

## Article

# Evolution of Rheological and Microscopic Properties of Asphalt Binders under Fuel Corrosion

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**Abstract:** Vehicle fuel leaks can adversely affect the performance of asphalt pavements. To study the mechanisms of fuel corrosion damage in asphalt, four asphalt binders were selected in this study, and the evolution of their rheological and microscopic properties was investigated. Fuel corrosion caused continuous mass loss in asphalt binders. Base asphalt lost more than 50% of its mass after 24 h of fuel corrosion, while modified asphalts had better resistance. According to dynamic shear rheometer tests and multiple stress creep recovery tests, modifiers improved the high-temperature rheological properties of these asphalt binders. As the degree of fuel corrosion deepened, the indexes characterizing the high-temperature performance deteriorated. Rubber-modified asphalt showed the best resistance to high-temperature deformation, while the performance of LDPE-modified asphalt was more stable. In contrast, fuel corrosion improved the resistance of asphalt binders to low-temperature cracking to some extent: the creep strength (S) decreased as the creep rate (m) increased, and the resistance of SBS-modified asphalt to low-temperature cracking was optimal, with a 36% decrease in S-value after 24 h of fuel corrosion. Fourier transform infrared spectroscopy tests showed that diesel corrosion was a process of this physical dissolution, with no change in the chemical functional groups. Meanwhile, by using fluorescence images and analyzing the four-component test results, we found that fuel corrosion disrupted the stabilized structure formed by the modifiers, and the heavy components in the asphalt binders were converted into light components. This study reveals the evolution of the rheological and microscopic properties of asphalt under fuel corrosion, which can provide a reference for the optimization of fuel corrosion resistance in asphalt pavement.

**Keywords:** asphalt binder; fuel corrosion; rheological; microscopic morphology; physical component



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## 1. Introduction

### 1.1. Background

The petroleum asphalt commonly used in road engineering is a by-product of crude oil distillation, and its chemical composition is similar to that of light oil, including polymer hydrocarbons and non-hydrocarbons, among other things. It is easily soluble in organic solvents such as gasoline and diesel fuel [1]. As the most common type of pavement, asphalt concrete pavement is highly susceptible to corrosion from vehicle fuel spills caused by traffic accidents and other factors. After being contaminated, the asphalt and aggregates have reduced adhesion [2,3], resulting in the deterioration of the gradation and integrity of the mixture, and early damage such as spalling and the loosening of the asphalt pavement

can occur. Cao [4] monitored diesel-contaminated pavements by using a highway in the Guangdong Province of China as a case study and found that diesel leakage had a greater effect on the skid resistance, high-temperature stability, and water stability of pavements, which affected their service lives. Thus, fuel corrosion is a damaging factor asphalt pavements face that deserves attention.

### 1.2. Literature Review

Studies on the effect of fuel corrosion on the performance of asphalt and asphalt mixtures have been conducted mainly by comparing changes in the mechanical properties of asphalt mixtures before and after fuel corrosion. To evaluate the extent of the effect of diesel leakage on asphalt concrete pavements, their mass loss, adhesive properties, rutting resistance, and resistance to water damage have been evaluated [2–9]. For example, Chen [5] investigated the effect of gasoline and diesel corrosion on the high-temperature performance of asphalt mixtures using Marshall specimens and rutted plate specimens and found that the oil erosion process significantly reduces the Marshall stability and dynamic stability of asphalt mixture specimens. Zhang [6] found that the properties of asphalt and asphalt mixtures deteriorate significantly after oil corrosion. Moreover, diesel and gasoline affect asphalt and asphalt concrete to different extents [5–7].

Regarding how fuel corrosion resistance is evaluated, in addition to common performance tests such as Marshall stability tests and rutting tests, new indexes have been proposed to characterize the resistance of asphalt and asphalt mixtures to fuel corrosion [10–16]. Felice Giuliani [10] concluded that solubility and rheology indexes can better differentiate their resistance to fuel corrosion. To enhance the fuel corrosion resistance of asphalt and asphalt mixtures, asphalt has been modified by blending with polymers such as SBS [6], rubber crumbs, synthetic wax [11,12], and other fuel-corrosion-resistant agents [13–15], which can be analyzed in terms of their high-temperature performance and low-temperature performance.

However, the current research is not sufficient to fully investigate the mechanisms of fuel corrosion damage in asphalt and to establish an evaluation system for it. The rheological properties of asphalt play a decisive role in the performance of pavements in use [17]. According to the principle of similar solubility, fuel corrosion will inevitably have an impact on the rheological properties of asphalt. The microscopic properties of a substance determine its macroscopic properties, and changes in the microscopic morphology and structure of asphalt due to fuel corrosion are closely related to its basic rheological properties. Previous studies have not involved the rheological and microscopic properties of asphalt after fuel corrosion, making it difficult to quantify the extent of fuel damage to the serviceability of asphalt pavement.

In general, modifying asphalt is an effective means of improving its performance. Modifiers are mainly polymers, resins, and rubbers. Asphalt can be blended with SBS, a kind of polymer, to improve its high-temperature fluidity, low-temperature ductility, thermal stability, and other road performance factors [18]. Although the low-temperature performance of low-density polyethylene (LDPE)-modified asphalt needs to be further improved, its excellent environmental and economic benefits make it one of the most commonly used materials in road engineering [19]. Given the characteristics of rubber particles, rubber-modified asphalt has a good elastic recovery ability, improving the deformation resistance of the pavement and fatigue cracking resistance performance [20].

Therefore, in this study, the evolution of asphalt rheology and microscopic properties under fuel corrosion was innovatively investigated for different asphalt binders, especially considering the effects of different fuel corrosion levels on high- and low-temperature performance [21–23], morphology observation [24,25], and chemical composition [26,27], which is particularly significant in revealing the mechanisms of resistance to fuel corrosion in asphalt.

## 2. Materials and Methods

### 2.1. Materials

To make the study representative and comprehensive, four commonly used asphalt binders were selected, including one base asphalt and three types of modified asphalt. The base asphalt selected was 70# petroleum asphalt, referred to as 70# in this paper. With reference to previous studies [14,15], the three modified asphalts were prepared by adding modifiers to 70#: 6% LDPE, 5% linear SBS, and 20% rubber powder (30 mesh), referred to as LA, SBS, and RA, respectively. Tables 1–3 summarize the main properties of these modifiers and asphalt binders.

**Table 1.** Physical properties of LDPE.

| Property | Density (g/cm <sup>3</sup> ) | Melting Point (°C) | Melt Flow Index (g/10 min) |
|----------|------------------------------|--------------------|----------------------------|
| LDPE     | 0.925                        | 121                | 50                         |

**Table 2.** Physical properties of linear SBS.

| Property   | Volatiles (%) | 300% Stress at Definite Elongation (MPa) | Tensile Strength (MPa) | Elongation at Break (%) | Hardness (A) |
|------------|---------------|------------------------------------------|------------------------|-------------------------|--------------|
| Linear SBS | ≤0.7          | ≥2.2                                     | ≥16                    | ≥700                    | ≥68          |

**Table 3.** Physical properties of asphalt binders.

| Property | Penetration at 25 °C (0.1 mm) | Softening Point (°C) | Ductility (cm) |
|----------|-------------------------------|----------------------|----------------|
| 70#      | 75.4                          | 55.4                 | 53.1 (10 °C)   |
| LA       | 38.2                          | 61.6                 | 29.6 (5 °C)    |
| SBS      | 30.0                          | 63.2                 | 32.3 (5 °C)    |
| RA       | 45.0                          | 58.4                 | 21.5 (5 °C)    |

### 2.2. Preparation of the Test Sample

The fuel used in this study was 0# diesel fuel. To fully investigate the properties of the asphalt binders under the action of fuel corrosion, the samples were immersed in fuel for some time to produce varying degrees of corrosion damage so that the rheological and microscopic properties of these fuel-treated samples could be studied. With reference to Giuliani [28], the ring-and-ball apparatus traditionally used for softening point measurements was used to prepare the original samples. Then, the asphalt samples were fuel-corroded according to the following steps:

- (1) The asphalt samples were prepared and demolded at 25 °C and used as original samples, as shown in Figure 1a,b.
- (2) The samples were immersed in a 100 mL beaker containing 20 mL of 0# diesel fuel, as shown in Figure 1c.
- (3) After durations of 1 h, 2 h, 4 h, 8 h, and 24 h, the samples were removed from the beaker, wiped with filter paper, and dried for 2 h at 25 °C to sample different degrees of fuel corrosion damage, as shown in Figure 1d.

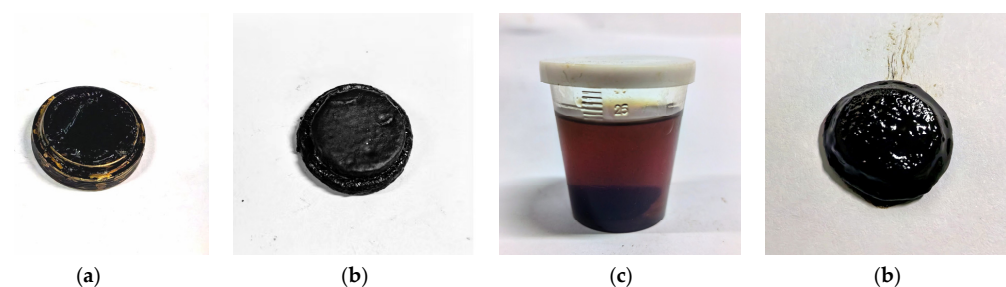


**Figure 1.** Fuel corrosion damage samples preparation: (a) poured asphalt, (b) original sample, (c) sample immersed in diesel fuel, and (d) fuel-treated sample.

### 2.3. Test Methods

#### 2.3.1. The Mass Loss Test

The dissolution of asphalt in diesel fuel can be characterized by the loss of mass in the asphalt due to fuel corrosion [16], as in Equation (1). Three replicate tests were performed for each set of samples, and the average value was analyzed.

$$\Delta m_0 = (1 - m_1/m_2) \times 100\% \quad (1)$$

Here,  $\Delta m_0$  is the mass loss in the asphalt due to fuel corrosion (%),  $m_1$  is the mass of the sample after fuel corrosion (g), and  $m_2$  is the mass of the original sample.

#### 2.3.2. The Dynamic Shear Rheometer (DSR) Test

The DSR test characterizes the elastic and cohesive properties of asphalt binders by measuring the complex shear modulus ( $G^*$ ) and phase angle ( $\delta$ ). The DSR test was conducted with reference to AASHTO T315 [29]. The values of  $G^*$ ,  $\delta$ , and the rutting factor ( $G^*/\sin\delta$ ) corresponding to the asphalt at different temperatures (58 °C, 64 °C, 70 °C, 76 °C, and 82 °C) were tested using DHR-20. The test was carried out at a frequency of 10 rad/s using a parallel plate of 25 mm in diameter and with 1 mm spacing.

#### 2.3.3. The Multiple Stress Creep Recovery (MSCR) Test

Since the original evaluation system for asphalt does not apply to modified asphalt, the MSCR test was proposed to solve this problem [30]. The MSCR test can better simulate repeated loading and unloading processes under different vehicular loads and reveal high-temperature rheological properties by quantifying elastic and permanent deformation.

The MSCR tests were performed using the DHR-20 at 64 °C and three samples of each asphalt binder. Continuous tests were performed at 0.1 and 3.2 kPa creep stress levels in stress control mode according to the AASHTO T350-14 standard [31]. The creep time was set to 1 s, and the unloading recovery time was set to 9 s. The shear deformation of the specimens after 10 cycles was recorded, and the creep recovery ( $R$ ), nonrecoverable creep compliance ( $J_{nr}$ ), and the sensitivity index ( $J_{nr-diff}$ ) of the specimens were calculated as shown in Equations (2)–(4).

$$R = (\varepsilon_p - \varepsilon_u) / \varepsilon_p \times 100\% \quad (2)$$

$$J_{nr} = \varepsilon_u / \sigma \quad (3)$$

$$J_{nr-diff} = (J_{nr3.2} - J_{nr0.1}) / J_{nr0.1} \times 100\% \quad (4)$$

Here,  $\varepsilon_p$  is the peak strain,  $\varepsilon_u$  is the unrecovered strain,  $\sigma$  is the stress,  $R_{0.1}$  and  $R_{3.2}$  are the average creep recoveries at the 0.1 kPa and 3.2 kPa stresses, and  $J_{nr0.1}$  and  $J_{nr3.2}$  are the average unrecoverable creep flexures at the 0.1 kPa and 3.2 kPa stresses.

#### 2.3.4. The Bending Beam Rheometer (BBR) Test

The BBR test can accurately evaluate the low-temperature rheological properties of asphalt binders with creep stiffness ( $S$ ) and creep rate ( $m$ ). BBR tests were performed on the asphalt binders at −12 °C according to the AASHTO T313 standard [32] by using the TE-BBR SD.

#### 2.3.5. Morphological Observation

Fluorescence microscopy tests were used with laser radiation of a specific wavelength on the modified asphalt binder so that a fluorescence reaction visible to the human eye could be excited in the modifier, forming an image for observation. The specimen was prepared using the hot-drop cover-glass molding method. Molten asphalt binders were dripped onto a slide, and then, a cover glass was quickly placed and kept horizontal to allow the samples to flow naturally to form a film.

### 2.3.6. Fourier Transform Infrared Spectroscopy (FTIR) Test

The FTIR test can analyze the chemical functional group composition of asphalt binders. FTIR tests were conducted using a BRUKER TENSOR 27 infrared spectrometer with an all-reflective ATR accessory from Germany. The spectral range was  $4000\sim 500\text{ cm}^{-1}$  with a resolution of  $4\text{ cm}^{-1}$  and 32 scan repetitions.

### 2.3.7. Asphalt Four-Component Test

Asphalt consists of asphaltene, resin, saturates, and aromatics, and the content of each component determines the properties of the asphalt. An MK-7s TLC/FID stick thin-layer chromatograph from IATROSCAN Analytical Instruments, Japan, was used with reference to ASTM D4124-09 [33]. Thin-layer chromatography–flame ionization detection (TLC/FID) is based on the principle that organic samples diluted with solvents can be spotted onto silica-coated alumina-adsorbent thin-layer rods. After developing and drying the samples, the rods were passed through a hydrogen flame, ionizing the samples and constituting detection via FID.

## 3. Results and Discussion

### 3.1. The Mass Loss Test

Figure 2 shows the mass loss rates of the different asphalt binders with different fuel corrosion durations.

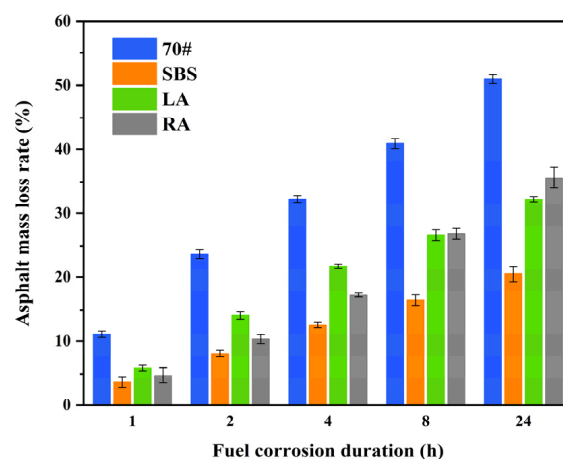


**Figure 2.** Asphalt mass loss rate under different fuel corrosion durations.

The mass loss of the four asphalt binders increased with an increase in the fuel immersion time. The mass loss rate of the 70# base asphalt was more than 50% after being immersed in fuel for 24 h. SBS, LA, and RA experienced less mass loss than the base asphalt at all levels, which indicated that the resistance of the base asphalt to fuel corrosion was improved to a certain extent after modification. LA lost mass quickly and then slowly, whereas the fuel corrosion resistance of SBS was superior, with a smoother overall trend in mass loss. RA lost less mass at 1 h, 2 h, and 4 h than LA and more than SBS, while its mass loss at 8 h and 24 h exceeded that of LA. Because rubber powder swells after adsorbing the light components of asphalt, there were relatively few light components in RA, and its initial resistance to fuel corrosion was stronger. However, it is difficult for rubber powder to completely dissolve in asphalt, and as the duration of fuel corrosion extends, its exposure and even shedding increases, thus causing greater mass loss. However, mass loss does not fully reflect the change in the performance of the asphalt binders, so their rheological and microscopic properties also need to be analyzed.

### 3.2. Rheological Properties

#### 3.2.1. DSR Tests

The complex shear modulus ( $G^*$ ) characterizes the ability of the asphalt to resist external loading, while the phase angle ( $\delta$ ) reflects the relative proportions of the elastic and viscous parts of the asphalt. The rutting factor ( $G^*/\sin\delta$ ) is defined to evaluate the high-temperature performance of the asphalt, and the larger the rutting factor, the better the rutting resistance. Figure 3 shows the DSR test results for the asphalt binders.

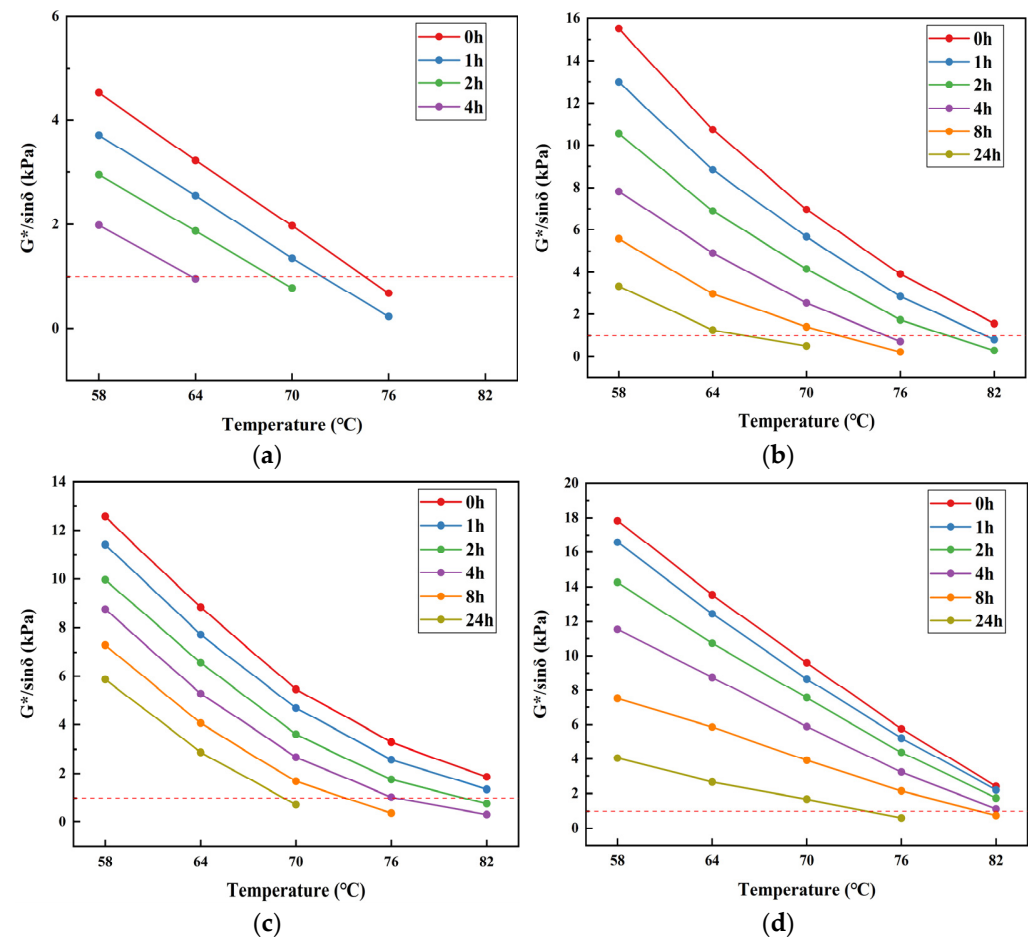


**Figure 3.** Rutting factor ( $G^*/\sin\delta$ ) of asphalt binders. (a) 70#, (b) SBS, (c) LA, and (d) RA.

Figure 3 shows that temperature has a significant effect on  $G^*/\sin\delta$ , which shows a decreasing trend with increasing temperature. Specifically, as a proportion of the composite modulus and the elastic portion of the asphalt decrease, as do the deformation resistance and deformation recovery ability. As the temperature increased from 58 °C to 82 °C, the differences in the rutting factor of the asphalt binders at the same temperature gradually decreased, indicating that temperature had a significant effect. Equally, under different fuel corrosion durations, the rutting factor of the three types of modified asphalt decreased to a smaller extent as the temperature increased, which indicated that the temperature-sensitive properties of the modified asphalt were all improved to different degrees.

At the same temperature,  $G^*/\sin\delta$  also appeared to reduce to varying degrees with the extension of the fuel corrosion duration, and the longer the duration, the smaller the rutting factor. This indicates that fuel corrosion has a significant effect on the high-temperature rheological properties of asphalt, and the greater degree of fuel corrosion, the poorer the high-temperature performance of the asphalt binder becomes. The rutting factors of the three types of modified asphalt were higher at the same temperature compared with the base asphalt, which indicates that adding modifiers improves the high-temperature stability

of asphalt to varying degrees; thus, its resistance to deformation and its deformation recovery ability are enhanced.

If the lower-limit temperature of the rutting factor ( $G^*/\sin\delta = 1$  kPa) is higher, this indicates that the asphalt can withstand loading at higher temperatures while maintaining a stable shape. Indeed, the lower-limit temperatures of SBS after 0 h, 1 h, 2 h, 4 h, 8 h, and 24 h of fuel corrosion were 82 °C, 76 °C, 76 °C, 70 °C, 70 °C, and 64 °C, respectively, for a temperature test interval from 58 °C to 82 °C. LA's lower-limit temperatures under the same conditions were 82 °C, 82 °C, 76 °C, 76 °C, 70 °C, and 64 °C, respectively. Meanwhile, RA's were 82 °C, 82 °C, 82 °C, 82 °C, 82 °C, 76 °C, 76 °C, and 70 °C. Under fuel corrosion conditions for 8 and 24 h, the  $G^*/\sin\delta$  of the base 70# asphalt struggled to meet the requirements, had the worst rheological properties at a high temperature, and was the most greatly affected by fuel corrosion among the four asphalt binders.

### 3.2.2. MSCR Tests

Figure 4 shows the creep recovery (R) and unrecoverable creep flexibility ( $J_{nr}$ ) of the different asphalt binders at 64 °C and at 0.1 kPa and 3.2 kPa stress levels. In terms of performance characterized by these indexes, a smaller  $J_{nr}$  and a larger R indicate a larger proportion of elastic deformation within the total deformation, a smaller proportion of permanent deformation, and better rutting resistance. For the same kind of asphalt, an increase in the stress level is marked by a decreased R and an increased  $J_{nr}$ , indicating that the asphalt is more prone to shear deformation at high stress levels. Compared with the base asphalt, SBS, LA, and RA showed a significant enhancement in R, while  $J_{nr}$  was significantly reduced. Even after 24 h of fuel corrosion, the modified asphalt still resisted deformation better than the base asphalt, indicating significant improvement in the high-temperature rheological properties of asphalt binders with modifiers, which agrees with the experimental results of the DSR tests.

The variations in the measured indexes for SBS, LA, and RA after fuel corrosion are similar. As the fuel corrosion degree deepens, R continues to decrease while  $J_{nr}$  continues to increase, which proves that an asphalt binder after fuel corrosion is more likely to undergo permanent deformation. SBS had the best recovery ability, with the highest R under the same degree of fuel corrosion and the same stress level. RA had the best deformation resistance, and its  $J_{nr}$  was smaller than that of SBS and LA.

Table 4 shows the  $J_{nr-diff}$  values of the asphalt binders.  $J_{nr-diff}$  characterizes the sensitivity of asphalt binders to stress changes, and the lower the value, the lower the binder's sensitivity to stress changes. The stress sensitivity of 70#, SBS, and LA to permanent deformation after fuel corrosion damage generally rose. Comparing  $J_{nr-diff}$  at 0 h and 24 h, 70# increased by 99%, SBS increased by 42%, and LA increased by 55%. This indicates that stress changes become more significant for these three kinds of asphalt after fuel corrosion, and their load-bearing capacity becomes worse. Among the asphalts, 70# had the most drastic performance decay, and SBS was relatively better. The  $J_{nr-diff}$  value of RA, on the other hand, did not change significantly, indicating that it still has good high-temperature performance under high stress levels and more easily maintains deformation resistance after fuel corrosion compared with the other asphalts. Rubber particles absorb the light components of asphalt and dissolve, acting as heavy components in the asphalt binder and making it more elastic. When diesel fuel dissolves some of these lightweight components, RA hardens, and the high-temperature rheological properties become more stable.

**Table 4.**  $J_{nr-diff}$  values of asphalt binders.

| Fuel Corrosion Duration (h) | 70#    | SBS     | LA      | RA      |
|-----------------------------|--------|---------|---------|---------|
| 0                           | 0.2798 | 31.6667 | 17.1159 | 29.0000 |
| 1                           | 0.2696 | 32.8889 | 17.3951 | 30.5385 |
| 2                           | 0.4488 | 35.2963 | 19.4717 | 32.3333 |
| 4                           | 0.5732 | 38.7143 | 21.2078 | 31.6923 |
| 8                           | 0.6031 | 43.7619 | 24.6938 | 28.0476 |
| 24                          | 0.5558 | 45.0317 | 26.4455 | 29.0000 |

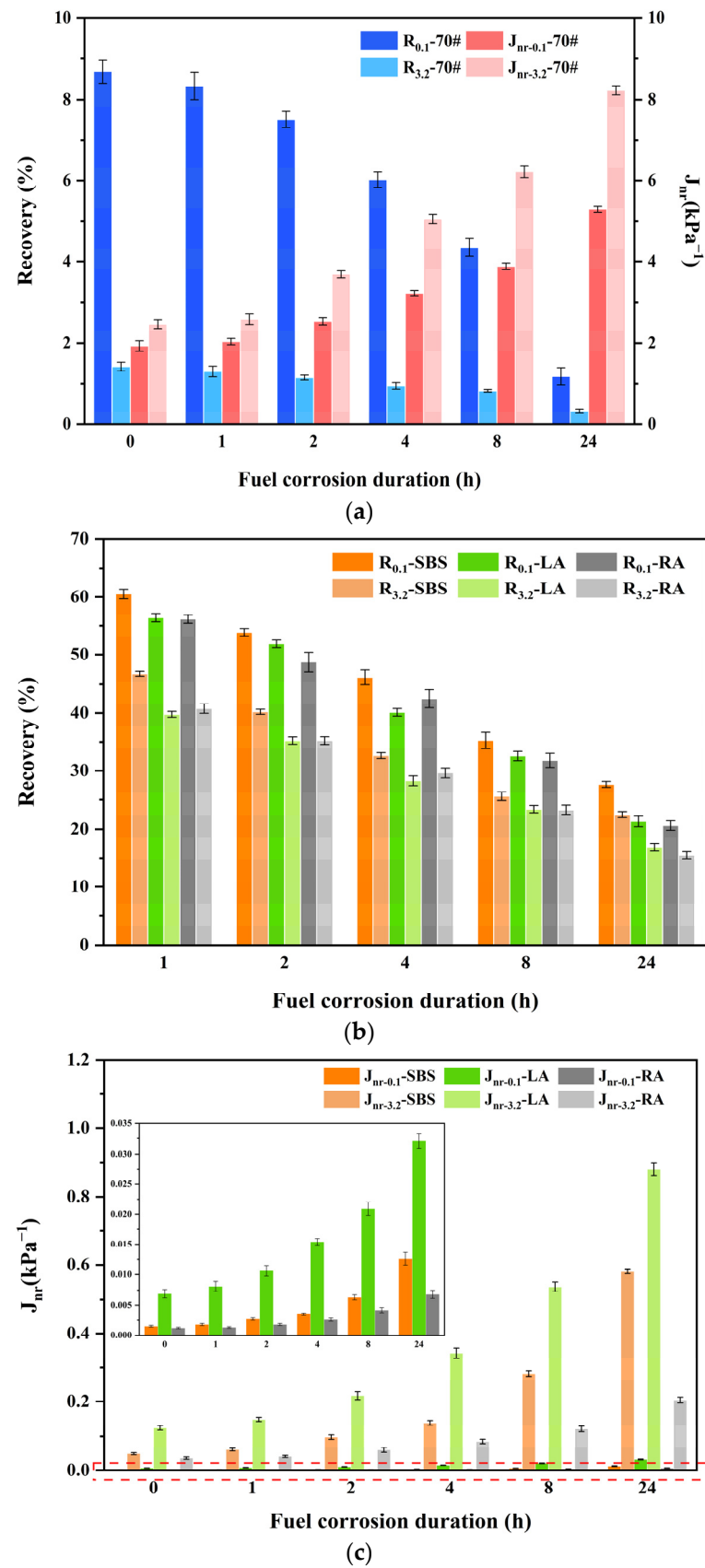


**Figure 4.** MSCR test results of asphalt binders. (a)  $R$  and  $J_{nr}$  of 70#, (b)  $R$  of modified asphalt binders, and (c)  $J_{nr}$  of modified asphalt binders.

### 3.2.3. BBR Tests

The BBR test results are shown in Figure 5. *S* represents the creep strength, and *m* represents the creep rate. The low-temperature rheological properties of the asphalt binders used in this study all satisfy the requirements of  $S \leq 300$  MPa and  $m \geq 0.3$ . Compared with the original asphalt before fuel corrosion, the *S*-values of the four asphalt binders decreased, and the *m* values increased as the fuel corrosion deepened. This shows that fuel reduces the hardness of asphalt binders, which helps to resist low-temperature cracking. Because of the principle of similar solubility, the components of the asphalt binder gradually dissolve in diesel. At the same time, the penetration of oily small molecules softens the asphalt gradually, so its low-temperature performance is improved to a certain extent.

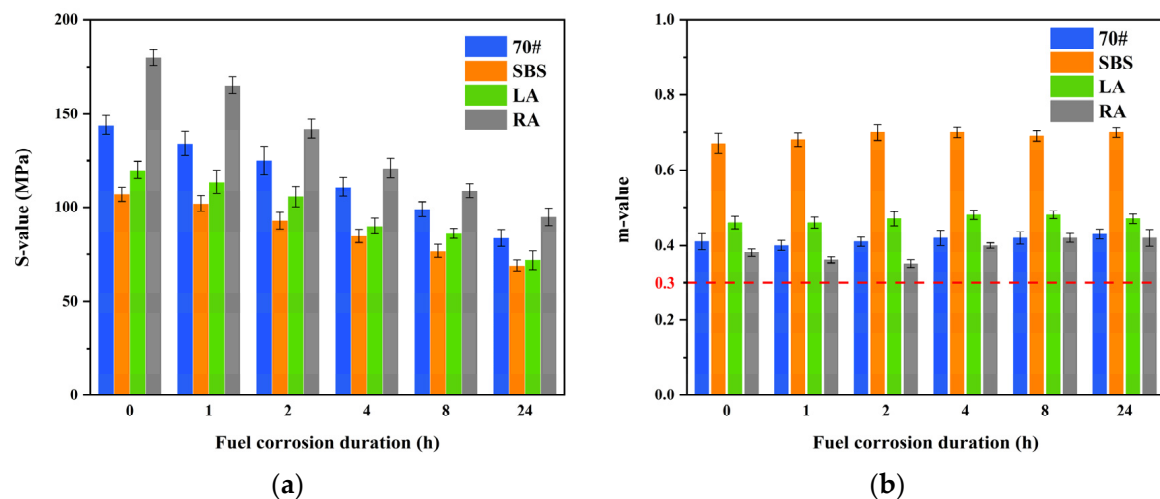


**Figure 5.** BBR test results of asphalt binders. (a) *S*-value and (b) *m* value.

The patterns of low-temperature performance determined by *S* and *m* at different levels of fuel corrosion are consistent, with both showing the best resistance to low-temperature cracking in SBS and the worst in RA. Compared with 0 h, SBS had the smallest decrease in *S* at 36% at 24 h of diesel corrosion, followed by LA at 40%, with RA being the most affected at 47%. This is because the modifiers in SBS and LA, with fine and uniformly distributed particles, can form a crosslinked structure with the asphalt, thereby limiting its softening flow and, thus, enhancing its ability to resist deformation. After RA was eroded by diesel, the rubber particles were easily aggregated and exposed at the surface of the asphalt binder, resulting in stress concentration and leading to a large difference in the creep strength.

### 3.3. Microscopic Mechanisms

#### 3.3.1. Morphological Observations

To reveal the effect of fuel corrosion on the macroscopic properties of the asphalt binders, their microscopic morphology was analyzed using fluorescence microscopy. To enhance the comparison, images of the asphalt binders as they were eroded by diesel fuel for 0 h and 24 h were selected, as shown in Figure 6. Figure 6a,b shows images of the base asphalt binder with a uniform low-fluorescence phenomenon before and after fuel corrosion, indicating its uniform microstructure.

Since linear SBS is a polymer, banded, linear, and dotted fluorescent regions are dispersed in the asphalt phase in the image of the SBS asphalt binder in Figure 6c,d. After it was eroded by diesel for 24 h, the band and line structures in the image decreased and disappeared, and the dot structures became smaller and more dispersed. This indicates that diesel fuel has a destructive effect on the crosslink structure formed by SBS, and the mutual constraints between the components are weakened, enabling flow deformation. However, after they were corroded by diesel, compared with 70#, the linear SBS components were not completely dissolved, so they still had a certain amount of resistance to deformation.

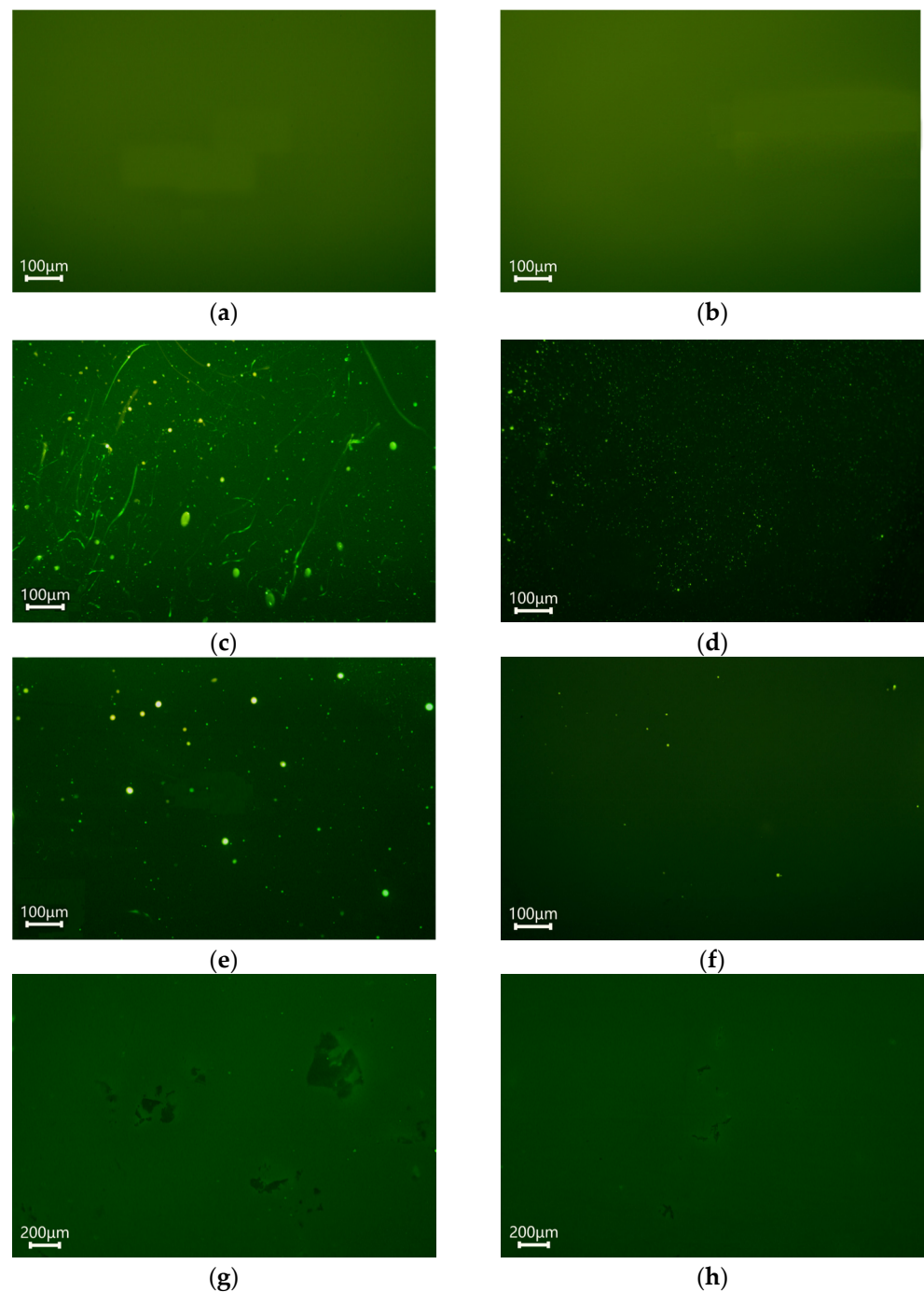


**Figure 6.** Fluorescence microscopy of different asphalt binders. (a) 70# for 0 h, (b) 70# for 24 h, (c) SBS for 0 h, (d) SBS for 24 h, (e) LA for 0 h, (f) LA for 24 h, (g) RA for 0 h, and (h) RA for 24 h.

Figure 6e,f shows that the LA asphalt binder contained dotted structures of different sizes, which represent the dispersion of LDPE in the asphalt phase. After fuel corrosion damage, the dotted structures almost disappeared, which proves that the diesel fuel stripped the LDPE particles from the asphalt and dissolved them. Compared with the images of SBS, the fluorescent areas of LA are smaller and more dispersed than in SBS, both before and after fuel corrosion, which explains its poorer rheological performance in all phases compared with SBS.

Figure 6g,h shows that the rubber particles in RA were large and numerous at 0 h. After 24 h of fuel corrosion, the rubber particles were depleted and smaller and had blurred edges. This implies that the bitumen component suffered damage after the diesel entered

the asphalt binder and reduced the friction between the rubber particles, dislodging some of them. This also explains the faster decay of RA, as shown in the DSR and BBR test results.

Space structures in SBS and LA and rubber particles in RA became fainter and fewer in number as the fuel corrosion deepened, meaning that the fuel dissolves and strips parts of the modifiers and destabilizes the structure formed by the modifiers and the asphalt. Fuel corrosion damages the asphaltene and resin in asphalt, preventing them from maintaining their original stabilizing properties. In addition, the invasion of the small-molecule composition of fuel into the asphalt increases the light components between asphaltene and resin; the mutual constraints between macromolecules are weakened, which makes it easier for the asphalt to experience flow deformation.

### 3.3.2. FTIR Tests

FTIR can test changes in the functional groups of asphalt after adding modifiers and diesel fuel corrosion to determine the type of reactions between substances. Figure 7 shows the results of our FTIR tests. The peaks at  $2915\text{ cm}^{-1}$  and  $2852\text{ cm}^{-1}$  indicate the antisymmetric contraction and symmetric contraction vibrations of methylene,  $\text{CH}_2$ . Equally, the peaks at  $1453\text{ cm}^{-1}$  and  $1372\text{ cm}^{-1}$  indicate the bending vibration of methyl,  $\text{CH}_3$ , and the peaks in the  $854\sim 729\text{ cm}^{-1}$  region indicate the bending vibration of long-chain methylene,  $-(\text{CH}_2)_n-$ , reflecting a substitution on the benzene ring.

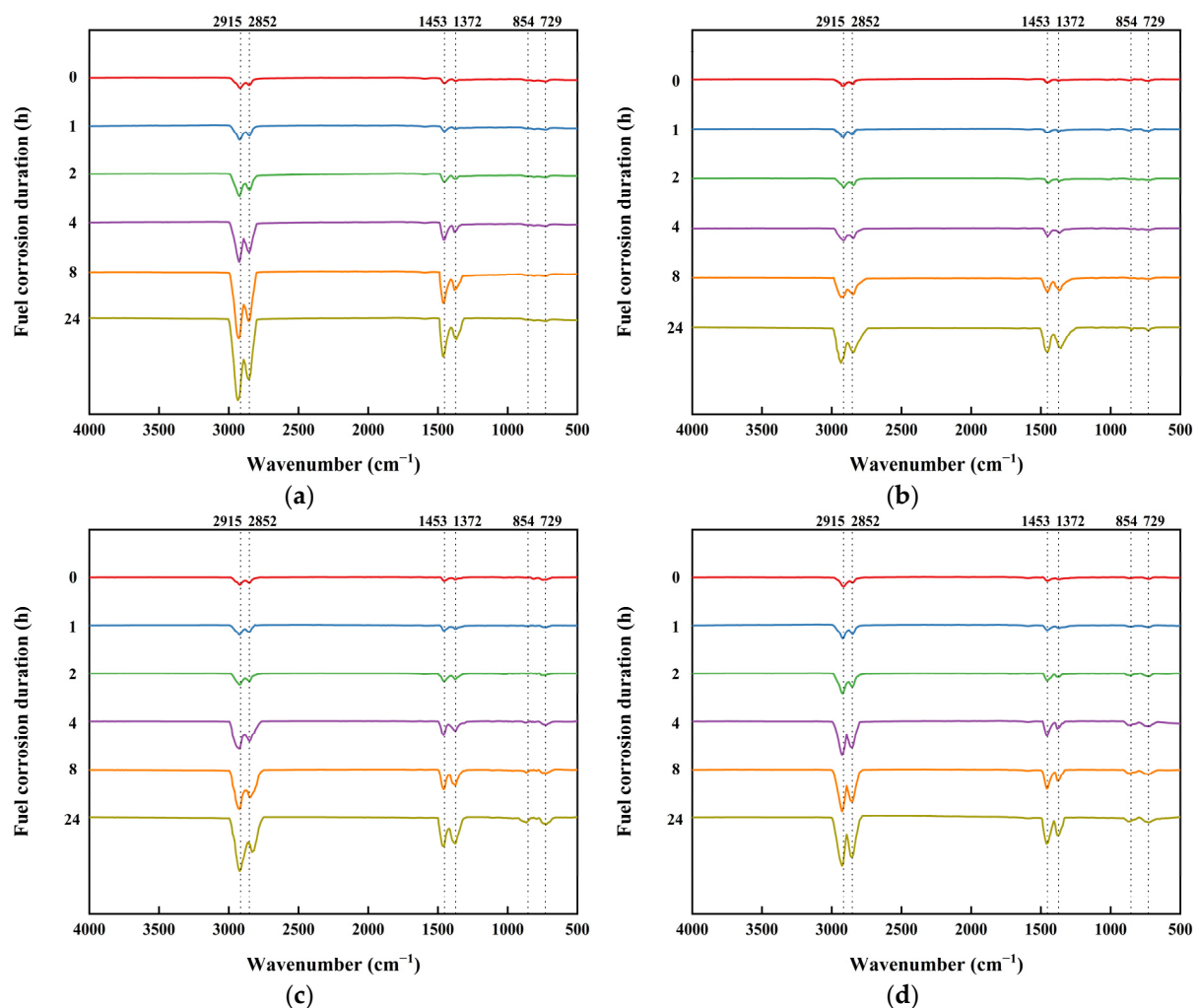


**Figure 7.** FTIR results of different asphalt binders. (a) 70#, (b) SBS, (c) LA, and (d) RA.

When uneroded by diesel fuel, the four asphalt binders are mainly in the above absorption peak position, indicating that these asphalt binders have the same functional

groups and that linear SBS, LDPE, and rubber particles mainly modify the base asphalt according to a physical process. After the diesel fuel corrosion, the position of the asphalt binder's absorption peak did not change significantly. This indicates that diesel fuel and asphalt binders have similar functional groups and a similar molecular structure and that the process of fuel corrosion is not a chemical reaction. In addition, as the degree of fuel corrosion deepened, the intensity of the absorption peaks of the asphalt binders at  $2915\text{ cm}^{-1}$ ,  $2852\text{ cm}^{-1}$ ,  $1453\text{ cm}^{-1}$ , and  $1372\text{ cm}^{-1}$  increased significantly. Compared to the three types of modified asphalt, the absorption peak intensity of 70# changed the most and was most affected by fuel corrosion. Therefore, the fuel corrosion resistance of modified asphalt was superior to that of the base asphalt, which is consistent with the results of the aforementioned rheological performance tests.

### 3.3.3. Asphalt Four-Component Tests

Figure 8 shows the four-component composition of different asphalt binders at different levels of fuel corrosion. Compared with 70#, the proportion of heavy components, such as asphaltene and resin, in the modified asphalts SBS, LA, and RA increased at all stages, while the proportion of light components, such as saturates and aromatics, decreased. This is because modifiers such as linear SBS, LDPE, and rubber powder act as heavy components in asphalt, and with the solubilization of the modifiers, they adsorb more light components. Furthermore, elevating heavy components can enhance the temperature stability of asphalt and improve its high-temperature rheological properties. The reduced light component content and the crosslinking structure of the modifiers caused the modified asphalt to have better fuel corrosion resistance, as shown in Figure 2.

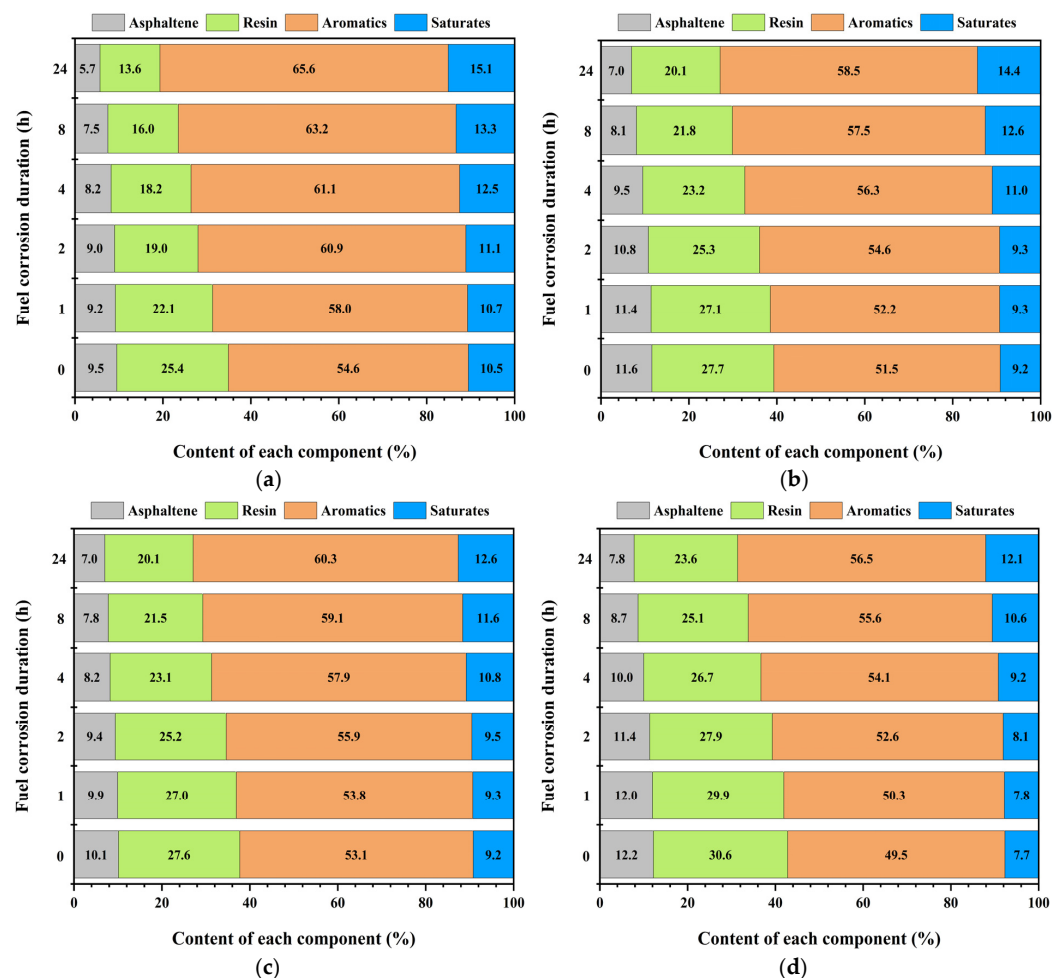


Figure 8. Four-component test results of different asphalt binders. (a) 70#, (b) SBS, (c) LA, and (d) RA.

As the fuel corrosion deepened, the trends in the components of the four asphalts were consistent, as manifested by the decrease in asphaltene and resin content and the increase in saturate and aromatic content, indicating that the fuel corrosion transformed the heavy components of the asphalts into light components. This means that the asphalt becomes softer, and its low-temperature deformation capacity is enhanced to a certain extent, consistent with the conclusions of the BBR tests. At lower degrees of fuel corrosion (1 h and 2 h), the rate of decrease in resin content in the three types of modified asphalt is higher than that of asphaltene because asphaltene has a high molecular weight and is less susceptible to fuel corrosion. Meanwhile, at higher degrees of fuel corrosion (8 h and 24 h), the spatial structure formed by the modifier was destroyed, and the original asphaltene in the asphalt gradually dissolved into small molecules, so the rate of component loss increased.

Compared with SBS and LA, RA had a higher content of heavy components. Its loss rate was smaller because rubber powder is less likely to be dissolved by fuel compared with linear SBS and LDPE. Equally, it was not fully swelled when it was distributed in the original asphalt. When the large molecules in asphalt are corroded by fuel and become small molecules, rubber powder can continue to absorb and swell to maintain a relatively large number of heavy components in RA. Thus, its ability to resist high-temperature deformation is superior.

#### 4. Conclusions

This study focused on the rheological and microscopic properties of asphalt binders under the action of fuel corrosion evolution, using a variety of experimental methods to evaluate multiple fuel corrosion levels and research objects. The results show that diesel corrosion changes the asphalt components, as described in references [6,8]. The high-temperature rheological properties of the asphalt binders deteriorated, consistent with previous studies [3,5], while the modified asphalts were better than the base asphalt [13,14]. However, the base asphalt's low-temperature rheological properties somewhat improved, which is a novel finding. Considering different degrees of fuel corrosion damage by controlling the fuel immersion time is a highlight of this study. It can be summarized as follows:

- (1) In terms of mass loss, modified asphalts such as SBS, LA, and RA are more fuel-corrosion-resistant than base asphalt. The asphalt binder is continuously dissolved, with greater mass loss as the degree of fuel corrosion deepens.
- (2) The rutting factor  $G^*/\sin\delta$  of the asphalt decreases as fuel corrosion increases. However, modified asphalts have a significantly improved high-temperature deformation resistance compared to base asphalt and a reduced temperature sensitivity. Among them, RA has the best high-temperature rheological performance, and LA is superior to SBS once it reaches high levels of fuel corrosion damage.
- (3)  $R$  and  $J_{nr}$  determined in the MSCR tests similarly demonstrate improvement in the high-temperature rheological properties of modified asphalt binders. Under the effect of fuel corrosion, the stress sensitivity of the asphalt binders is elevated, and their load-bearing capacity deteriorates. RA has a better resistance to deformation, and SBS demonstrates excellent recovery.
- (4) The results of the BBR tests show that fuel corrosion improves the low-temperature cracking resistance of the asphalt binders to some extent, with SBS having the best resistance to low-temperature cracking and RA having the worst.
- (5) By observing the microscopic morphology of the asphalt binders, it is shown that diesel fuel erodes the modifiers, which can disrupt the structure of the bands and lines formed by linear SBS, the point structure of LDPE, and the morphology of the rubber particles, resulting in a change in the binders' rheological properties.
- (6) Fuel and asphalt binder have similar chemical compositions. Therefore, the corrosion process mainly involves physical dissolution, and no chemical reaction occurs. At the same time, heavy components are converted into light components. The evolution of

the rheological and microscopic properties of asphalt under fuel corrosion is consistent and can be mutually corroborated.

Further research should focus on studying the fuel corrosion resistance of asphalt mixtures as a complement to this study. In addition, given the limited test conditions, the coupling effect of environmental factors such as sunlight, moisture, and temperature could not be considered. To reflect the effects of fuel corrosion in a real environment, field tests or more rigorous and comprehensive simulations of test conditions are required for further research.

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