Effects of a Fuel-Resistant Modifier on the High-Temperature Characteristics of Asphalt Binders

Wenchang Liu 1, Hongjun Li 2, Hongwei Lin 1,*, Xiaobo Du 1, Mutian Sun 1 and Shaohui Liu 1

1 Key Laboratory of Road and Traffic Engineering of Ministry of Education, Tongji University, Shanghai 201804, China; 1810521@tongji.edu.cn (W.L.); duxb@tongji.edu.cn (X.D.); 1931343@tongji.edu.cn (M.S.); 1933387@tongji.edu.cn (S.L.)
2 CCCC Wuhan Harbour Engineering Design & Research Institute Co., Ltd., Wuhan 430040, China; lihongjun128@163.com
3 CCCC Wenshan Expressway Construction and Development Company Ltd., Wenshan 663000, China
* Correspondence: 201712105@chd.edu.cn; Tel.: +86-15626213096

Abstract: To effectively evaluate the high-temperature characteristics of a fuel-resistant modified asphalt (FRMA), five different types of asphalt were selected, and a fuel-resistant modifier (FRM) was added to the asphalt to prepare five kinds of FRMA, and the fuel resistance of the 10 above-mentioned asphalt samples was then evaluated. Moreover, the high-temperature performance of different asphalt samples was explored, the influences of the FRM on the penetration, softening point, and rheological indexes of the different asphalt samples were analyzed. A Pearson correlation analysis was conducted on the different high-temperature indexes. Based on the results, compared with the original asphalt, the fuel resistance of the FRMA was improved by about 22% on average; the FRM was able to reduce the penetration, phase angle, and non-recoverable creep compliance of the asphalt; increase the softening point, complex modulus, rutting factors, and creep recovery; and effectively improve the high-temperature performance of the asphalt. However, as the temperature increased, the effect of the FRM on the improvement of the high-temperature performance of the asphalt declined. In addition, compared with the base asphalt, the FRM exerted a more significant effect on the rheological properties of the modified asphalt. According to the Pearson correlation analysis of the high-temperature indexes, apart from penetration, the softening point and rheological indexes featured excellent accuracy and applicability in the evaluation of the high-temperature performance of FRMAs.

Keywords: asphalt; fuel-resistant performance; high-temperature performance

1. Introduction

With the rapid development of transportation, fuel and engine oil leakages caused by traffic accidents have become increasingly common. In high-grade highways, fuel leakages are usually caused by some poorly conditioned vehicles, especially heavy-duty trucks that can leak large amounts of diesel fuel, thus forming large areas of oil erosion. On low-grade highways, the dripping of fuel is usually caused by parked vehicles or engine maintenance. The problem of fuel leakage is more serious at special sections of roads, such as gas stations, intersections, parking lots, and toll stations.

As a refined product of crude oil, bitumen has a material composition similar to that of light oil, and it is easily dissolved in fuel oil and other light oils [1]. When fuel oil, such as gasoline or diesel, drips onto asphalt pavement, the asphalt mixture will cause oil corrosion damage if the fuel oil is not cleaned up in time. Fuel oil can dissolve the asphalt binder, resulting in a serious reduction or loss of the adhesion between the aggregate and the asphalt. Therefore, asphalt pavements corroded by diesel oil or gasoline will experience early problems, such as spalling and loosening, resulting in a decline in the performance of the pavement [2]. Chen et al. found that the Marshall stability and dynamic stability of
the SMA-13 and AK-13 mixtures decreased significantly under the action of oil erosion [3]. In a study by Li et al., after seven days of fuel corrosion, the dynamic stability of SMA-13 mixtures with the application of #70 petroleum asphalt and SBS-modified asphalt decreased by 68.6% and 46.7%, respectively [4]. It is thus clear that fuel corrosion significantly deteriorates the high-temperature performance of asphalt pavements. In engineering practice, adding FRM to a mixture or applying a fuel-resistant modified asphalt (FRMA) is the primary approach to improving the fuel resistance of asphalt pavements. High-temperature performance is the most important aspect of asphalt pavements. The Strategic Highway Research Program (SHRP) showed that 40% of the anti-rutting performance of an asphalt mixture is determined by the high-temperature characteristics of the asphalt [5]. Hence, when considering the fuel resistance of an asphalt mixture, it is also necessary to focus on the evaluation of the high-temperature characteristics of its additive or the FRMA, thereby giving consideration to both the fuel resistance and high-temperature performance.

Current studies on the fuel resistance of asphalt and asphalt mixtures mainly focus on the mechanism, influence, and evaluation of fuel corrosion, as well as the research and development of FRMs and FRMAs. Different types of asphalt and fuels have similar compositions that contain more C and H elements and a large number of C-H, C=O, and C=C functional groups [6]. Merusi et al. found that the loss of adhesion at the interfaces of the mastic–aggregate system leads to premature pavement deterioration under prolonged and repetitive conditions of fuel spilling [7]. A similar study proposed that the oil content in asphalt is 45–60%, and it is easily dissolved in fuel [8]. Steernberg et al. outlined some fundamental aspects of bitumen–fuel interactions [9]. In particular, the dissolution process of bitumen was associated with the subsequent absorption of fuel into the bitumen. Tan et al. found that the composition of asphalt before and after diesel pollution did not significantly change, while the number of functional groups at the absorption peak changed significantly [10]. Li et al. indicated that the surface of the asphalt mixture showed a rough and loose mass structure after oil immersion and that the asphalt films and fine aggregates fell off in an SEM experiment [11]. Mora and Hilpert studied the evaporation and permeability of diesel and gasoline in concrete pavements [12]. The asphalt modified with a fuel-resistant polymer and without coal tar that was developed by Ronald et al. was successfully applied in many international airports [13]. Pratico et al. proposed and verified a new model for analyzing the degree of corrosion of asphalt pavements caused by fuel leakage, which could be used for the selection of a hot-mix asphalt mixture and the prediction of its fuel resistance [14]. Felice et al. recommended that a solubility test should be used to evaluate the fuel resistance of asphalt and proposed that asphalt could be modified with an appropriate polymer based on its composition in order to improve the asphalt’s fuel resistance [15]. Li et al. pointed out the similar dissolvability between asphalt and light oil and explained the mechanism by which fuel corrodes asphalt on this basis [16]. Irfan et al. studied the effect of a fuel-resistant polymer on the consistency and performance of an asphalt binder and an HMA mixture [17]. Chaturabong et al. developed a tack coat of an asphalt emulsion with chip-seal coating, making it possible to repair asphalt pavements on which oil has been spilled within a short time [18]. The above studies have promoted the research and development of the fuel resistance of asphalt and asphalt mixtures, but the high-temperature characteristics of FRMAs have rarely been studied. In addition, whether the high-temperature performance evaluation indexes for traditional asphalt are applicable to FRMAs also remains to be confirmed.

In view of this, five different types of asphalt were selected, and the FRM was added to the asphalts to prepare five kinds of FRMAs; the fuel resistance of the 10 above-mentioned asphalt samples was then evaluated. Meanwhile, the penetration and softening-point tests, DSR test, and multiple stress creep recovery (MSCR) test were conducted to study the high-temperature performance of the asphalt, and the effect of the FRM on the base asphalt and modified asphalt was analyzed. In the end, based on an analysis of the correlations among the high-temperature indexes of the asphalt samples, the appropriate high-temperature evaluation indexes were recommended for the FRMAs.
2. Experiment
2.1. Experimental Materials

In the experiment, #70 petroleum asphalt, #90 petroleum asphalt, rubberized asphalt (RA), SBS-modified asphalt, and high-viscosity SBS (HSBS)-modified asphalt were the asphalt samples used. In this study, FRM (see Figure 1) in the amount of 5% of the mass of the sample was added to the original asphalts mentioned above to prepare 5 types of FRMAs. The properties of the FRM are listed in Table 1. To facilitate the follow-up analysis of the experimental data, the above 5 asphalt samples and their corresponding FRMA samples were numbered as shown in Table 2.

Figure 1. Anti-oil corrosion modifier.

Table 1. Technical indexes of FRM.

| Index | Appearance | Particle Diameter (mm) | Density (g/ cm³) |
|-------|------------|------------------------|------------------|
| Test result | Powdered particle | 0.01–2 | 0.82–0.85 |

Table 2. The type and code name of asphalt.

| Asphalt Type | Code name | 70# | 5%FRM + 70# | 90# | 5%FRM + 90# | RA | 5%FRM + RA | SBS | 5%FRM + SBS | HSBS | 5%FRM + HSBS |
|--------------|-----------|-----|-------------|-----|-------------|----|------------|-----|-------------|------|------------|
| 70#          | F-70#     | 90# | F-90#       | RA  | F-RA        | SBS| F-SBS      | HSBS| F-HSBS      |      |            |

2.2. Preparation of the FRMA

In the experiment, the FRMA binder was prepared as follows:

(1) The original asphalt was put into the drying oven and heated at 170 °C to make the asphalt fluid.
(2) The FRM was weighed (5% of the mass of the original asphalt).
(3) The temperature of the asphalt was maintained at about 170 °C, and a high-speed shearing machine was used to slowly pour the weighed FRM a little at a time into the heated asphalt, the asphalt was constantly stirred at the speed of about 350 r/min for 60 min to ensure that the FRM was evenly distributed in the asphalt.
(4) The prepared FRMA was put into the drying oven for heat preservation.
2.3. Experimental Methods

2.3.1. The Fuel Corrosion Test

Based on the fuel corrosion test proposed by Li et al. [6], the weight of solid asphalt lost due to fuel corrosion in 100 mL of fuel was measured at a specific temperature to evaluate the fuel resistance of the asphalt. The fuel corrosion test was repeated on 3 samples in parallel for each type of asphalt.

In the experiment, a 50 × 50 × 20 mm stainless-steel mold with a diameter of 25 mm was applied to guarantee that each asphalt sample had the same weight (10 ± 0.2 g) and the same contact surface area with the fuel when immersed in fuel. The specific experimental steps were as follows (see Figure 2):

![Figure 2. The fuel corrosion test. (a) Sample forming mold; (b) Asphalt sample after demolded; (c) The fuel corrosion test.](image)

(1) According to section T0702-2011 on the Chinese standard test methods for bitumen and bituminous mixtures for highway engineering (JTG E20-2011) [19], the heating temperatures of the base asphalt and modified asphalt were, respectively, chosen to be 160 and 170 °C. The asphalt was quickly and uniformly poured into the mold when heated to a certain temperature, and it was cooled at 25 °C for 2 h before demolding.

(2) The formed solid asphalt was weighed, and the qualified solid asphalt samples were placed into the measuring cups. A total of 100 mL of #0 diesel oil was poured into the measuring cups, and the cups were then sealed and held at 25 °C for 0.5, 2, 4, 8, 24, or 48 h.

(3) After a certain period of time, the liquid in the measuring cups was poured out, and the solids in the cups were taken out. The mixtures of the liquid asphalt and diesel oil on the surface of the solid asphalt samples were gently wiped off with a paper towel, the remaining solids were weighed, and the weight of the asphalt samples was lost after fuel immersion was calculated.

2.3.2. The Ductility, Penetration, and Softening-Point Tests

In traditional asphalt performance tests, the penetration, ductility, and softening point are often used to characterize the performance of asphalt, and they are determined as per T0604-2011, T0605-2011, and T0606-2011 [19]. All tests were repeated with 3 samples in parallel for each type of asphalt. It should be noted that the base asphalt and modified asphalt were tested at 15 and 5 °C, respectively, for the ductility test, as per the technical standards of the Chinese technical specifications for the construction of asphalt highway pavement (JTG F40-2004) [20].
2.3.3. Test of the Rheological Properties

The test of the rheological properties of asphalt was carried out with reference to T0628-2011 [19]. The Discovery Hybrid Rheometer 20 in Figure 3 (DHR-20; produced by the TA Company) was used to measure the complex modulus ($G^*$), phase angle ($\delta$), and rutting factors ($G^*/\sin\delta$) of the asphalt at different temperatures (58, 64, 70, 76, and 82 °C). In the experiment, the strain control mode was adopted with a target strain level of 12%. The diameter of the parallel plates was 25 mm, and the distance between the upper and lower parallel plates was 1 mm. The test frequency was 10 rad/s. The rheological property test was repeated for 3 samples in parallel for each type of asphalt.

![Figure 3. DHR-20.](image)

2.3.4. The Multiple Stress Creep Recovery (MSCR) Test

The MSCR test was proposed to solve the problem of the original evaluation system being inapplicable to the modified asphalt. The MSCR test was able to better simulate the repeated loading and unloading processes under different vehicle loads so as to reveal the high-temperature performance of the actual pavement.

The MSCR test was performed on the DHR-20. The MSCR test was repeated for 3 samples in parallel for each type of asphalt. Under the stress control mode, continuous tests were carried out at creep stress levels of 0.1 and 3.2 kPa, respectively. The creep time was set to 1 s, and the unloading recovery time was set to 9 s. After 10 cycles, the shear deformation of the samples was recorded, and the creep recovery ($R$) and non-recoverable creep compliance ($J_{nr}$) of the samples were calculated. Figure 4 shows a diagram of the strain of the samples within a single creep recovery cycle. The creep recovery ($R$) and non-recoverable creep compliance ($J_{nr}$) of the asphalt samples measured in each creep recovery cycle were calculated according to Equations (1) and (2), respectively.

\[
R = \frac{\varepsilon_p - \varepsilon_u}{\varepsilon_p} \times 100\% \quad (1)
\]

\[
J_{nr} = \frac{\varepsilon_u}{\sigma} \quad (2)
\]

where $\varepsilon_p$ denotes the peak strain, $\varepsilon_u$ is the unrecovered strain, and $\sigma$ represents the stress.
According to AASHTO T 350-14 [21], a rotor with a diameter of 25 mm was used in this test. The test was conducted at a temperature of 58 °C. The average values within 10 cycles at the stress levels of 0.1 and 3.2 kPa were taken as the evaluation indexes and were listed as R0.1, R3.2, Jnr,0.1, and Jnr,3.2, respectively. Moreover, the percent difference in recovery between 0.100 and 3.200 kPa (Rdiff) and percent difference in non-recoverable creep compliance between 0.100 and 3.200 kPa (Jnr-diff) were calculated, as shown in Equations (3) and (4):

\[ R_{\text{diff}} = \left[ \frac{(R_{0.1} - R_{3.2})}{R_{0.1}} \right] \times 100\% \]  

\[ J_{\text{nr-diff}} = \left[ \frac{(J_{\text{nr},3.2} - J_{\text{nr},0.1})}{J_{\text{nr},0.1}} \right] \times 100\% \]  

3. Results and Analysis
3.1. The Fuel Corrosion Test

Table 3 shows the results of the different asphalt samples submitted to fuel corrosion for different amounts of time.

Table 3. Mass loss rate of asphalt with different fuel immersion times.

| Asphalt | Average Asphalt Mass Loss Rate (%) | Standard Deviation (%) |
|---------|-----------------------------------|------------------------|
|         | 0.5 h 2 h 4 h 8 h 24 h 48 h | 0.5 h 2 h 4 h 8 h 24 h 48 h |
| 70#     | 10.9 28.0 35.7 56.2 70.8 91.1 | 4.6 4.5 3.4 1.9 2.7 3.3 |
| F-70#   | 5.9 16.3 33.5 51.6 59.4 85.9 | 0.5 2.1 1.7 0.9 2.5 2.6 |
| 90#     | 9.2 29.9 43.0 60.3 78.9 93.3 | 0.8 3.9 3.9 3.8 2.7 1.2 |
| F-90#   | 7.0 17.5 33.6 56.8 71.6 87.3 | 0.5 0.9 2.3 1.1 1.5 1.5 |
| SBS     | 5.1 8.1 12.7 28.0 45.4 79.4 | 0.5 0.3 1.5 2.5 0.5 3.5 |
| F-SBS   | 4.7 6.3 7.1 17.3 38.2 71.3 | 0.5 0.2 0.2 0.1 4.3 5.1 |
| HSBS    | 4.6 6.6 9.3 22.3 33.9 69.9 | 0.2 0.0 0.7 1.5 1.6 3.5 |
| F-HSBS  | 4.4 6.1 8.4 13.8 22.1 58.0 | 0.7 0.2 0.6 0.7 0.3 1.7 |
| RA      | 3.9 14.7 22.8 40.6 65.1 91.7 | 1.7 0.6 0.8 0.7 1.5 2.0 |
| F-RA    | 3.1 9.6 12.8 28.8 51.7 83.5 | 1.7 2.4 1.8 1.3 2.0 2.9 |

Note: The symbol # refers to a serial number and is commonly used in base asphalt performance grading.

As shown in Table 3, the weight loss of the 10 kinds of asphalt samples increased with the increase in fuel immersion duration. When the fuel corrosion lasted for 48 h, the weight of the asphalt samples corroded by the fuel exceeded 50%. As the dissolved and light components of the asphalt were gradually saturated in the fuel, the rate of the weight loss tended to slow down. In addition, compared with the original asphalt, the FRMAs had
smaller amounts of weight loss regardless of the fuel corrosion duration. The FRM was able to effectively absorb the light components in the asphalt and form a three-dimensional network structure with the asphalt in order to effectively enhance its fuel resistance.

It can be seen in Figure 5 that the effects of FRM on the improvement of the fuel resistance of the different types of asphalt were greatly different. Compared with the original asphalt, the fuel resistance of the base asphalt with the FRM added was increased by 8.5% on average, while that of the modified asphalt with the FRM added was remarkably improved by 30%. Since the added modifier formed a cross-linked structure with the asphalt to play the role of a “protective film”, the FRMAs showed better fuel resistance.

Figure 5. Asphalt mass loss rate after 48 h fuel immersion.

3.2. The Ductility, Penetration, and Softening-Point Tests

Table 4 and Figures 6–8 show the results of the penetration and softening-point tests. The evaluation indexes that are commonly used for asphalt include high-temperature evaluation indexes (penetration and softening point) and a low-temperature performance evaluation index (ductility). According to Table 4, the five types of original asphalts met the specification requirements. Table 5 shows the results of an independent-sample T-test at the confidence level of $p = 0.05$. The results indicated that, except for the softening point of the HSBS, the FRM caused a significant difference between the original and modified asphalts in terms of the ductility, penetration, and softening point.

Table 4. The results of ductility, penetration and softening point test.

| Technical Indexes | 70# | 5%FRM + 70# | 90# | 5%FRM + 90# | SBS | 5%FRM + SBS | HSBS | 5%FRM + HSBS | RA | 5%FRM + RA |
|------------------|-----|-------------|-----|-------------|-----|-------------|------|--------------|----|--|---|
| Ductility (cm)   | Test result | 107.3 | 41 | 112.5 | 46.6 | 38.1 | 28.3 | 33.7 | 23.6 | 22.9 | 14.8 |
| Standard         | - | ≥100 $^a$ | - | ≥100 $^a$ | - | ≥20 $^a$ | - | ≥30 $^b$ | - | ≥10 $^c$ | - |
| Penetration (0.1 mm) | Test result | 75.4 | 36.4 | 94.2 | 50.5 | 49.3 | 32.1 | 40.8 | 36.3 | 30.4 | 24.1 |
| Standard         | - | 60–80 $^a$ | - | 80-100 $^a$ | - | 40-60 $^a$ | - | ≥40 $^b$ | - | 30–60 $^c$ | - |
| Softening point ($^\circ$C) | Test result | 55.4 | 61.1 | 50.5 | 56.5 | 82.2 | 78.7 | 88.2 | 89.9 | 63.2 | 77.9 |
| Standard         | - | ≥45 $^a$ | - | ≥60 $^a$ | - | ≥80 $^b$ | - | ≥60 $^c$ | - | - | - |

Note: The letter $^a$ refers to Technical standards of the Chinese technical specifications for construction of highway asphalt pavements (JTG F40-2004). The letter $^b$ refers to the Chinese technical specifications for the design and construction of porous asphalt pavement (JTG/T 3350-03-2020); The letter $^c$ refers to the Chinese technical standard for rubberized asphalt pavement (CJJ/T 273-2019).
Figure 6. Ductility of original asphalt before and after added with the fuel-resistant modifier.

Figure 7. Penetration of original asphalt before and after added with fuel-resistant modifier.
Ductility characterizes the low-temperature performance of asphalt. As shown in Figure 6, compared with the original asphalt, the ductility of the FRMAs decreased significantly, indicating that the FRM was not conducive to the low-temperature performance of the asphalt. In addition, compared with the modified asphalt, the FRM has a more significant impact on the ductility of the base asphalt.

Penetration characterizes the consistency of asphalt at room temperature. As shown in Figure 7, before and after adding the FRM, the penetration of the SBS-modified asphalt, HSBS-modified asphalt, and RA was always lower than that of the #70 and #90 petroleum asphalts, with the penetration of the RA being the lowest. Compared with the original asphalt, different types of asphalt samples to which the FRM was added all experienced a significantly decreased penetration. The FRM absorbed the light components in the original asphalt and kept swelling, and the macromolecular and polar components were expanded to form a network structure in order to further limit the movement of molecules, thereby effectively improving the consistency of the original asphalt.

Moreover, the decrease in penetration of the different asphalt samples was significantly different, with the average decreases in the base asphalt and modified asphalt being about 49% and 22%, respectively. The unmodified base asphalt contained more fuel,
which contributed to the full absorption and swelling of the FRM. Therefore, the FRM exerted a more significant effect on the thickening of the base asphalt. Moreover, after adding the FRM, there were no obvious differences between the different types of asphalt samples in terms of penetration, so it was less accurate to characterize the high-temperature performance of the asphalt by using penetration.

Referring to the temperature at which the asphalt is softened to a certain viscosity, the softening point can be used to evaluate the high-temperature stability of asphalt. As shown in Figure 8, with the added FRM, the softening point of the base asphalt increased by 10% on average, the softening point of the HSBS-modified asphalt was slightly improved, and that of the RA was significantly increased by about 23%, which implied that the FRM could effectively improve the thermal stability of asphalt. In addition, there was little difference between the softening points of the different types of asphalt samples before and after the addition of the FRM, indicating that the addition of the FRM hardly affected the accuracy of the softening point in the characterization of the thermal stability of the asphalt.

In addition, according to Figures 7 and 8, the FRM affected the penetration and softening point of the HSBS-modified asphalt less significantly than those of the other asphalt samples. With the addition of high-viscosity particles, there were fewer oils in the SBS-modified asphalt that could be fully absorbed by the FRM.

3.3. The Test of the Rheological Properties

3.3.1. The Results for the Phase Angle ($\delta$)

Figure 9 shows the results of the phase angle ($\delta$) tests that were conducted on the different asphalt samples. The phase angle ($\delta$) is an index that reveals the viscoelastic characteristics of asphalt samples. The larger the phase angle ($\delta$), the higher the proportion of the viscoelastic component in the asphalt.

![Figure 9. Phase angles of different asphalt at different test temperatures.](image)

As shown in Figure 9, as the temperature rose, the phase angles ($\delta$) of the different asphalt samples increased, approaching $90^\circ$. The higher the temperature, the higher the proportion of high-viscosity particles, and the more significant the viscosity of the asphalt at high temperatures. At the same temperature, the phase angles ($\delta$) of the FRMAs apparently
decrease in comparison with that of the original asphalt, which indicated that the addition of the FRM could increase the proportion of high-viscosity particles in asphalt. Based on the results obtained in the penetration test, for the same kind of asphalt, penetration is positively correlated with the phase angle, implying that the phase angle can also reflect the high-temperature performance of asphalt to some extent.

Furthermore, at the same temperature, the phase angles of the SBS-modified asphalt, RA, and HSBS-modified asphalt were much smaller than those of the #70 petroleum asphalt and #90 petroleum asphalt, regardless of whether they contained the FRM or not, with the HSBS-modified asphalt having the smallest phase angle. Given the same temperature, with the FRM added, the phase angle of the modified asphalt decreased more significantly than that of the base asphalt. It is thus clear that the FRM exerted a more significant impact on the phase angle of the modified asphalt.

3.3.2. The Results for the Complex Modulus ($G^*$)

Figure 10 shows the complex modulus ($G^*$) of each asphalt sample. The complex modulus ($G^*$) characterizes the ability of asphalt to resist shear deformation under an external load.

It can be seen from Figure 10 that the complex modulus ($G^*$) of the different asphalt samples decreased with the increase in temperature. Under the action of high temperature, the asphalt became softer, and its elastic behavior was weakened, resulting in a decline in its ability to resist deformation. In addition, at the same temperature, the complex modulus ($G^*$) of each asphalt sample came increasingly closer with smaller differences, which showed that the temperature significantly influenced the complex modulus.

At the same temperature, the FRMAs had a greater complex modulus ($G^*$) than the original asphalt, indicating that the addition of the FRM could effectively improve the ability of asphalt to resist an external load and that the asphalt was less prone to shear deformation. This also explained the significant drop in the penetration of asphalt with the FRM.
In addition, at the same temperature, whether the FRM was added or not, the complex modulus \((G^*)\) of the SBS-modified asphalt, RA, and HSBS-modified asphalt was higher than that of #70 and #90 petroleum asphalt, with the complex modulus \((G^*)\) of the HSBS-modified asphalt being the largest. At the same temperature, with the addition of the FRM, the modified asphalt had an increased complex modulus \((G^*)\) compared with that of the base asphalt, which apparently showed that the FRM exerted a more significant impact on the complex modulus of the modified asphalt.

### 3.3.3. The Results for the Rutting Factors \((G^*/\sin \delta)\)

Figure 11 shows the test results of the different asphalt samples at different temperatures. According to the SHRP specification, the rutting factors \((G^*/\sin \delta)\) are used to assess the asphalt’s resistance to permanent deformation. The greater the values of the rutting factors are, the better the rutting-resistant performance of the asphalt will be.

As shown in Figure 11, the rutting factors of each asphalt sample gradually decreased as the temperature increased, and the viscoelasticity of the asphalt varied with the increase in temperature. Specifically, the complex modulus and the proportion of the elastic part of the asphalt decreased, and the anti-deformation ability and deformation recovery ability of the asphalt were weakened. Nonetheless, as the temperature rose from 58 to 82 °C, the difference between the rutting factors of the asphalt samples at the same temperature gradually decreased, which indicated that the temperature also significantly affected the differentiation of the rutting factors of the asphalt samples.

After the fuel-resistant modification, the rutting factors of all asphalt samples at the same temperature increased, but the range of this increase declined with the increase in temperature. The results showed that the FRM could effectively improve the high-temperature stability of the asphalt, but this impact was weakened at high temperatures.

In addition, at the same temperature, the rutting factors of the SBS-modified asphalt, RA, and HSBS-modified asphalt were smaller than those of the #70 and #90 petroleum asphalt—with or without the FRM—and the HSBS-modified asphalt possessed the largest rutting factors. Given the same temperature, with the addition of the FRM, the rutting
factors of the modified asphalt were more significantly improved than those of the base asphalt, which obviously indicated that the FRM exerted a more significant effect on the rutting factors of the modified asphalt. The above conclusion is consistent with the conclusion about the complex modulus.

3.4. The MSCR Test

3.4.1. The Results for the Percent Recovery (R) and Non-Recoverable Creep Compliance (\(J_{nr}\))

Figures 12 and 13 show the average recovery (R) and non-recoverable creep compliance (\(J_{nr}\)) of the different asphalt samples under the stress levels of 0.1 and 3.2 kPa at 58 °C. Figure 14 shows the relationship between \(J_{nr,3.2}\) and \(R_{3.2}\). The average recovery (R) and the non-recoverable creep compliance (\(J_{nr}\)) are important indexes for the evaluation of an asphalt binder’s resistance to deformation at high temperatures. The smaller the value of \(J_{nr}\) is, the larger the value of R will be. This shows that the recovered elastic deformation accounts for a larger proportion of the total deformation, while the proportion of non-recoverable deformation is smaller. The higher the asphalt’s high-temperature elasticity is, the stronger its resistance to deformation will be.

![Figure 12. Percent recovery R of different asphalt under different stress level.](image-url)
As shown in Figures 12 and 13, under different stress levels, compared with the original asphalt, the FRMAs experienced an increase in creep recovery (R) and a decrease in non-recoverable creep compliance ($J_{nr}$). The addition of the FRM mainly increased the complex modulus of the asphalt and delayed its elastic deformation, which effectively strengthened the elastic recovery of the asphalt. This is particularly important for the high-temperature pavement performance of an asphalt binder. In the analysis of the phase angle ($\delta$), it was mentioned that the addition of the FRM could increase the elastic components while reducing the viscous components of asphalt, which was better verified in the MSCR test, where the increased delayed elasticity was more accurately investigated.
By comparing the test results under two stress levels—namely, 0.1 and 3.2 kPa—it was found that the test results followed the same variation pattern under different stress levels. Nevertheless, as the stress level increased, the creep recovery (R) declined, while the non-recoverable creep compliance ($J_{nr}$) increased, which implied that the asphalt was more prone to shear deformation under high-stress levels.

According to Figure 14, all data points were above the reference curve. The original asphalts were effectively modified with the FRM. This modifier can help improve the fuel resistance of asphalt, as shown by the results in Figures 5 and 14.

3.4.2. The Results of $R_{diff}$ and $J_{nr-diff}$

Table 6 shows the values of $R_{diff}$ and $J_{nr-diff}$ of the different asphalt samples. The percent difference in non-recoverable creep compliance between 0.100 and 3.200 kPa ($J_{nr-diff}$) can be used to evaluate the stress sensitivity of asphalt, and the percent difference in recovery between 0.100 and 3.200 kPa ($R_{diff}$) reveals the formation degree of the polymer network structure in asphalt; a smaller value indicates a more complete polymer network structure [22].

As shown in Table 6, compared with the original asphalt, the $R_{diff}$ of the FRMAs decreased, which indicated that the FRM dispersed in the asphalt formed a completely interconnected network structure. The #70 petroleum asphalt, #90 petroleum asphalt, and HSBS-modified asphalt—to which the FRM was added—experienced a decrease in $J_{nr-diff}$, making them less sensitive to stress. However, it was exactly the opposite when it came to the SBS-modified asphalt and RA with the FRM added.

4. Correlation Analysis of the High-Temperature Performance Indexes of the Asphalt

As the traditional indexes for evaluating the high-temperature performance of asphalt, the penetration and softening point have been recognized by road engineers and extensively applied to current engineering practices. Moreover, it has been proposed that the correlation coefficient between non-recoverable creep compliance ($J_{nr}$)—the main evaluation index used in the MSCR test—and high-temperature rutting-resistant performance of asphalt can reach a value as high as 0.8167 [23]. Therefore, in this study, we conducted a Pearson correlation analysis with a confidence level of 0.05 between the penetration, softening point, non-recoverable creep compliance ($J_{nr}$), and other high-temperature performance indexes to investigate the accuracy and applicability of other indexes in the evaluation of the high-temperature performance of an FRMA. Table 7 shows the results of the Pearson correlation analysis. The conventional indexes of the above-mentioned FRMAs and the rheological indexes at 58 °C were selected as the data.

As shown in Table 7, the indexes of the rheological properties of the five asphalt samples were poorly correlated with the penetration, which was consistent with the above...
conclusion that “there is no obvious difference between different types of asphalt samples in terms of penetration after the addition of the FRM, so it is less accurate to characterize the high-temperature performance of asphalt by using penetration”. On the contrary, the correlation coefficient between the five rheological indexes and the softening point was about 0.90. Moreover, the absolute values of the correlation coefficients between the softening point, phase angle (δ), complex modulus (G*), rutting factors (G*/sinδ), and non-recoverable creep compliance (Jnr 0.1 and Jnr 3.2) were all greater than 0.90. The results indicated the excellent accuracy and applicability of the softening point and rheological indexes in evaluating the high-temperature performance of the FRMAs. Nonetheless, compared with the test of the softening point, tests of rheological properties have higher requirements in terms of the necessary instruments and are less frequently applied, which makes popularization very hard. Hence, it is suggested that the commonly used softening point should be applied for the evaluation of the high-temperature performance of FRMAs, and the rheological properties can be further determined if the conditions permit.

5. Conclusions

An investigation into the fuel resistance and high-temperature performance of original asphalt and FRMAs was conducted, and the high-temperature indexes were studied and compared. The following conclusions can be drawn from this paper.

(1) This FRM can effectively improve the fuel resistance of asphalt. With the addition of the FRM, the fuel resistance of the base asphalt and modified asphalt increased, on average, by 8.5% and 30%, respectively, which shows that the FRM improved the fuel resistance of the modified asphalt more significantly than that of the base asphalt.

(2) The addition of the FRM can reduce the penetration and increase the softening point of asphalt. After adding the FRM, there were no obvious differences between the different types of asphalt samples in terms of penetration, so it was less accurate to characterize the high-temperature performance of asphalt by using penetration.

(3) Adding the FRM can increase the proportion of the elastic component in asphalt, reduce the phase angle and the non-recoverable creep compliance (Jnr), increase the complex modulus, rutting factors, and creep recovery (R), strengthen the asphalt’s ability for elastic recovery and resistance of external loads, and effectively improve the high-temperature performance. Generally speaking, the FRM had a more significant effect on the rheological properties of the modified asphalt than on those of the base asphalt.

(4) Compared with the original asphalt, the creep recovery rate (R) of the FRMAs increased and the non-recoverable creep compliance (Jnr) decreased at different stress levels.

(5) Apart from penetration, the softening point and rheological indexes featured excellent accuracy and applicability in the evaluation of the high-temperature performance of the FRMAs. Furthermore, to simplify the index tests, it is suggested that the softening point be used to evaluate the high-temperature performance of FRMAs.

The present experiments focused primarily on high-temperature performance. The fatigue properties and low-temperature performance of FRMAs will be investigated in future studies.

Author Contributions: Conceptualization, H.L. (Hongwei Lin); Data curation, Formal analysis and Validation, W.L.; Funding acquisition, H.L. (Hongjun Li); Investigation, W.L., X.D., M.S. and S.L.; Methodology, H.L. (Hongwei Lin) and X.D.; Writing—Original Draft Preparation, X.D., M.S. and S.L.; Writing—Review & Editing, H.L. (Hongwei Lin) and W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Star Project of the Shanghai City, grant number NO.10QA1407200 and Science and Technology Innovation Demonstration Project of the Transportation Department of Yunnan Province (Science and Technology Education Section of Transport Department of Yunnan Province [2019] No. 14).
Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.
Data Availability Statement: Not applicable.
Conflicts of Interest: The authors declare no conflict of interest.

References
1. Fischer, H.R.; Cernescu, A. Relation of chemical composition to asphalt microstructure—Details and properties of micro-structures in bitumen as seen by thermal and friction force microscopy and by scanning near-filed optical microscopy. Fuel 2015, 153, 628–633. [CrossRef]
2. Cao, X.F.; Li, H.; Li, S.Q. Long term effect of diesel leakage on asphalt pavements. Highway 2016, 61, 194–198.
3. Chen, K.; Yuan, J.A.; Zhang, Y.C. Effect of oil erosion on high temperature performance of asphalt mixture. Shanghai Highw. 2013, 1, 59–60.
4. Li, Q.; Ma, X.; Li, K.; Zhao, K. Experiment on anti-fuel oil corrosion performance of stone mastic asphalt mixtures. J. Build. Mater. 2020, 23, 664–670.
5. Liu, B.F. Comparative analysis of high temperature performance evaluation indexes of asphalt. China Highw. 2012, 14, 118–119.
6. Li, S.Q.; Li, H. Asphalt mixture oil corrosion evaluation method based on oil corrosion degree. J. Wuhan. Univ. Technol. 2015, 37, 32–37.
7. Merusi, F.; Giuliani, F.; Filippi, S.; Moggi, P.; Polacco, G. Kerosene-Resistant Asphalt Binders Based on Nonconventional Modification. J. Transp. Eng. 2011, 137, 874–881. [CrossRef]
8. Li, H.; Li, S.Q. Research on asphalt oil corrosion mechanism. Highw. Eng. 2016, 41, 229–231.
9. Steernberg, K.; Read, J.M.; Seive, A. Fuel Resistance of Asphalt Pavements. In Proceedings of the 2nd Euroasphalt and Eurobitume Congress, Barcelona, Spain, 5 January 2001; pp. 558–567.
10. Zhenyu, T.; Hao, L. Diesel oil spill’s impact on road performance of asphalt pavement. Sci. Technol. Eng. 2018, 18, 326–330.
11. Li, Q.; Li, K.; Zhao, K.; Sun, G.; Luo, S. Fuel oil corrosion resistance of asphalt mixtures. Constr. Build. Mater. 2019, 220, 10–20. [CrossRef]
12. Mora, B.A.; Hilpert, M. Differences in infiltration and evaporation of diesel and gasoline droplets spilled onto concrete pavement. Sustainability 2017, 9, 1271. [CrossRef]
13. Van Rooijen, R.C.; De Bondt, A.H.; Corun, R.L. Performance evaluation of jet fuel resistant polymer-modified asphalt for airport pavements. In Proceedings of the FAA Worldwide Airport Transfer Conference, Kunming, China, 23 April 2004.
14. Pratico, F.G.; Ammendola, R.; Moro, A. Fuel Resistance of HMAs: Theory and Experiments. Int. J. Pavement Res. Technol. 2008, 1, 100–106.
15. Merusi, F.; Polacco, G.; Nicoletti, A.; Giuliani, F. Kerosene resistance of asphalt binders modified with crumb rubber: Solubility and rheological aspects. Mater. Struct. 2010, 43, 1271–1281. [CrossRef]
16. Giuliani, F.; Merusi, F.; Filippi, S.; Biondi, D.; Finocchiaro, M.L.; Polacco, G. Effects of polymer modification on the fuel resistance of asphalt binders. Fuel 2009, 88, 1539–1546. [CrossRef]
17. Irfan, M.; Saeed, M.; Ahmed, S.; Ali, Y. Performance evaluation of elvaloy as a fuel-resistant polymer in asphaltic concrete airfield pavements. J. Mater. Civil Eng. 2017, 29, 04017163. [CrossRef]
18. Chaturabong, P.; Lim, T.T.; Wong, Y.D. Effective surface treatment techniques for refinishing oil-stained road surface. Constr. Build. Mater. 2018, 159, 64–72. [CrossRef]
19. Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011); Research Institute of Highway Ministry of Transport; China Communications Press: Beijing, China, 2011.
20. Technical Standards of the Chinese Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004); Research Institute of Highway Ministry of Transport; China Communications Press: Beijing, China, 2004.
21. Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR); AASHTO Designation: T 350-14; American Association of State Highway and Transportation Officials: Washington, DC, USA, 2014.
22. Wu, C.Y.; Lv, Z.L. Evaluation on high temperature performance of activated rubber modified asphalt binder based on the multiple stress creep recovery test. J. China Foreign Highw. 2017, 37, 244–246.
23. D’angelo, J. The relationship of the MSCR test to rutting. Road Mater. Pavement Des. 2009, 10, 61–80. [CrossRef]