the rutting factor (the result is shown in Table 4). The results show that the high-temperature failure temperatures of LDPE and RPE increased with the increase in LDPE (or RPE) content and reached a maximum at 8% content.

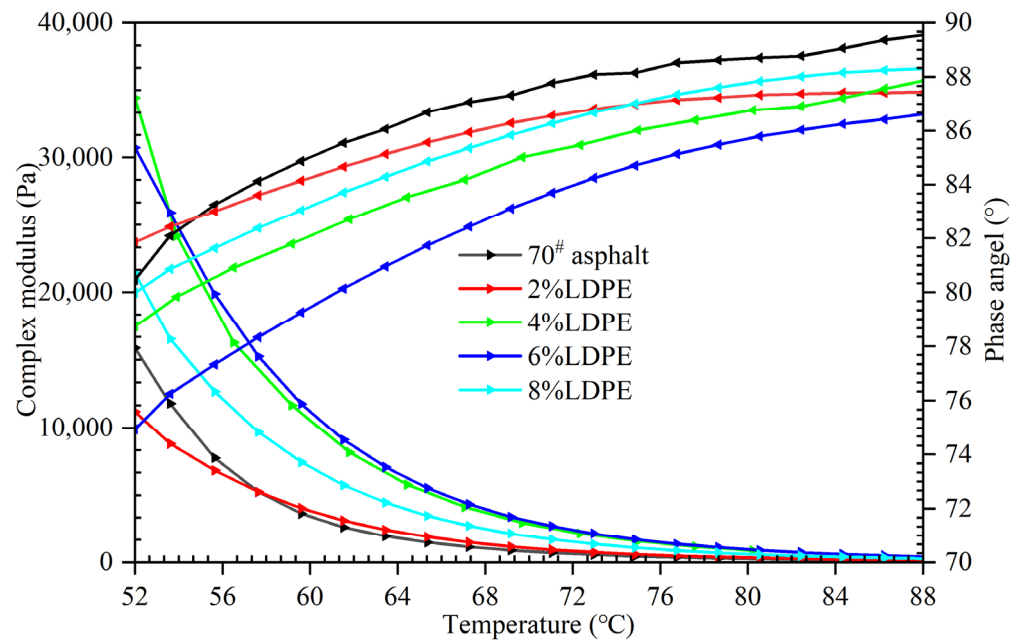


Figure 5. Testing of G^* and δ for different proportions of LDPE-modified asphalt.

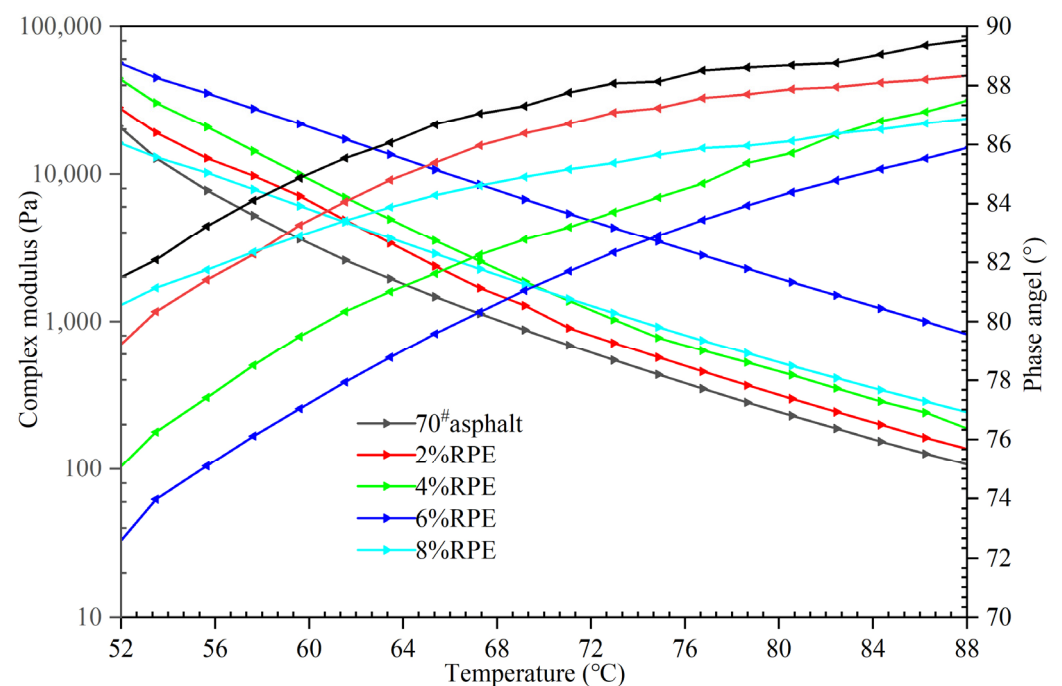


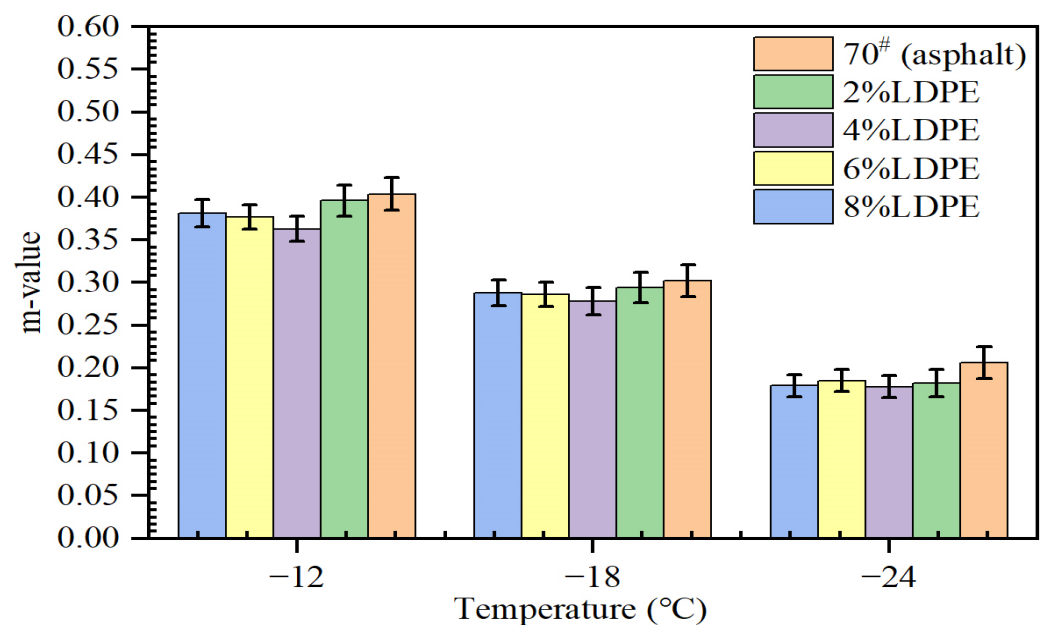
Figure 6. Testing of G^* and δ for different proportions of RPE-modified asphalt.

Table 4. Failure temperature determined according to rutting parameter.

Modifier	Parameter	Dosage (%)				
		0	2	4	6	8
RPE	Failure temperature (°C)	54.7	70.2	73.2	75.2	76.7
	High-temperature PG grade (°C)	52	70	70	70	76
LDPE	Failure temperature (°C)	54.7	55.6	59.2	60.6	62.8
	High-temperature PG grade (°C)	52	52	58	58	58

3.3.2. Effect of PE on the Low-Temperature Rheological Behavior of Asphalt

Data on the m and S values for different compositions of the LDPE-modified asphalt are presented in Figures 7 and 8. The data for the m and S values of the RPE-modified asphalt at various dosages are presented in Figures 9 and 10. Table 5 presents the low-temperature failure temperature of the LDPE- and RPE-modified asphalt, which is calculated using the S and m values. At -12 °C, the S values of the asphalt with different dosages are all less than 300 MPa, and the m values of the asphalt are all larger than 0.300. The smaller m value for the modified asphalt indicates a reduction in low-temperature performance with the addition of LDPE and RPE. At -18 °C, the S values of the asphalt are all greater than 300 MPa, and the m value of the modified asphalt is less than 0.300. The larger S -value of the modified asphalt than that of the virgin asphalt indicates that the modified asphalt is less resistant to cracking at low temperatures than virgin asphalt and becomes less capable of releasing stress. The -24 °C and -18 °C results are consistent. They also show that asphalt is more prone to fracture at this temperature. Under the optimum dosage for rheology corresponding to high temperatures, the modified asphalt presents a higher S value than that of asphalt, but this value is not in accordance with the specifications. Table 5 suggests that the failure temperatures of the two PE-modified asphalt types increase gradually with an increasing PE content and are greater than those of the original asphalt but do not exceed one PG grade, indicating that the low-temperature reliability of the PE-modified asphalt has decreased.

**Figure 7.** The m values of LDPE-modified asphalt under different dosages.

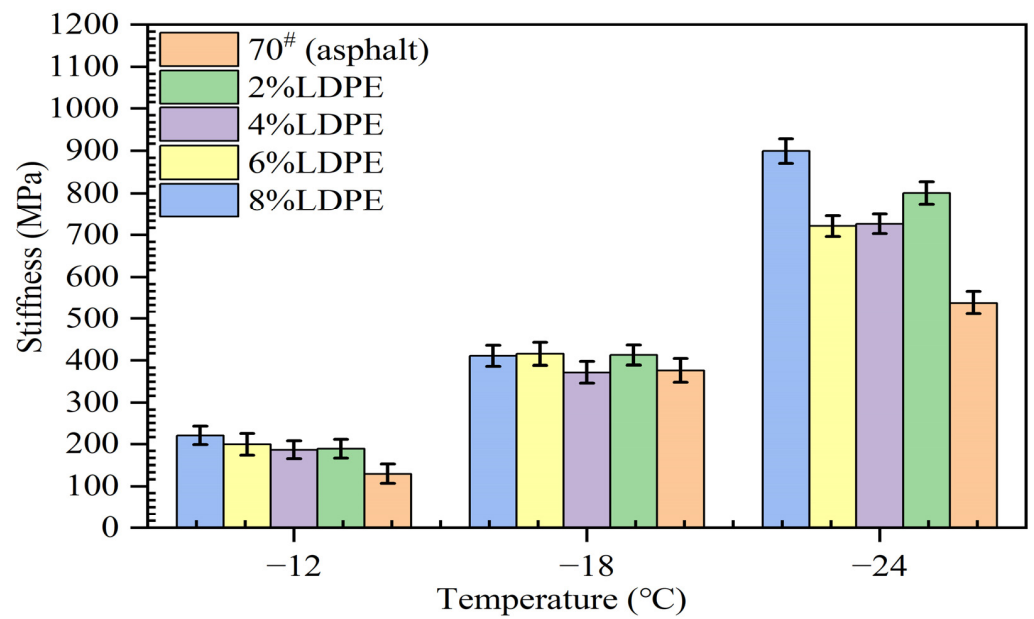


Figure 8. S values of LDPE-modified asphalt under different dosages.

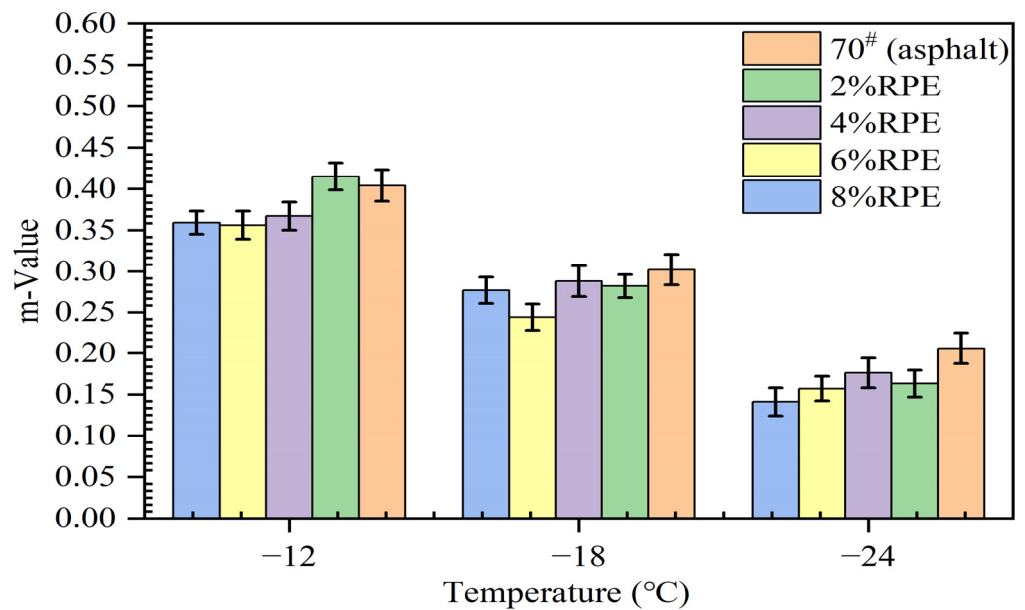


Figure 9. The m values of RPE-modified asphalt under different dosages.

Table 5. Low-temperature failure temperature.

Modifier	Parameter	Dosage (%)				
		0	2	4	6	8
RPE	Low-temperature failure temperature (°C)	-16.1	-15.4	-15.1	-15.0	-14.7
	Low-temperature PG grade (°C)	-18	-16	-16	-16	-16
LDPE	Low-temperature failure temperature (°C)	-16.1	-15.2	-15.1	-14.8	-14.8
	Low-temperature PG grade (°C)	-18	-16	-16	-16	-16

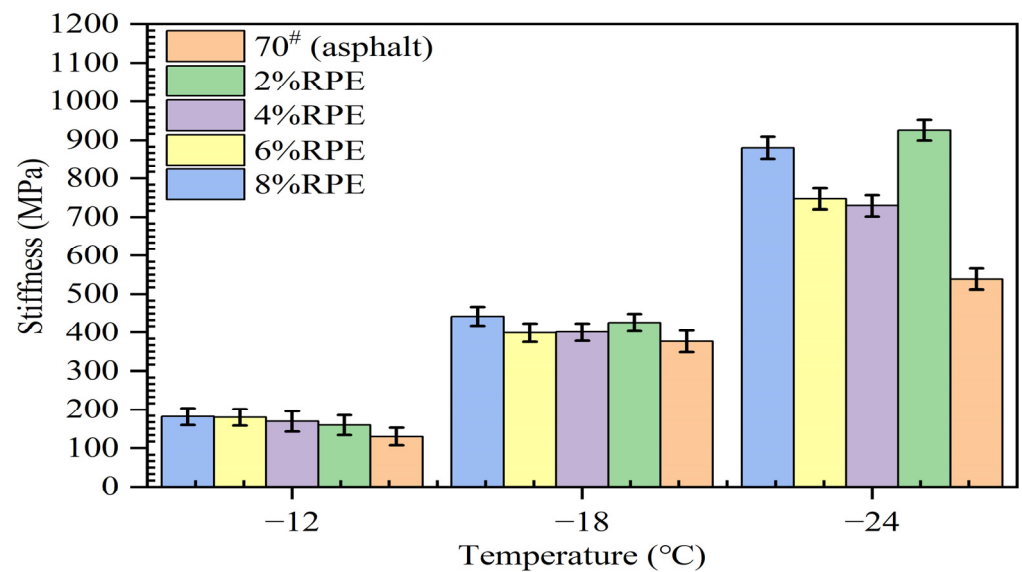


Figure 10. S values of RPE-modified asphalt under different dosages.

3.3.3. Impact of PE on the Creep Characteristics of Asphalt

Figures 11 and 12 indicate the strain variation at different stress levels for 70# asphalt and the PE-modified asphalt. The results show that the cumulative strain of 70# asphalt is the largest. With the increase in PE content, the cumulative strain of the modified asphalt decreases gradually. The strain increases again when the PE content reaches 6%. This is because PE enhances the modulus of elasticity of the asphalt material and significantly increases the recoverable deformation capacity of the asphalt, allowing the modified asphalt to achieve excellent high-temperature performance. If the content is too high, PE polymerization decreases elasticity.

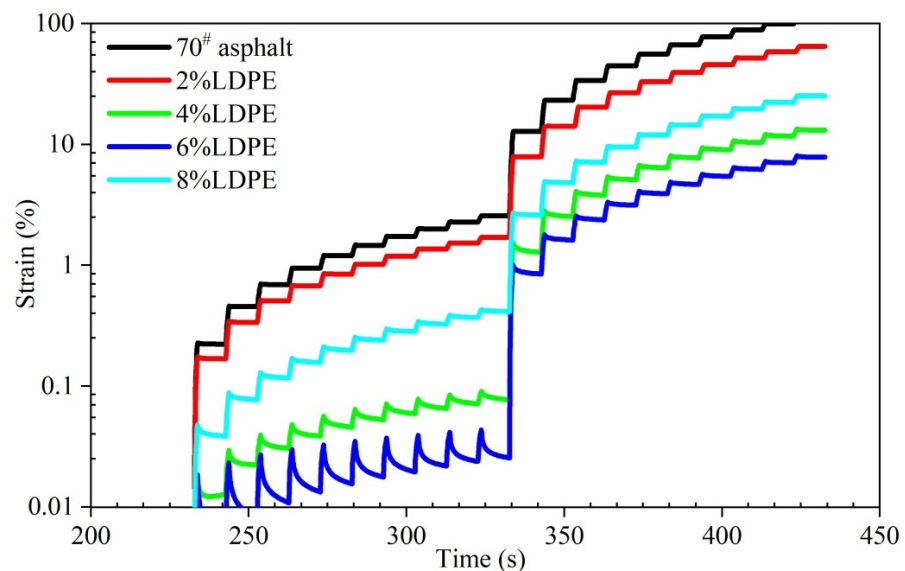


Figure 11. Creep of LDPE-modified asphalt with different proportions of LDPE.

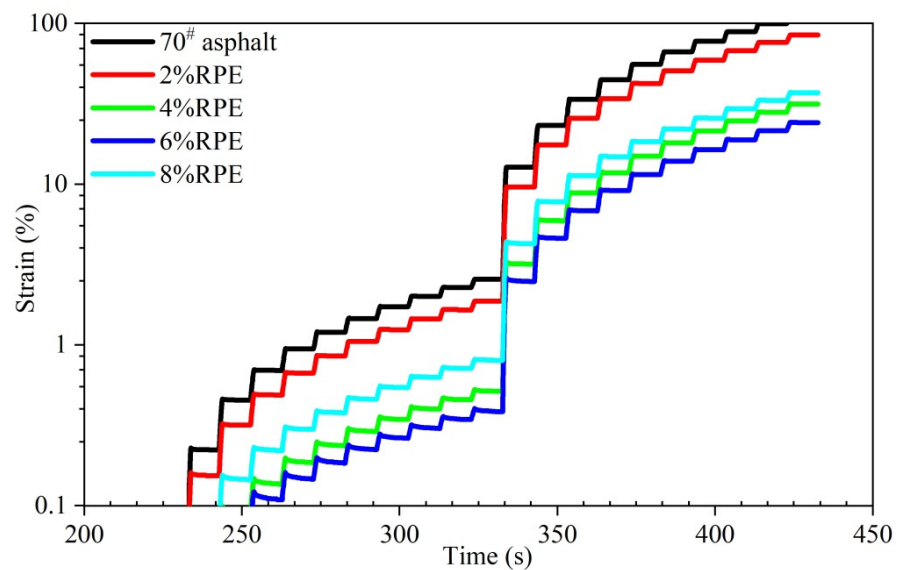


Figure 12. Creep of RPE-modified asphalt with different proportions of RPE.

As can be seen in Figures 13 and 14, for both PE-modified types of asphalt, J_{nr} at 3.2 KPa is greater than J_{nr} at 0.1 KPa. This result shows that J_{nr} increases with the increase in shear stress; that is, shear stress affects the resistance of asphalt to high-temperature deformation. With the increase in modifier content, the J_{nr} under two stress levels showed a downward trend. This result suggests that viscous deformation decreases as the content of the modifier increases. Modifier content is positively correlated with resistance to high-temperature deformation within a certain range, with the resistance to high-temperature deformation reaching a peak at 6% modifier content. For both modified types of asphalt, the bitumen trends are the same, and the $J_{nr-diff}$ values increase with the increasing modifier content. The higher the content of the modifier, the more resistant the resulting asphalt is to high-temperature deformation, but cohesive deformation is more dependent on shear stress.

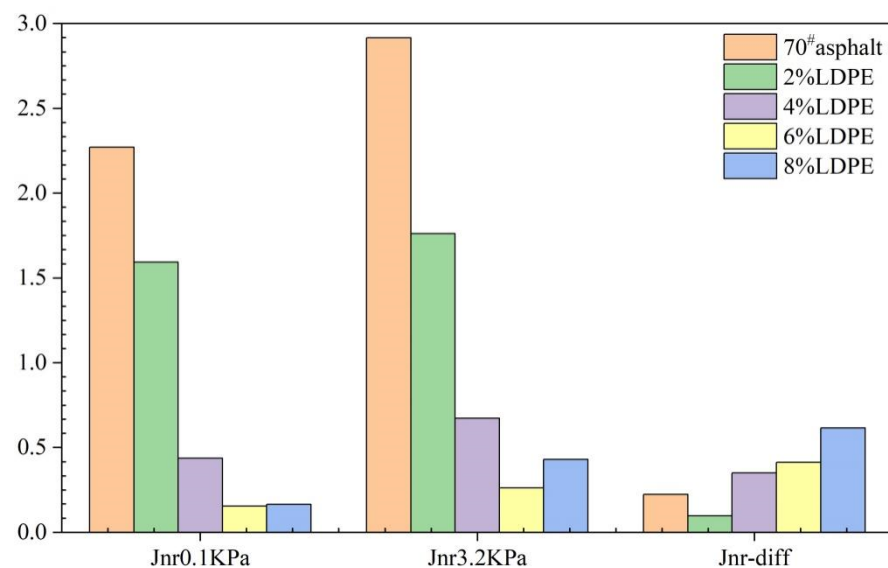


Figure 13. Creep results regarding LDPE-modified asphalt with different proportions of LDPE.

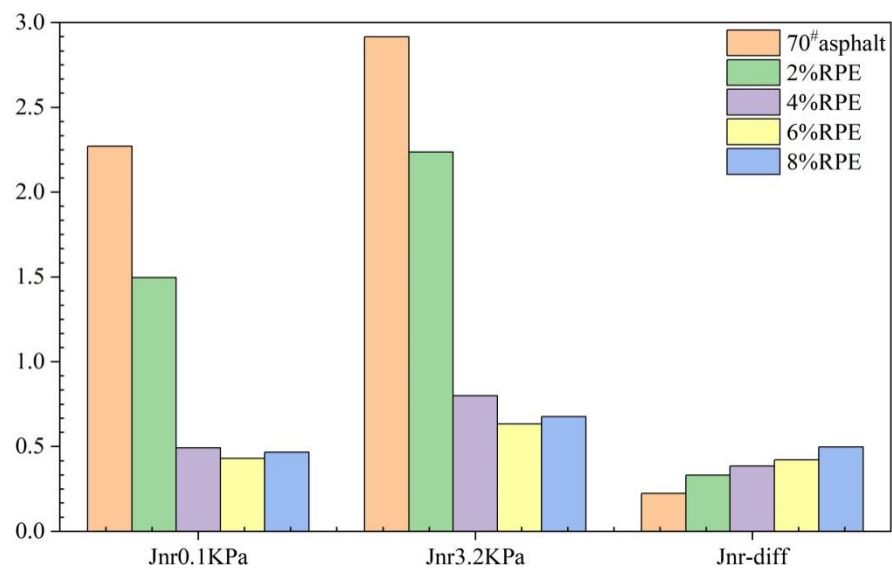


Figure 14. Creep results regarding RPE-modified asphalt with different proportions of RPE.

3.4. Stability Improvement Method for PE-Modified Asphalt

Figure 15 presents the results regarding the softening point of the modified asphalt with and without laboratory-made inorganic additives with different proportions of LDPE and RPE. As can be seen in Figure 15, the difference in the dissociation softening point of the modified asphalt after the addition of 2% RPE and LDPE is within 2.5 °C, which is in accordance with the specifications. After adding more than 4% RPE and LDPE, the softening point difference after segregation reaches more than 30 °C, indicating that the modified asphalt exhibits serious segregation and poor storage stability. The density of LDPE and RPE should be between 0.91 and 0.94, while the density difference with respect to asphalt is large, resulting in serious segregation. After adding 4% inorganic stabilizer, the segregation softening point of the PE-modified asphalt greatly reduced. The segregation softening point of the 6% RPE content asphalt decreased from 45.65 °C to 1.45 °C, thereby meeting the working performance requirements. The density of the stabilizer was 1.99 g/cm⁻³, and the density of the PE modifier greatly improved, making it difficult for polymers to float in the asphalt.

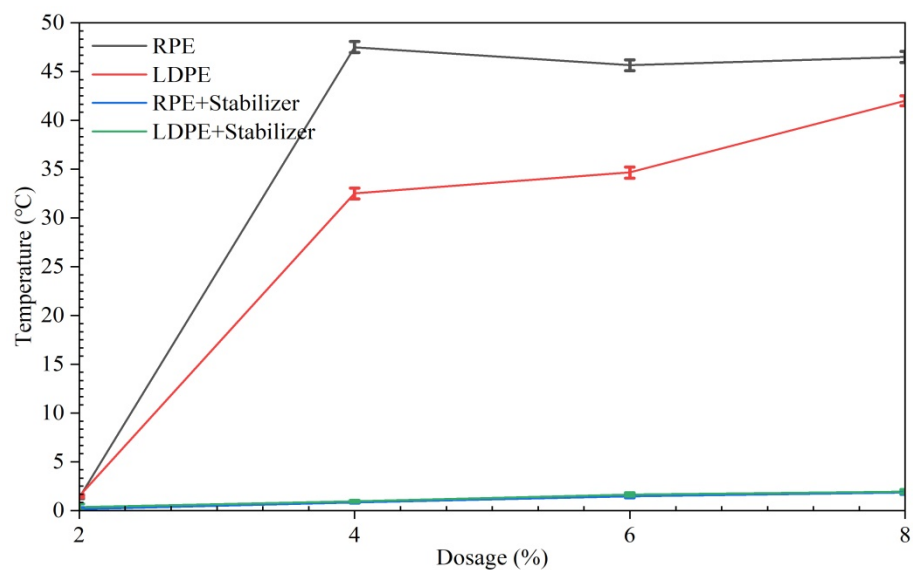


Figure 15. The segregation softening point of LDPE- and RPE-modified asphalt before and after adding stabilizers.

Figure 16 illustrates the infrared spectrum of the asphalt with a 6% PE dosage and a 4% inorganic stabilizer dosage. According to Figure 16, there is S-C bond absorption peak at 604 cm^{-1} ; the PE-modified asphalt contains such a bond, while the matrix asphalt does not. This result shows that the sulfur in the inorganic stabilizer can form S-C bonds with PE to form a cross-linked structure, allowing PE to be stably dispersed in the asphalt.

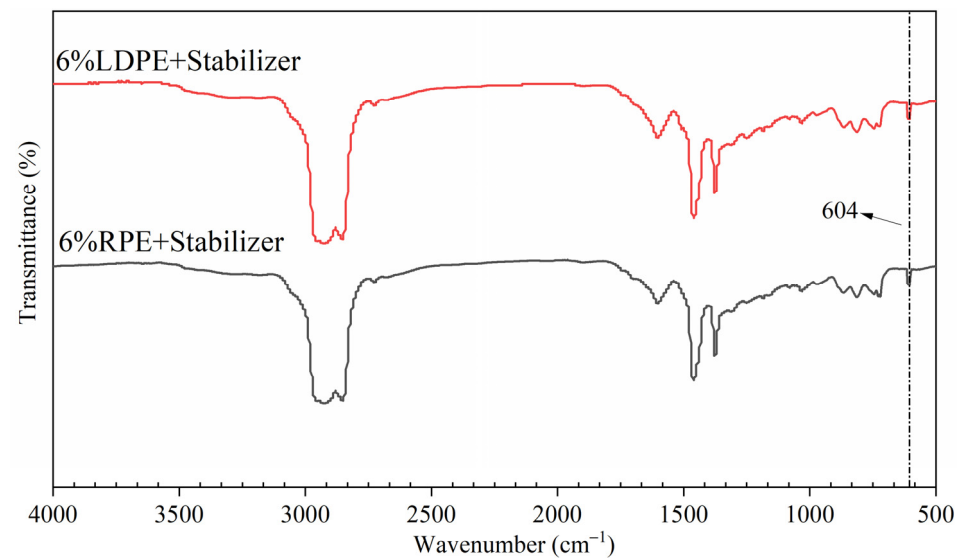


Figure 16. Infrared spectra of 6% PE-modified asphalt with 4% inorganic stabilizer.

4. Conclusions

In this paper, the chemical structures of LDPE- and RPE-modified asphalt and the distribution of RPE were studied. The effects of PE and its content on the physical properties, high- and low-temperature rheological properties, and creep properties of modified asphalt were analyzed. In addition, inorganic stabilizers were added to analyze whether the working performance met the regulatory requirements. The following conclusions have been drawn:

(1) Upon observing the $-\text{CH}_2-$ vibration absorption peaks at 2918 cm^{-1} , 2850 cm^{-1} , and 1472 cm^{-1} in the infrared spectrum, it is evident that the structures of LDPE and RPE are basically the same. According to the fluorescence spectrum, the two modifiers are uniformly dispersed in the asphalt, and the 6% content of RPE accounts for 13.52%, excluding the effects of structure and the shear forces on the PE-modified asphalt's properties. Asphalt can produce stable chemical bonds with 6% PE and stabilizer.

(2) The addition of LDPE and RPE helps to improve the high-temperature stability of asphalt but is detrimental to ductility and penetration. The softening point of the high-temperature performance index of the asphalt is obviously improved, reaching more than $70\text{ }^{\circ}\text{C}$ at 6% content, and the ductility of the asphalt is reduced, but it is still more than 50 cm at 6% content. In the range investigated in this study, penetration decreases with an increasing PE admixture, and the penetration of 6% content presents a 27% decrease.

(3) Under the action of high temperature and stirring, RPE (LDPE) can be uniformly dispersed in asphalt. Asphalt colloids are connected by RPE (LDPE). At the same time, RPE (LDPE) absorbs oil swelling in asphalt, causing a relative increase in the asphalt content, changing the colloidal structure and viscoelasticity of the asphalt, and enhancing the ability of asphalt to resist external forces. The continuous network structure formed by RPE (LDPE) in asphalt limits the fluidity of the asphalt colloidal system, decreases the deformation ability of asphalt, and raises the deformation resistance and strength of asphalt at high temperatures. The high-temperature failure temperature of the 6% RPE content asphalt can reach $75.2\text{ }^{\circ}\text{C}$. The low-temperature performance of RPE (LDPE) is poor, and a performance change is not obvious after a small amount is incorporated. At $-24\text{ }^{\circ}\text{C}$,

the S and m values do not conform to the specifications, but the low-temperature failure temperature is still within a PG grade.

(4) The cumulative strain of the modified bitumen decreases as the PE content increases, reaching the best value when the content is 6%. Upon increasing the amount of PE, the asphalt's high-temperature performance worsens, which echoes the results regarding the high-temperature modulus and phase angle.

(5) By adding 4% stabilizer, the segregation softening point can reach 2.5 °C, and the working performance meets the working requirements. On the one hand, due to the high density of the inorganic stabilizer, the density of the modifier increases after the addition of the stabilizer, which makes it difficult for the polymer to float in the asphalt. On the other hand, the infrared spectroscopy results showed that 604 cm⁻¹ is the S-C bond absorption peak. The inorganic stabilizer and PE form S-C bonds to, in turn, form a cross-linked structure, allowing the PE to be stably dispersed in the asphalt. Adding a small amount of stabilizer largely solves the problem wherein PE-modified asphalt must be used first and provides promising prospects for the wide application of PE modification. In general, the addition of 6% RPE and 4% stabilizer can induce the best degree of crosslinking with asphalt and provide good storage stability.

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