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Performance Evaluation of Asphalt and Asphalt Mixtures Modified by Fuel-Resistant Admixture

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Abstract: In the course of asphalt pavement usage, exposure to fuel infiltration accelerates particle detachment, leading to the occurrence of problems such as looseness and peeling. The aim of this study was to comprehensively evaluate the impact of a fuel-resistant modifier (FRM; 1%, 3%, 5%, 7%) on the performance of asphalt and asphalt mixture. Conventional physical tests and high–low temperature rheological tests were conducted on the fuel-resistant modified asphalt (FRMA). The results indicate that, with increased FRM content, the penetration and ductility of FRMA decreased, while the softening point increased. The high-temperature performance improved, but the low-temperature ductility declined. High–low temperature rheological test results demonstrate that the addition of FRM significantly enhanced the asphalt's shear deformation resistance. A moderate amount of FRM modification improved the asphalt's low-temperature crack resistance, but excessive FRM resulted in reduced flexibility. In addition, fuel-resistant modified asphalt mixture (FRMAM) specimens were prepared and evaluated for performance. In comparison to the base asphalt, FRM modification enhanced the resistance to oil erosion and peeling as well as the Marshall stability of asphalt mixtures. It reduced the scattering loss caused by fuel dissolution and improved both low-temperature indirect tensile (IDT) strength and high-temperature shear strength. A low content of FRM effectively reduced the sensitivity of asphalt mixtures to fuel infiltration, thus enhancing their road performance.

Keywords: asphalt; asphalt mixture; fuel-resistant modifier; road performance

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1. Introduction

Due to its high technological and service properties, asphalt concrete is a preferred material for road pavement construction [1]. As asphalt concrete contains asphalt as a binding material, and asphalt is a mixture of aromatic, aliphatic, and cycloalkane hydrocarbons generated during the refining of crude oil that are readily soluble in all oil-derived fuel [2]. Consequently, in the event of an accidental fuel spill, asphalt pavement can undergo surface softening, loosening, and other forms of damage. Fuel oil can dissolve the asphalt binder, leading to a significant reduction or even complete loss of adhesion between aggregates and asphalt. Moreover, vehicles traveling at high speeds create powerful vacuum suction, continuously pulling away aggregates in the pavement, ultimately resulting in problems such as looseness, peeling, and potholes [3]. In order to prevent oil infiltration from causing damage to asphalt pavement and compromising traffic safety, research on FRMAMs is particularly crucial.

Currently, research on the resistance of asphalt and asphalt mixtures to oil erosion predominantly focuses on experimental methods, assessment criteria, and the development of modifiers to enhance oil erosion resistance. In terms of experimental methods, the majority of researchers conduct experiments based on existing evaluation methods for asphalt and asphalt mixtures. By comparing the performance differences of materials before and after oil erosion using conventional testing methods, they assess the oil erosion resistance. Cao et al. [4] evaluated the impact of oil erosion on the performance of asphalt mixtures using the laboratory IDT test. Chen et al. [5] analyzed the impact of oil erosion on the high-temperature performance of asphalt mixtures, and found that oil erosion significantly reduced the Marshall stability and dynamic stability, with diesel oil having a greater impact than engine oil. Furthermore, mass loss testing is widely used to assess the oil erosion resistance. Zhang et al. [6], by comparing mass loss tests, rutting tests, and IDT tests before and after oil erosion on asphalt mixtures, demonstrated that oil erosion led to a significant decrease in asphalt mixture performance. By measuring the mass loss of asphalt binder samples in kerosene, Giuliani et al. [7] assessed asphalt solubility and compared the influence of polymer modification on the morphology, composition, and fuel resistance of asphalt.

Building upon this foundation, some researchers delve into the oil erosion resistance of asphalt and asphalt mixtures by starting with evaluation criteria, coupled with traditional asphalt mixture tests. Referencing the residual stability method of the Marshall immersion test, Li et al. [8] improved the method to obtain an oil erosion coefficient to assess the anti-oil erosion ability of asphalt mixtures. Based on the concept of oil erosion degree, Li et al. [9] proposed an asphalt oil erosion test method, validated its effectiveness, and recommended prioritizing rutting tests and Cantabro tests to evaluate the high-temperature stability and water stability of asphalt mixtures.

Currently, widely utilized fuel-resistant modifiers include but are not limited to non-coal tar sealers and polymer-modified binder [10]. The first type involves applying a seal over the pavement to prevent fuel penetration, while the latter type chemically reacts with asphalt, imparting inherent fuel-resistant properties. Due to the need for preparing modified asphalt in this study, the latter option is more suitable. Some researchers have investigated this by employing polymer-modified binders. Merusi et al. [11] investigated the enhancement of asphalt's resistance to oil erosion by incorporating aggregate materials, recycled rubber crumb, and synthetic wax as modifiers. The study revealed that the improvement in oil erosion resistance of polymer-modified asphalt is attributed to its compatibility with asphalt. Li et al. [12] added anti-oil erosion modifiers to asphalt mixtures and conducted partial road performance tests, and found that the anti-oil erosion technology effectively alleviated the pavement damage caused by oil erosion. Rizvi et al. [13] used biopolymers as anti-oil erosion modifiers, and the results indicated that the biopolymers not only significantly improved the anti-oil erosion performance of base asphalt but also enhanced its mechanical properties. Li et al. [14] studied the anti-oil erosion performance of five types of crushed stone–mastic asphalt mixtures, analyzing the impact of asphalt type, oil immersion time, anti-oil erosion agent, and other factors on their mechanical and road performance. The results showed that SBS-modified asphalt mixtures exhibited certain resistance to oil erosion in a short period, and the addition of anti-oil erosion agents significantly improved the oil erosion damage. Liu [15] added anti-oil erosion modifiers and high-viscosity particles to SBS-modified asphalt to investigate the effect on the anti-oil erosion and high-temperature performance of high-viscosity asphalt. The results showed that anti-oil erosion modifiers effectively improved the high-temperature performance of high-viscosity asphalt and had a good modifying effect on its anti-oil erosion performance. Liu et al. [16] explored the impact of anti-oil erosion modifiers on the high-temperature performance and anti-oil erosion modification of different asphalts. The results showed that anti-oil pollution modifiers effectively improved the high-temperature and anti-oil erosion performance of asphalt. Compared to the base asphalt, the impact of anti-oil erosion modifiers on the rheological properties of modified asphalt was more significant.

Yao et al. [17] used SBS-modified asphalt and polyamide resin to prepare a novel modified asphalt. The results indicated that polyamide resin enhanced the high-temperature and anti-oil erosion performance of asphalt and asphalt mixtures. From these studies, it is evident that polymer-modified binder can effectively enhance the fuel-resistance of both asphalt and asphalt mixtures. All of these research achievements promoted the further development of research on the anti-oil erosion performance of asphalt and asphalt mixtures. However, these studies focused on the high-temperature performance of both asphalt and asphalt mixtures, and there is limited literature on the impact of anti-oil erosion agents on the low-temperature and scattering performance as well as other aspects of asphalt and mixtures.

Building upon this foundation, the aim of this study was to comprehensively assess the impact of anti-oil erosion agent concentration on the performance of asphalt and asphalt mixtures through a variety of performance experiments. In this study, the internal doping method was used to incorporate FRM at concentrations of 1%, 3%, 5%, and 7% of the asphalt mass into the 70# asphalt base, resulting in the preparation of FRMA. Conventional physical tests and high–low temperature rheological tests were conducted to evaluate the influence of FRM on asphalt performance. Subsequently, FRMAMs were prepared, and tests on oil erosion, high–low temperature performance, and scattering performance, among other aspects, were conducted to gauge the improvement effect of FRM on the performance of the mixture.

2. Experimental Programs

Figure 1 shows the methodology followed in this study. It mainly includes materials, sample preparation, experiments used and test analysis.

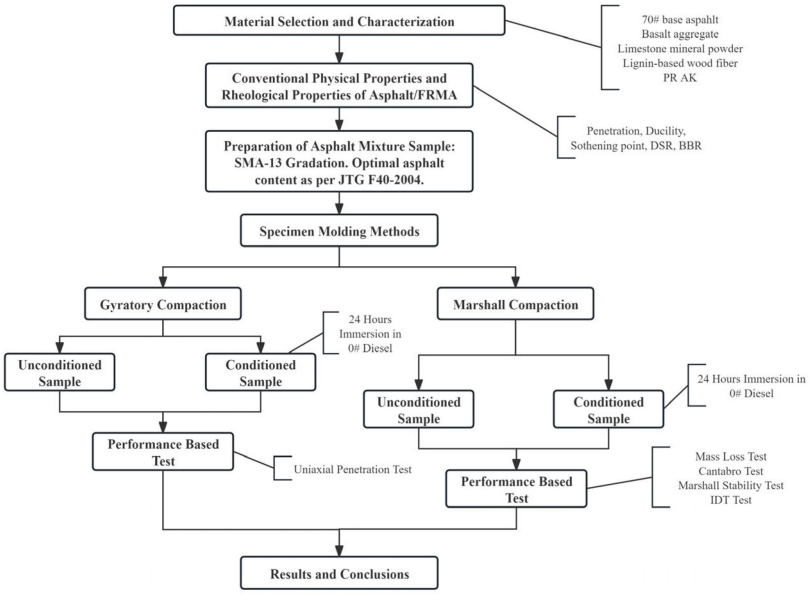

Figure 1. Experimental plan used in this study.

2.1. Raw Materials and Mixture Design

2.1.1. FRM

The present study utilized FRM developed by PR INDUSTRIE, as depicted in Figure 2. The material properties of the FRM are detailed in Table 1.

Figure 2. FRM.

Table 1. Technical indexes of FRM.

Index	Test Result
Appearance	Powdered particle
Particle diameter (mm)	0.01~2.00
Density (g/cm^3)	0.82~0.85
Melting point (°C)	<150 °C

2.1.2. Asphalt

In this study, 70# base asphalt was employed as the base material. The technical performance indicators are outlined in Table 2. This 70# asphalt met the requirements stipulated by the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) [18].

Table 2. Technical performance indicators of 70# base asphalt.

Property	70# Asphalt
Density (15 °C)/(g·cm^{-3})	1.018
Penetration (25 °C)/(0.1 mm)	72.3
Ductility (15 °C)/cm	>100
Softening point/°C	52.4
Flash point/°C	304
Solubility/%	99.84
Dynamic viscosity (60 °C)/(Pa·s)	210.5

2.1.3. Aggregates and Fiber

For this study, coarse and fine basalt aggregates and limestone mineral powder were selected as the aggregates. Lignin-based wood fiber was chosen as the fiber component, with an inclusion rate of 0.3% by mass of the mixture. The technical specifications for the aggregates and fiber met the requirements outlined in the Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004) [19].

2.1.4. Asphalt Mixture Design

The road performance of FRMAMs prepared with varying FRM content (0%, 1%, 3%, 5%, 7%) was evaluated. The selected aggregate gradation was SMA-13, and the gradation curve is illustrated in Figure 3. The mixture design for different SMA-13 blends followed the specifications outlined in Standard JTG F40-2004 [19], and the optimal asphalt content results are presented in Table 3.

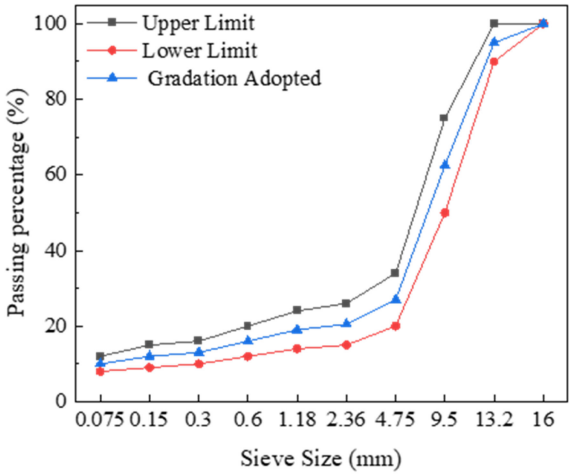

Figure 3. Design gradation of SMA-13 asphalt mix.

Table 3. Results of optimal asphalt content.

FRM content	0%	1%	3%	5%	7%
Optimal asphalt content	5.25	5.33	5.47	5.55	5.62

2.2. Laboratory Assessment

2.2.1. Experimental Methods for Asphalt

(1) Preparation of FRMA

FRMA was prepared using a high-speed shearing machine. Initially, the base asphalt was heated to a fluid state in a 165 °C oven. Subsequently, FRM with asphalt mass fractions of 1%, 3%, 5%, and 7% was individually added to the base asphalt. The mixture was then subjected to shear at a rate of 3600 r/min for 60 min at 180 °C, resulting in various FRMA compositions.

(2) Conventional Physical Tests

To effectively assess the impact of FRM on the conventional physical properties of asphalt, the 25 °C penetration, 15 °C ductility, and softening point of the asphalt were determined per T 0604-2011, T 0605-2011, and T 0606-2011 in Standard JTG E20-2011 [18]. Three parallel replicates are needed for penetration test, ductility test and softening point test on the same sample.

(3) Dynamic Shear Rheometer (DSR) Test

The purpose of the DSR test is to characterize the elastic and viscous properties of asphalt binders by measuring complex modulus $|G^*|$ and phase angle δ. The complex modulus $|G^*|$, phase angle δ, and rutting factor $|G^*|/\sin\delta$ of asphalt binders were determined at different temperatures to assess their high-temperature performance. The DSR test was conducted using the Discovery HR 20 hybrid rheometer (DHR-20) manufactured by TA Instruments (New Castle, DE, USA). Following AASHTO T 315 [20], the test employed a strain-controlled mode with a target strain level of 12% and a loading frequency of 10 rad/s. Complex modulus $|G^*|$ and phase angle δ of the asphalt were measured at various temperatures (58, 64, 70, 76, 82 °C). Two parallel replicates are needed for DSR test on the same sample.

(4) Bending Beam Rheometer (BBR) Test

The asphalt samples were subjected to the BBR test in accordance with AASHTO T 313 [21]. The low-temperature rheological behavior of the asphalt binder was evaluated by measuring the stiffness modulus (S-value) and creep rate (m-value) of the asphalt samples. For the test, asphalt binder beams with dimensions of 127 mm × 6.35 mm × 12.7 mm were used. The test temperatures were set at −6 and −12 °C. Two parallel replicates are needed on the same sample.

2.2.2. Experimental Methods for Asphalt Mixtures

(1) Oil Immersion Treatment

Considering that surface brushing and towel spreading can affect test stability due to diesel volatilization, the specimens were subjected to oil immersion treatment in this study. The mixture specimens were immersed in #0 diesel for 24 h and removed, and then were tested after the diesel had completely evaporated. A cylindrical stainless steel container was utilized for the oil immersion in this study. After placing standard Marshall specimens into the container, diesel was poured to a height of 70 mm, as depicted in Figure 4.

Figure 4. Marshall specimen oil immersion treatment.

(2) Mass Loss Test

The mass loss test utilized Marshall specimens. The experiment needs three parallel tests on the same sample. Prior to oil immersion, the mass of the specimens (m_1) was determined. After oil immersion, the specimens were retrieved, and once the diesel had evaporated, their mass (m_2) was measured. The mass loss of the specimens was calculated using Equation (1):

$$Q = (1 - \frac{m_2}{m_1}) \times 100\%, \quad (1)$$

where Q represents the mass loss due to oil erosion, m_1 is the mass of the asphalt mixture specimen before oil immersion, and m_2 is the mass of the asphalt mixture specimen after immersion.

(3) Cantabro Test

Specimens molded using the standard Marshall compaction method, with compaction applied to both sides for 50 cycles, were used for the test. The specimens had a diameter of 101.6 ± 0.2 mm and a height of 63.5 ±1.3 mm. The test was conducted at a temperature of 20 ± 0.5 °C. Three parallel tests are needed on the same sample. For detailed test procedures, refer to Section T 0733-2011 in Standard JTG E20-2011 [18]. The scattering loss (ΔS) of the asphalt mixture was calculated according to Equation (2):

$$\Delta S = \frac{m_0 - m_1}{m_0}, \quad (2)$$

where ΔS denotes the asphalt mixture loss due to flying debris, m_0 is the specimen mass before the test, and m_1 is the specimen mass after the test.

(4) Marshall Stability Test

The Marshall specimens conformed to the dimensions of 101.6 ± 0.2 mm diameter and 63.5 ± 1.3 mm height. The mechanical properties of the SMA-13 mixture were assessed using the Marshall stability test at 60 °C. Three parallel tests on the same sample are

required for the experiment. For detailed test procedures, refer to Section T 0709-2011 in Standard JTG E20-2011 [18].

In this study, the retained Marshall stability ratio (OR_{MS}) was chosen as the evaluation criterion for Marshall stability before and after oil erosion of FRMAMs. The calculation method is described by Equation (3):

$$OR_{MS} = \frac{MS_1}{MS_2} \times 100\%, \quad (3)$$

where OR_{MS} stands for the retained Marshall stability ratio, MS_1 represents the Marshall stability after oil immersion, and MS_2 represents the Marshall stability before oil immersion.

(5) IDT Test

The specimens were prepared using the standard Marshall compaction method, with a specimen diameter of 101.6 ± 0.2 mm and a height of 63.5 ± 1.3 mm. The compaction was carried out at a temperature of −10 ± 0.5 °C, and the loading rate was set at 1 mm/min. The experiment necessitates three parallel tests on the identical sample. The detailed experimental procedure is outlined in Section T 0716-2011 of Standard JTG E20-2011 [18]. The IDT strength (R_T) was computed using Equation (4). The retained IDT strength ratio (OR_{RT}) was employed as an assessment metric for the low-temperature performance change of FRMAMs before and after oil erosion, as calculated by Equation (5):

$$R_T = 0.006287\frac{P_T}{h}, \quad (4)$$

$$OR_{RT} = \frac{RT_1}{RT_0} \times 100\%, \quad (5)$$

where R_T represents IDT strength, P_T is the maximum experimental load, h is the specimen height, OR_{RT} is the retained IDT strength ratio, and RT_0 and RT_1 denote IDT strength before and after oil immersion, respectively.

(6) Uniaxial Penetration Test

In the uniaxial penetration test, the distribution of shear stress within the specimen during loading closely resembles that of an actual road surface under vehicle loading. Compared to other methods for evaluating shear strength in asphalt mixtures, this test demonstrates certain advantages in terms of data stability and experimental convenience [22]. The experiments were conducted using a universal testing machine (UTM). Specimens with a diameter of 100 ± 2.0 mm and a height of 100 ± 2.0 mm were shaped using a gyratory compactor at a temperature of 60 °C. The penetration head consisted of a thin upper plate with dimensions 50 mm length, 50 mm width, and 10 mm thickness, and a cylindrical lower body with a diameter of 28.5 mm and a height of 50 mm. Five parallel tests are needed on the same sample. The shear strength (R_τ) of standard height asphalt mixtures was computed according to Equation (6). For the detailed experimental procedure, refer to Appendix F of the Specifications for Design of Highway Asphalt Pavement (JTG D50-2017) [23]. Additionally, the retained shear strength ratio ($OR_{R\tau}$) was employed as an assessment metric for the high-temperature performance change of FRMAM before and after oil erosion, as calculated by Equation (7):

$$R_\tau = f_\tau \sigma_p = f_\tau \frac{P}{A}, \quad (6)$$

$$OR_{R\tau} = \frac{R\tau_1}{R\tau_0} \times 100\%, \quad (7)$$

where σ_p is the penetration stress, P is the ultimate load at specimen failure, A is the cross-sectional area of the penetration head, R_τ is the shear strength, and f_τ is the shear stress coefficient for a specimen with a diameter of 100 mm, with f_τ = 0.34. $OR_{R\tau}$ represents the retained shear strength ratio, with $R_{\tau 0}$ and $R_{\tau 1}$ denoting shear strength before and after oil immersion, respectively.

3. Results and Discussion

3.1. Performance of FRMA

3.1.1. Penetration, Ductility, and Softening-Point Test

Figure 5 illustrates the impact of FRM on asphalt penetration, softening point, and ductility. The parallel experimental results of the three experiments meet the error tolerance requirements specified for repetitive tests in Standard JTG E20-2011 [18]. The results indicate that with an increased FRM dosage, the asphalt's penetration and ductility decreased, while the softening point increased, consistent with existing literature trends [10]. The reduced penetration and increased softening point suggest enhanced viscosity and temperature stability of the asphalt, leading to improved high-temperature performance. The decreased ductility, on the other hand, indicates deteriorated low-temperature ductility, reflecting a negative influence of FRM on low-temperature performance. This can be attributed to FRM absorbing light components from the original asphalt and continuously expanding, resulting in expanded high-molecular-weight and polar components, which formed a network structure that further restricted molecular movement [7,16]. In summary, adding FRM contributes to enhancing the high-temperature performance of asphalt but has an adverse effect on low-temperature performance.

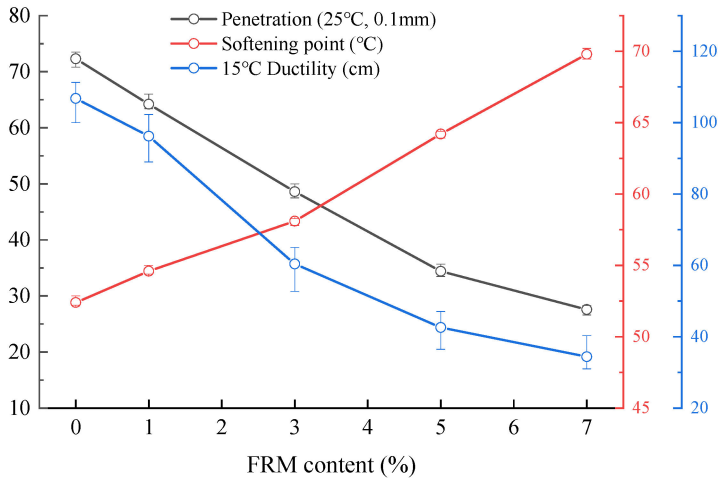

Figure 5. Variations in penetration, softening point, and ductility with varying FRM dosages.

3.1.2. DSR Test

The results of the DSR test are presented in Figure 6. The parallel experimental results meet the error tolerance requirements specified for repetitive tests in AASHTO T 315 [20].

The complex modulus is primarily used to assess the shear resistance characteristics of asphalt, as shown in Figure 6a. With increasing temperature, the complex modulus of FRMA with different dosages of FRM significantly decreased, and the differences among various compositions gradually diminished, indicating a substantial influence of temperature on the complex modulus of asphalt. At higher temperatures, the asphalt became softer, leading to a significant reduction in its ability to resist shear deformation. Additionally, under the same temperature conditions, the introduction of the modifier resulted in a significant increase in the complex modulus, indicating that adding the modifier effectively enhanced the asphalt's resistance to shear deformation.

The phase angle reflects the variation in the asphalt's viscoelasticity ratio, with a larger phase angle indicating more significant viscosity. The results of the phase angle in Figure 6b show that the phase angle of all asphalt samples increased with increasing test temperature. Increased temperature prompts asphalt to transition to a non-Newtonian viscous fluid state, with an increased proportion of viscous components, making the viscosity more pronounced at high temperatures. Under the same temperature conditions, the addition of FRM reduces the phase angle of the asphalt, and with an increasing dosage, the phase angle

gradually decreases. This suggests that adding FRM increases the stiffness and elasticity of the asphalt.

The Superpave design method employs the high-temperature rutting factor ($|G^*|/\sin\delta$) to evaluate asphalt's resistance to rutting, with a stipulated requirement for the original asphalt: $|G^*|/\sin\delta \geq 1.0$ kPa. A higher rutting factor value indicates better resistance to rutting. As shown in Figure 6c, at the same temperature, the addition of FRM enhanced the asphalt's resistance to rutting, indicating that FRM can effectively improve the high-temperature stability of asphalt. With increased FRM dosage, the rutting factor of FRMA decreased significantly at elevated temperatures, signifying considerable changes in the asphalt's viscoelasticity, a decrease in the proportion of elasticity, and reduced deformation recovery capability. As the temperature increased, the differences in the rutting factor for FRMA with different FRM dosages diminished, indicating an increased influence of temperature on the high-temperature performance of asphalt with increasing FRM dosage. The high-temperature performance of FRMA became more sensitive to temperature changes.

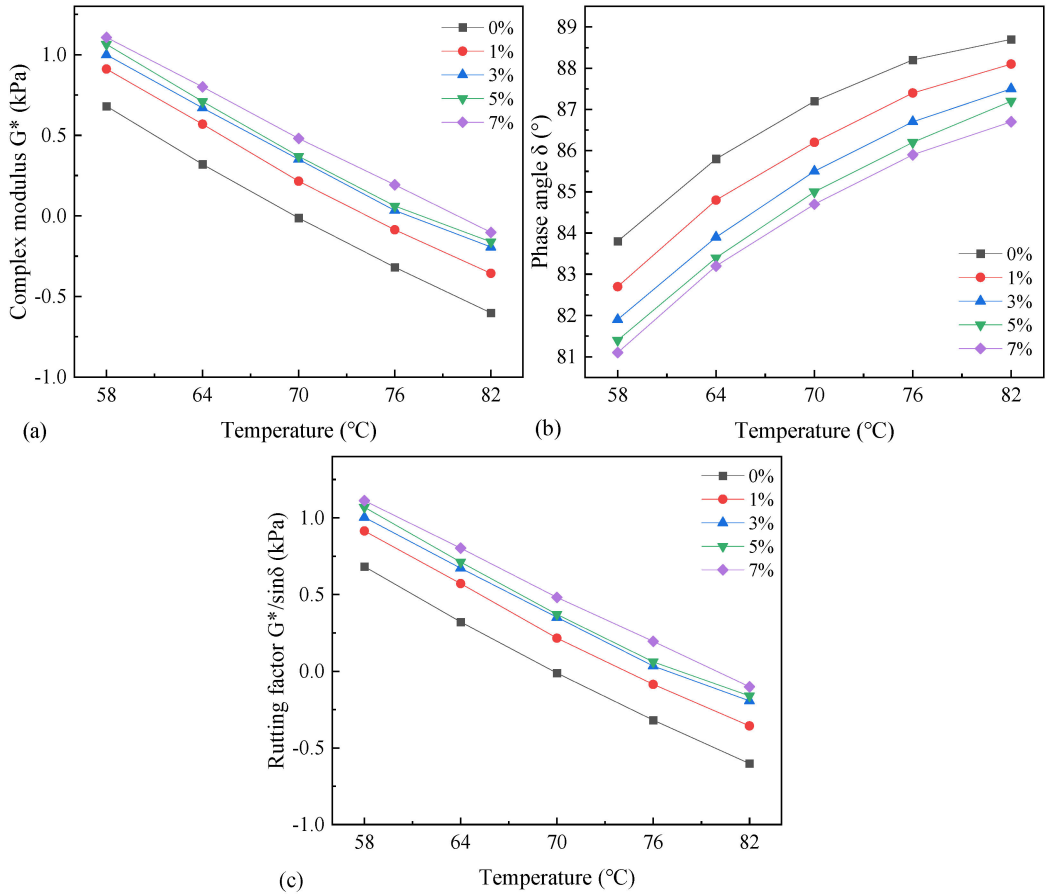

Figure 6. DSR test results of modified asphalt at different test temperatures: (**a**) complex modulus; (**b**) phase angle; (**c**) rutting factor.

3.1.3. BBR Test

The S-value and m-value from the BBR test are depicted in Figure 7. The experimental results satisfy the error tolerance criteria stipulated for repetitive tests outlined in AASHTO T 313 [21]. The S-value and m-value reflect the flexibility and stress relaxation ability of asphalt at low temperatures, respectively. Generally, higher S-values and lower m-values indicate poorer crack resistance performance of asphalt at low temperatures.

As shown in Figure 7a, the S-value of asphalt at −6 °C exhibits an upward trend with increasing FRM dosage, albeit a relatively minor overall increase. The S-value at −6 °C fluctuates with increasing FRM, which may be attributed to uneven distribution

of FRM in the asphalt caused by excessive dosage. The S-value at −12 °C demonstrates a V-shaped variation. In comparison to the base asphalt, the S-value of FRMA with 1% and 3% FRM decreases by 52.9% and 43.2%, respectively, indicating a significant reduction in stiffness and a shift toward elastic behavior. However, when the FRM dosage exceeds 3%, the S-value increases, resulting in a notable decrease in low-temperature flexibility. Additionally, as the test temperature decreases, the S-value of the same asphalt increases, indicating a reduction in low-temperature flexibility.

As observed in Figure 7b, the m-value at different temperatures exhibits a parabolic variation with increasing FRM dosage. In comparison to the other dosages, 1% FRMA has the highest m-value, and when the dosage exceeds 1%, the m-value significantly decreases. These results suggest that an appropriate amount of FRM is beneficial for the temperature stress dissipation of asphalt, but as the dosage increases, the stress relaxation performance diminishes.

In summary, the judicious use of FRM can effectively enhance the low-temperature flexibility and stress dissipation ability of asphalt, thereby strengthening its resistance to low-temperature cracking. The emergence of this outcome is hypothesized to be linked to the establishment of an elastic network structure within the asphalt facilitated by the modifier, thereby enhancing the asphalt's elasticity and flexibility [24]. This phenomenon contributes to the attenuation of asphalt deformation at lower temperatures, consequently bolstering its resistance to low-temperature creep. However, when the dosage of FRM is excessively high, interactions among polymers may intensify, resulting in a structure that is relatively deficient in elasticity [25,26]. This rigid configuration at lower temperatures could render the modified asphalt mixture more brittle, consequently diminishing its susceptibility to low-temperature creep. Furthermore, heightened concentrations of the modifier may lead to a decline in compatibility between the modifier and asphalt, resulting in an uneven dispersion of polymers within the asphalt. Under such circumstances, the formed structure could adversely affect the low-temperature performance.

According to SHRP specifications, the low-temperature performance at −12 °C for 1% and 3% FRMA meets the usage requirements of S ≤ 300 MPa and m ≥ 0.3.

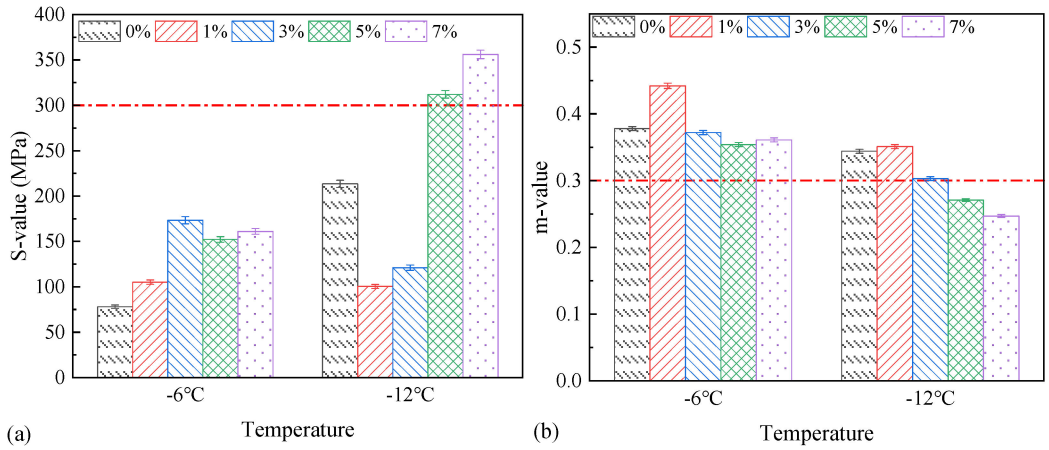

Figure 7. BBR test results: (**a**) S-value; (**b**) m-value.

3.2. Performance of SMA-13 Mixture

3.2.1. Mass Loss Test

As shown in Figure 8, after immersing the asphalt mixture specimens in diesel for 1 min, a noticeable change was observed in the diesel inside the container, which transitioned from clear pale yellow to turbid black. This indicates that diesel has a strong eroding effect on asphalt, as it rapidly dissolved the asphalt within the specimens. This is because the main components of diesel are hydrocarbons in the range of C15–C18, which are similar and highly soluble in the saturated fractions of asphalt [27].

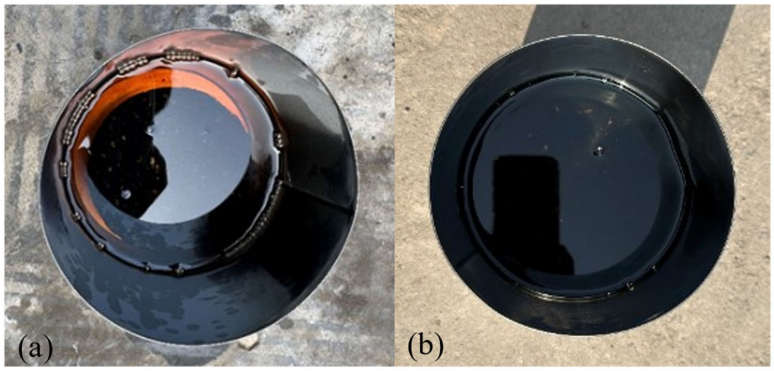

Figure 8. Marshall specimens after oil immersion treatment: (**a**) immediately after addition of diesel; (**b**) after 1 min of oil immersion.

The appearance of asphalt mixture specimens after 24 h of oil erosion is illustrated in Figure 9. Following the oil erosion treatment, specimens without added FRM exhibited extensive asphalt stripping, exposed aggregates, and partial aggregate loss on the surface. In contrast, the appearance of the mixture specimens remained relatively intact when FRM was added. Within the range of 1% to 5% FRM, there was no significant difference in the appearance of different FRMAM specimens. However, when the FRM dosage was increased to 7%, localized areas of severe asphalt stripping were observed in the asphalt mixture specimens. This phenomenon may be attributed to an excessively high FRM dosage, resulting in uneven distribution within the asphalt and leading to localized severe oil erosion.

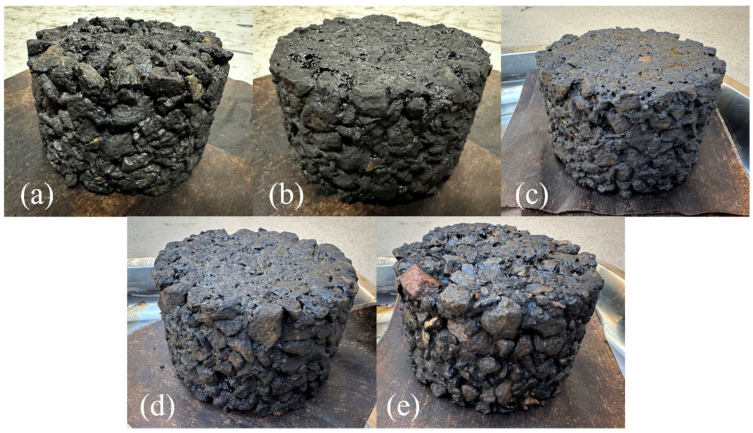

Figure 9. Post oil erosion conditions of asphalt mixture with different FRM dosages: (**a**) 0%; (**b**) 1%; (**c**) 3%; (**d**) 5%; (**e**) 7%.

After the diesel completely evaporated, the mass of each group of specimens was determined. The mass loss of the specimens was calculated using Equation (1), and the test results are shown in Figure 10. The asphalt mixture specimens without FRM exhibited the greatest mass loss after oil erosion, reaching 8.92%. In comparison to the base asphalt mixture specimens, the mass loss of FRMAM specimens was reduced. This indicates that the addition of FRM effectively enhanced the resistance of asphalt mixture to oil erosion.

When the dosage of FRM reached 1%, the mass loss of FRMAM specimens basically remained stable. It is inferred that the alteration in the rheological performance and oil erosion resistance of FRMA may have reached a certain level with a 1% FRM dosage. However, as the FRM dosage (>1%) is increased, a subsequent decline in the rheological performance of FRMA is observed.

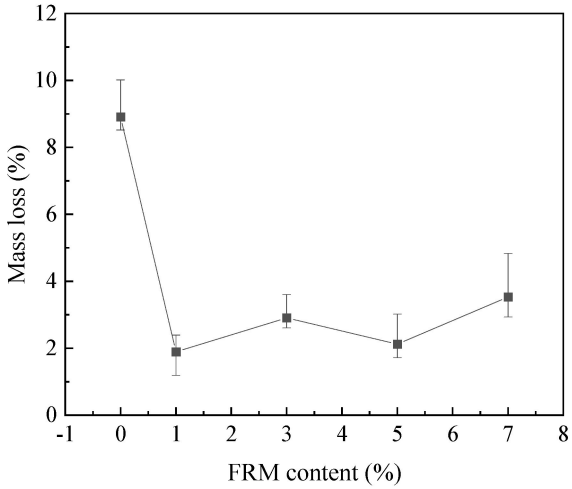

Figure 10. Variation curve of quality losses with different FRM concentrations.

3.2.2. Cantabro Test

The results of scattering loss are illustrated in Figure 11. As the FRM concentration increased, the pre-immersion and post-immersion scattering loss of asphalt mixture specimens initially decreased and then increased. Among the specimens, those containing 1% FRM exhibited the least scattering loss. In comparison to the absence of FRM, all FRMAM specimens showed a reduction in scattering loss, mainly attributed to the enhanced adhesion between aggregates and asphalt resulting from the co-solubilization of FRM and asphalt, forming an elastic network structure [7,24]. Additionally, post-immersion treatment led to a significant increase in scattering loss for all specimens. The scattering loss of the non-FRM-modified specimens reached 28.9%, an increase of 18.7% compared to pre-immersion. This is attributed to the dissolution of asphalt in the fuel after immersion treatment, leading to reduced asphalt film thickness and a substantial decrease in adhesion between aggregates. Consequently, the scattering loss significantly increased. Specimens containing 1% FRM exhibited the smallest difference in scattering loss, only 5.0%. When the FRM concentration exceeded 1%, the difference in scattering loss increased, which may be related to the change in rheological properties of asphalt. All FRMA samples showed larger scattering loss differences than the control group, consistent with the results of the massing test.

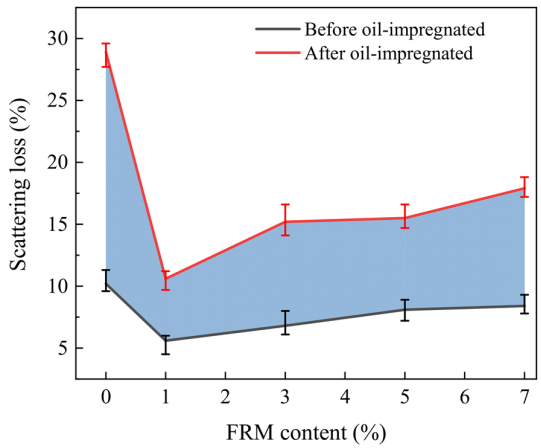

Figure 11. Results of the Cantabro test.

3.2.3. Marshall Stability Test

The results of the Marshall stability test are depicted in Figure 12. The parallel experimental results satisfy the error tolerance requirements stipulated for repetitive tests in Standard JTG E20-2011 [18].

Prior to immersion, the Marshall stability reached its peak at an FRM concentration of 1%, exhibiting a 21.07% improvement compared to the matrix asphalt. This improvement may be attributed to the enhanced rheological properties of FRMA in terms of strengthening the adhesion between asphalt and aggregates. The Marshall stability decreased with increased FRM concentration but still surpassed that of the matrix asphalt.

After the oil erosion treatment, the specimens without FRM exhibited the minimum OR_{MS}, reaching only 24.5%, accompanied by a significant decrease in Marshall stability. In comparison to the control group, specimens containing 1% to 7% FRM showed a substantial increase in OR_{MS}, approximately 31.3%, 37.4%, 28.8%, and 23.2%, respectively. Therefore, the addition of FRM effectively mitigated the impact of oil erosion on the Marshall stability of asphalt mixtures. Due to the influence of changes in the rheological properties in asphalt and the uniform distribution of FRM in FRMA, OR_{MS} exhibited a parabolic trend.

According to Standard JTG F40-2004, the Marshall stability requirements for SMA mandate a minimum of 5.0 kN for base asphalt and 5.5 kN for modified asphalt [19]. Before oil immersion, Marshall stability of all specimens met the requirements. After oil immersion, the requirements for Marshall stability were maintained with FRM contents of 1% and 3%. Nevertheless, at an FRM content of 5%, Marshall stability closely aligned with the requirements.

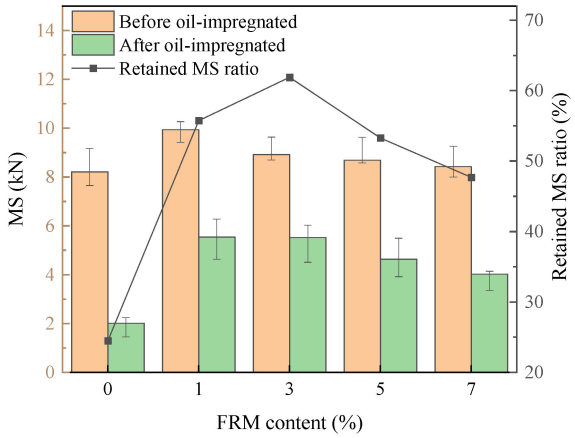

Figure 12. Results of the Marshall stability test.

3.2.4. IDT Test

The fracture strength of asphalt mixture at −10 °C is depicted in Figure 13. The experimental results satisfy the error tolerance criteria stipulated for repetitive tests outlined in Standard JTG E20-2011 [18].

As the FRM concentration increased, the pre-immersion IDT strength of the asphalt mixture increased, while the post-immersion IDT strength fluctuated. In comparison to samples without FRM, FRM effectively enhanced the low-temperature IDT strength of the asphalt mixture. Additionally, OR_{RT} exhibited a parabolic trend with increasing FRM concentration, reaching its peak at a concentration of 1%; however, beyond 1%, it significantly decreased. These results indicate that specimens containing 1% FRM had optimal sensitivity to the effects of fuel erosion on low-temperature performance, while those with FRM concentration >1% had significantly increased sensitivity.

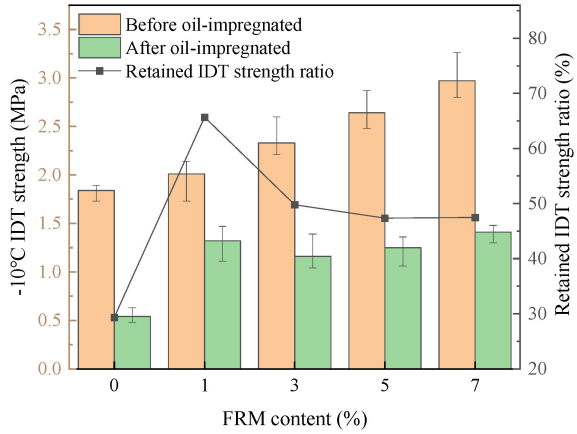

Figure 13. Results of the IDT test.

3.2.5. Uniaxial Penetration Test

The effect of FRM on the high-temperature shear strength of asphalt mixture is illustrated in Figure 14. The error tolerance requirements specified for repetitive tests in Standard JTG D50-2017 are met by the parallel experimental results [23].

Clearly, before oil immersion, the shear strength of asphalt mixture specimens with added FRM increased, and the increase was more pronounced with higher FRM concentrations. The greatest enhancement in shear strength occurred when the FRM concentration was increased from 0% to 1%. This improvement can primarily be attributed to the enhancement of high-temperature rheological properties of asphalt by FRM.

After oil immersion, the shear strength of asphalt mixture specimens without added FRM significantly decreased, with $OR_{R\tau}$ of only 36.39%, indicating a substantial negative impact of oil erosion on the high-temperature performance of the asphalt mixture. Conversely, specimens with FRM exhibited a noticeable increase in $OR_{R\tau}$, demonstrating that FRM can effectively mitigate the sensitivity of high-temperature performance of asphalt mixture to oil erosion. The most significant increase of $OR_{R\tau}$ occurred when the FRM concentration was increased from 0% to 1%, during which FRM was uniformly distributed in FRMA, resulting in the most pronounced improvement in high-temperature performance after oil erosion. When the FRM concentration was increased from 1% to 5%, the increase in $OR_{R\tau}$ was less pronounced, indicating that the dispersion of FRM in FRMA gradually reached saturation. Beyond a concentration of 5%, $OR_{R\tau}$ remained relatively stable, suggesting that FRM was fully saturated in FRMA, and there may have even been uneven dispersion, leading to a slight decrease in $OR_{R\tau}$.

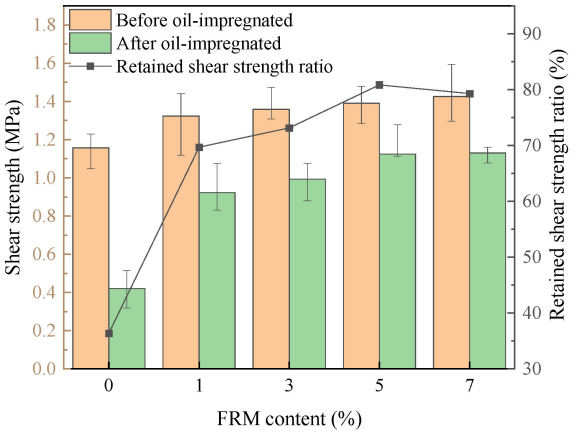

Figure 14. Results of uniaxial penetration test.

3.3. Economic Analysis

The current price of this FRM, including shipping costs, is Rmb30,000 per ton. The cost of FRM per ton of FRMA is detailed in Table 4.

Analyzing the example of a specific region, the average price of base asphalt in that area is Rmb3000 per ton, while 4.5% SBS modified asphalt is priced at Rmb7000 per ton. Even when the blending ratio of FRM reaches 7%, the cost of FRMA remains significantly lower than that of 4.5% SBS modified asphalt. However, based on the experimental results presented earlier, the optimal FRM dosage should be less than or equal to 3%. At this level, the cost increase for each ton of FRMA is kept within Rmb874. Compared to 4.5% SBS modified asphalt, approximately fifty percent of costs can be saved with each ton of FRMA. Therefore, from an economic cost perspective, research on FRMA holds practical significance and economic value.

Table 4. Cost of FRM per ton of FRMA.

FRM content	1%	3%	5%	7%
Cost of FRM (Rmb)	297	874	1429	1963

4. Conclusions

In this study, we employed FRM to prepare FRMA with the aim of enhancing the resistance of asphalt mixture to oil erosion. A comprehensive series of tests on the properties of asphalt and asphalt mixture were conducted to assess the feasibility of utilizing FRM in the preparation of FRMA. The conclusions are as follows:

- FRM has a significant impact on the high and low temperature performance of asphalt. With increased FRM concentration, the penetration, ductility, and phase angle of the asphalt decrease, while the softening point, complex modulus, and rutting factor increase. Adding FRM improves the high-temperature performance of asphalt but has some negative effects on low-temperature performance. Low concentrations of FRM can effectively enhance the low-temperature creep resistance of asphalt.
- The results of the mixture tests indicate that FRMA significantly enhances the performance of asphalt mixtures, effectively improving mass loss due to the oil erosion, scattering loss, Marshall stability, low-temperature IDT strength, and high-temperature shear strength of the specimens.
- Based on the evaluation results of oil erosion, FRM effectively reduces the mass loss due to oil erosion in asphalt mixtures and mitigates the impact of oil erosion on road performance. Specifically, low concentrations of FRM have the highest effectiveness in reducing the sensitivity of road performance to oil erosion.
- The impact of FRM concentration on the road performance of both asphalt and asphalt mixtures is substantial, and the influence on different performance aspects varies. Following the principle of achieving optimal comprehensive performance, it is recommended that the optimal dosage of FRM should be $\leq$3%, resulting in favorable rheological performance and oil erosion resistance for FRMA. An excess of FRM may potentially result in a degradation of rheological performance and an oversaturation of the modifier in the asphalt.

This study utilized various proportions of FRM in 70# asphalt binder and SMA-13 aggregate gradation to ascertain the optimal FRM proportion in the asphalt mixture. The research findings provide crucial insights into the application of FRMA in road engineering. Nonetheless, a more in-depth analysis of the modification mechanism for oil erosion resistance in FRMA and a correlation analysis between the micro-level properties of FRMA and the macro-level properties of FRMAM were lacking. Subsequent studies will focus on further evaluating how to improve the oil erosion resistance mechanism of FRM, as well as its impact on the fatigue performance of both asphalt and asphalt mixtures.

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Conflicts of Interest: Author Shuguang Zhang was employed by the company Wenshan Expressway Construction and Development of CCCC Co., Ltd., CCCC Western Investment Co., Ltd. Author Meng Tu was employed by the company Wenshan Tianwen Expressway Investment Development Co., Ltd. Author Wenchang Liu was employed by the company Shanghai Fengxian Construction Development Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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