A Study on the Application of Rock Asphalt from Sichuan China Based on Anti-Rutting Performance

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Received: 24 January 2019; Accepted: 25 February 2019; Published: 28 February 2019

Abstract: To solve the early rutting failure of asphalt pavement, the application of rock asphalt from Sichuan, China, based on anti-rutting performance, was studied. Preparations of North Sichuan rock asphalt (NS RA) and NS RA-modified asphalt mixture were elaborated in detail. Using Zhonghai AH-70 asphalt, Esso AH-70 asphalt, North American rock asphalt (NA RA) and NS RA, the performances of NS RA modified asphalt were researched based on index tests, Brookfield rotary viscosity test and bending beam rheometer test. A performance verification of NS RA-modified asphalt was carried out using rutting calculation, the rutting, indirect tensile fatigue, freeze–thaw split and small beam bending tests based on five kinds of selected gradations. The results indicated that in comparison with NA RA, the NS RA has a good modification effect as well. The NS RA can obviously improve the anti-rutting ability of the asphalt binder, and it can enhance its anti-aging performance as well. For the NS RA-modified asphalt mixture, it is feasible to determine the optimum NS RA content, based on its anti-rutting performance, and its optimum NS RA content is about 8%. The dynamic stability values of NS RA-modified asphalt mixtures are at least 3-fold higher than those of the base asphalt mixtures, and they are all far greater than the summer hot area requirement (no less than 2800 times/mm). NS RA-modified asphalt mixtures used in the middle course of asphalt pavement can obviously improve the anti-rutting performance of the pavement, and to enhance the anti-rutting ability of pavements, it should be used in the middle course of the pavement. The fatigue life values of NS RA-modified asphalt mixtures are at least 14.5-fold higher than those of the base asphalt mixtures. The freeze–thaw splitting strength ratio values of NS RA-modified asphalt mixtures are improved by at least 9.5% over the base asphalt mixtures, and their freeze–thaw splitting strength ratio values are all greater than the requirement (no less than 75%). In comparison with the base asphalt, the low temperature performances of NS RA-modified asphalt and its mixtures slightly decline, but they can meet the requirements for the zones with a minimum temperature of no less than –21.5 °C too. Therefore, except for the extremely low temperature area, it is an effective method for solving the rutting problem of pavement for using NS RA-modified asphalt.

Keywords: NS RA; asphalt mixture; anti-rutting performance; low temperature performance; fatigue performance; pavement

1. Introduction

With the constant increase heavy-traffic flow, heavy axle loads, and the traffic channelization of modern highway traffic, early rutting failure has been regarded as a serious issue confronting
asphalt pavement in China, especially in high-temperature areas in summer [1,2]. To solve the early rutting failure of asphalt pavement, it is necessary to research a new type of modified asphalt with excellent thermal stability. At the same time, it should meet the requirements of durability, such as fatigue resistance, low-temperature cracking resistance, and the moisture susceptibility etc., of asphalt pavement. To gain a more satisfactory pavement performance, rock asphalt (RA)-modified asphalt has attracted research interest in recent years, due to its excellent properties [3–7]. Many studies on RA have been performed. Menglan Zeng et al. investigated the performance of European RA-modified asphalt mixture, and found that the aging resistance, temperature susceptibility, and high-temperature behavior of RA-modified asphalt binder were improved considerably as the RA content increased [8]. Wentong Huang studied the microstructure, modified mechanism, and viscoelastic behavior of North American rock asphalt (NA RA), and found that its modification effect was excellent [9]. Ruixia Li et al. found that NA RA can reduce the relax potential and increase the stiffness of bitumen mastics [10]. Xueyuan Lu et al. studied the pavement performance of Buton RA mixture, and found that rock mineral the in raw materials of Burton RA have a significant effect on the pavement performance [11]. Menglan Zeng et al. studied the effect of proportion of Buton RA on the performance of modified asphalt mixture with the wet method, and found that with the increase of RA percentage, the high temperature rutting resistance, moisture damage resistance, permeability resistance, stiffness, and strength of the modified asphalt mixture improve gradually to varying degrees [12]. The effect of production processes on the high-temperature performance of Buton RA mixture was performed by Liping Liu et al. [13]. The mechanism and performance of Buton RA modified asphalt were studied by Songtao Lv et al. [14]. Hongliang Li investigated the modification mechanism of Wuerhe RA from Xinjiang China [15]. A performance evaluation of petroleum bitumen binders and mixtures that were modified by natural RA from Wuerhe, Xinjiang Province, China was performed by Ke Zhong et al. [16]. The modification mechanism and performance of Qingchuan RA from China-modified asphalt were investigated by Limin Li et al. [17]. Lu Zhaofeng et al. investigated the performance of native RA and its modified asphalt mixture, but their studies do not focus on solving the rutting problem [18–20]. Although some research work has been carried out for RA, there are still some research gaps at this stage. Most existing studies mainly focus on some specific properties of the RA binder or the RA mixture, such as the fatigue property or the high-temperature property. At the same time, few studies have conducted investigations on the application of RA, based on anti-rutting performance, with respect to the comprehensive performance of the RA mixture. Further, it was found that since the properties of RA can vary significantly, depending on the type and proportions of the components, the RA properties and sources have a great influence on the modification results [21]. There are rich reserves of RA in the northern part of Sichuan Province, China, and only a few studies have conducted investigations on this. To solve the early rutting failure of the pavement, and to promote the use of North Sichuan rock asphalt (NS RA), it beneficial to systematically research the application of NS RA-modified asphalt, based on anti-rutting performance.

2. Materials

In this study, NA RA and the NS RA were used, and their characteristic properties are given in Table 1. Zhonghai AH-70 asphalt and Esso AH-70 asphalt were employed as the base asphalts, and their properties are listed in Table 2. The coarse and the fine aggregates used in the study were gabbro, sourced from Panzhihua, Sichuan Province, China. The properties of coarse aggregates are given in Table 3. The mineral filler was crushed limestone. The test values in Table 4 reflect its properties. The aggregate gradations used in the study are shown in Figure 1. The preparation procedure of RA-modified asphalt was as follows: first, the base asphalt was preheated to a constant temperature of 140 °C. Second, a required dosage of RA was added to the base asphalt. Then, the mix was heated and maintained at a temperature of 175–180 °C. Afterward, the mix was stirred with a high-shear mixer for 20 min, then stopped for 10 min and stirred again for 20 min.
Table 1. Rock asphalt properties.

| Properties                              | Color          | Flash Point (°C) | Water Content (%) | Passing Percentage of Sieves (%) |
|-----------------------------------------|----------------|------------------|-------------------|----------------------------------|
| North American rock asphalt             | Block          | >260             | 1.0               | 26.1                             |
| North Sichuan rock asphalt              | Block blown    | >260             | 1.2               | 24.1                             |
| Methods                                 |                |                  |                   |                                 |
|                                         | T0611-2011 [22]| T0612-1993 [22] |                   |                                 |

Table 2. Base asphalt properties.

| Properties                              | Criteria         | Zhonghai AH-70   | Esso AH-70       | Methods                          |
|-----------------------------------------|------------------|------------------|------------------|----------------------------------|
| Ductility at 15 °C (cm)                 | ≥100             | 135              | 195              | T0604-2011 [22]                  |
| Penetration degree at 25 °C (0.1mm)     | 60–80            | 70               | 60.0             | T0605-2011 [22]                  |
| Softening point (°C)                    | ≥46              | 51               | 49               | T0606-2011 [22]                  |
| Dynamic viscosity at 60 °C (Pa·s)       | ≥180             | 217              | 223              | T0625-2011 [22]                  |
| Mass loss (%)                           | ±0.8             | −0.15            | −0.36            | T0609-2011 [22]                  |
| After the thin film oven test (TFOT)    | Ductility at 15 °C (cm) | 16.2           | 21.2             | ≥15                             |
|                                         | Ductility at 10 °C (cm) | ≥6             | 9.1              | 6.7                             |
|                                         | Penetration degree | −61.5           | 65               | ≥58                             |
|                                         | Mass loss (%)     |                  |                   |                                 |

Table 3. Coarse aggregate properties.

| Technical Indexes                        | Results         | Criteria       | Methods         |
|------------------------------------------|-----------------|----------------|-----------------|
| Crush value (%)                          | 13.5            | ≤28            | T0316-2005 [23] |
| Content of acicular and flaky shape particles (%) | 8.06           | ≤15            | T0312-2005 [23] |
| Losses of the Los Angeles Abrasion Test (%) | 17             | ≤30            | T0317-2005 [23] |
| Water absorption (%)                     | 0.22            | <2             | T0307-2005 [23] |
| Asphalt adhesion (gradation)             | 4               | ≥4             | T0616-1993 [23] |
| Impact value (%)                         | 17              | <30            | T0322-2000 [23] |
| Firmness (%)                             | 2.8             | ≤12            | T0314-2000 [23] |
| Mud content (%)                          | 0.7             | ≤1             | T0310-2005 [23] |

Table 4. Mineral filler properties.

| Properties                              | Hydrophilic Coefficient | Water Content (%) | Apparent Density (t/m³) | Size Distributions (%) |
|-----------------------------------------|-------------------------|-------------------|-------------------------|------------------------|
| Results                                 | 0.622                   | 0.932             | 2.699                   | 77.17 99.62 100       |
| Criteria                                | <1                      | ≤1                | ≥2.50                   | 75–100 90–100 100     |
| Methods                                 | T0353-2000 [23]         | T0350-1994 [23]   | T0352-2000 [23]         | T0351-2000 [23]       |

Figure 1. Aggregate gradations.
3. Performance of NS RA-Modified Asphalt

3.1. Index Tests

For comparison, the index tests of NA RA modified asphalt and NS RA modified asphalt for softening point, penetration and penetration ratio before and after aging were conducted in the study. RA was added to the base asphalt at the weight ratios of 0%, 2%, 4%, 6% and 8%, respectively. Aging was addressed by a rolling thin-film oven (RTFO) (air flow at 4 L/min, 163 °C and 85 min) according to American Society for Testing Materials D2872. The index tests were carried out according to the stand testing methods of bitumen and bituminous mixtures for highway engineering (JTG E20–2011) in China. Figure 2 shows the results.

![Figure 2. Index test results of the RA-modified asphalt.](image-url)

It can be seen from Figure 2 that for the same base asphalt, whether original asphalt or aging asphalt, the change trends of the softening point, penetration and penetration ration of NS RA modified asphalt were same as those of NA RA-modified asphalt. In comparison with NA RA, NS RA also had a good modification effect. However, there were performance differences to a certain extent,
for different RA-modified asphalts. The penetration value reflects the soft and hard extents and consistencies of asphalt. This has an important influence on the high-temperature stability and the low-temperature crack resistance of asphalt pavement. Figure 2a,b show that whether it is original asphalt or aging asphalt, the softening point value of NS RA-modified asphalt was larger than that of base asphalt, and that it is greatly increased with the increase of the NS RA content. Therefore, the NS RA can enhance the high-temperature deformation resistance of the asphalt binder. At the same time, the high-temperature performance became greater with increasing NS RA content. It can be seen from Figure 2c,d that whether it was original asphalt or aging asphalt, the penetration value of NS RA-modified asphalt was lower than that of base asphalt, and the penetration value was greatly decreased with the increase of NS RA content. Therefore, the NS RA can obviously improve the consistency and the deformation resistance of asphalt binder. As seen in Figure 2e, the penetration ratio was elevated with an increase in NS RA, which indicates that the anti-aging performance of NS RA-modified asphalt is improved with the increase of NS RA content.

3.2. Brookfield Rotary Viscosity Test

The viscosity can reflect the actual usage of pavement structure asphalt at high temperatures. Under loading, the shear deformation of the high-viscosity asphalt is small; its elastic recovery ability is strong, and its permanent plastic deformation becomes small. Therefore, its anti-rutting capability becomes strong. The Brookfield rotary viscosity tests of NS RA-modified asphalts for Esso AH-70 base asphalt were conducted according to American Association of State Highway and Transportation Officials T316 by using a Digital Viscometer BROOKFIELD DV-II (Brookfield Company, Middleboro, MA, USA). According to the Superpave specifications, the viscosity of the original asphalt is required to be a maximum of 3 Pa·s at 60 °C. The results are shown in Figure 3.

![Figure 3. Viscosity of the NS RA-modified asphalt.](image)

Figure 3 shows that comparing the base asphalt and the NS RA-modified asphalt at the same temperature, the viscosity value of the modified asphalt was significantly increased with an increase in NS RA content. At 135 °C, the viscosity value of modified asphalt with 8% NS RA content was 1.56 Pa·s, and it was approximately three times larger than the viscosity value of the base asphalt, indicating that under loading, the shear deformation of the NS RA-modified asphalt was smaller than that of the base asphalt, and that its ability for elastic recovery was stronger. Therefore, its permanent plastic deformation became smaller, and its anti-rutting ability was enhanced. At the same time, the viscosity values of the modified asphalts with NS RA ranged from 2% to 8% less than 3 Pa·s at 135 °C, which could meet the Superpave specifications for an asphalt binder.
3.3. BBR Test

The low temperature performance of NS RA was evaluated by a bending beam rheometer (BBR) test. The creep stiffness change rate, m, at 60 s, and the creep stiffness S, are the most important two parameters of the BBR test. A larger m-value and a lower S-value correspond to a better stress relaxation ability and deformation ability, respectively. That is, a larger m-value and a lower S-value correspond to a better low-temperature crack resistance of bitumen binder. A maximum S-value of 300 MPa and a minimum m-value of 0.3 f are set by the Superpave binder specifications. NS RA-modified asphalts for Esso AH-70 base asphalt before and after aging and at three different temperatures (−10 °C, −16 °C and −22 °C) were used in the BBR test. According to Superpave specifications, BBR tests were conducted by using a BBR 9728-V30 from the Cannon Company. The test results are shown in Figure 4.

Figure 4 shows that whether original asphalt or aging asphalt, the m-value decreased, and the S-value increased with a decrease in temperature, from −10 °C to 22 °C for NS RA-modified asphalts. According to the Superpave specifications, for modified asphalt with different NS RA content (2%~8% by weight), the low-temperature performance grade was −16 °C. At the same time, the content of NS RA has a great influence on the m-value decrease and the S-value. In detail, whether it was the original asphalt or aging asphalt, the m-value obviously decreased and the S-value increased with an increase of NS RA content. Under the same conditions, the m-value of the NS RA-modified asphalt was lower than that of the base asphalt, and the S-value of the NS RA-modified asphalt was higher than that of the base asphalt. That is, in comparison with the base asphalt, the low-temperature performance of NS RA-modified asphalt slightly declined, and its low-temperature performance becomes weaker with an increase in NS RA content. Therefore, considering the low-temperature cracking resistance, RA-modified asphalt was not appropriate for extremely low-temperature areas.
4. Performance of a NS RA-Modified Asphalt Mixture Based on Anti-Rutting Performance

To validate the performance of NS RA, performance tests of its modified asphalt mixtures for Esso AH-70 base asphalt were conducted, according to the standard test methods for bitumen and bituminous mixtures for highway engineering (JTG E20-2011) in China. The best asphalt aggregate ratios of NS RA-modified asphalt mixtures with the optimum NS RA content were used in the performance tests. The best asphalt aggregate ratio of the NS RA-modified asphalt mixture was determined through the Marshall test.

4.1. Preparation of the NS RA-Modified Asphalt Mixture

Based on the optimum amount of asphalt and the required NS RA dosage, the amount of asphalt replaced by NS RA was obtained. The preparation of NS RA-modified asphalt mixture was as follows: first, aggregates and mineral filler determined by the gradation used were preheated to a temperature of 175–180 °C, respectively. Second the required dosage of NS RA and the preheated aggregates were added into the mixing pot, and they were stirred for 25–30 s. Then, the Esso AH-70 base asphalt, preheated to the constant temperature of 150 °C was added into the mixing pot and stirred for 60–90 s. Finally, the preheated mineral filler was added into the mixing pot and stirred for 90 s. Meanwhile, the mixing temperature of the asphalt mixture was controlled at 170–175 °C, during the preparation of the NS RA-modified asphalt mixture.

4.2. Determination of the Optimum NS RA Content

To solve the rutting failure of the pavement, the optimum NS RA content was determined based on the anti-rutting performance of the NS RA-modified asphalt mixture. Gradation 5 was used, and the rutting tests of its NS RA-modified asphalt mixtures were conducted by using a rutting tester from China. The test results are shown in Figure 5.

As observed in Figure 5, when the NS RA content was less than 8%, the dynamic stability of its modified asphalt mixture dramatically increased with an increase in NS RA content. The dynamic stability of the modified asphalt mixture with 8% NS RA content is was 3.52-fold higher than that of the base asphalt mixture. However, it is interesting to find that when the NS RA content was more than 8%, the dynamic stability of its modified asphalt mixture had no significant increase. The dynamic stability with 12% NS RA content was only 1.03-fold higher than that of the base asphalt mixture. Therefore, considering the raw material price of NS RA, based on its anti-rutting performance, the optimum NS RA content was about 8%.

4.3. Anti-Rutting Performance

To validate the anti-rutting performance of the optimum NS RA contents, rutting tests of the NS RA modified asphalt mixtures with different gradations were performed by using a rutting tester from China. The results are shown in Figure 6.

It can be seen from Figure 6 that for five kinds of selected gradations, under the same experimental conditions, the dynamic stability values of the NS RA-modified asphalt mixtures were far higher those of the base asphalt mixtures. The dynamic stability values of NS RA-modified asphalt mixtures were at least 3-fold higher than those of the base asphalt mixtures, and their...
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To validate the anti-rutting performance of the modified asphalt mixtures of the optimum NS RA contents, rutting tests of the NS RA modified asphalt mixtures with different gradations were performed by using a rutting tester from China. The results are shown in Figure 6.

![Figure 6](image_url)

**Figure 6.** Dynamic stability of NS RA-modified asphalt mixtures with different gradations.

It can be seen from Figure 6 that for five kinds of selected gradations, under the same experimental conditions, the dynamic stability values of the NS RA-modified asphalt mixtures were far higher than those of the base asphalt mixtures. The dynamic stability values of NS RA-modified asphalt mixtures were at least 3-fold higher than those of the base asphalt mixtures, and their dynamic stability values were all far greater than the summer hot area requirement (no less than 2800 times/mm) of the technical Specifications for the construction of highway asphalt pavements (JTG F40-2004) in China. Therefore, for a NS RA content of 8%, the anti-rutting performances of their modified asphalt mixtures are excellent.

To further validate the anti-rutting performances of the NS RA-modified asphalt mixtures, considering that the middle course is the anti-rutting key layer of the pavement [24], the rutting calculations of the pavement structure shown in Table 5 were carried out. Aggregate gradations of asphalt mixtures are shown in Figure 7. For asphalt mixture, the materials model of Burgers model was employed. The 15, 20, 35, 40, and 60 °C uniaxial creep tests of asphalt mixtures with the optimal asphalt aggregate ratios were done, and the results are shown in Table 6. According to the pavement temperature, the material parameters of the Burgers model were obtained by interpolation. According to the literature [25], other calculation parameters are shown in Table 7, and the axle load times of $4.2 \times 10^5$ were adopted. The rutting calculation method from the literature [25] was used, where the error between the test data and the calculation result was 8.5%, as shown in Figure 8. The calculation results are shown in Figure 9.

| Structure A                  | Structure B                                      |
|-----------------------------|-------------------------------------------------|
| 4 cm AC-13C                 | 4 cm AC-13C                                     |
| 6 cm AC-20 (NS RA modified asphalt) | 6 cm AC-20C (Shell SBS-70 modified asphalt)    |
| 8 cm AC-25C                 | 8 cm AC-25C                                     |
| 8 cm ATB-25                 | 8 cm ATB-25                                     |
| 20 cm Cement stabilized aggregate | 20 cm cement-stabilized aggregate             |
| 20 cm Lime soil subgrade    | 20 cm Lime soil subgrade                        |

Table 5. Pavement structure of calculation.
Different gradations were conducted by using an asphalt mixture pneumatic servo-test system NS RA content, the indirect tensile fatigue tests of the NS RA-modified asphalt mixtures with NS RA content, the indirect tensile fatigue tests of the NS RA-modified asphalt mixtures with NS RA content.

4.4.1. Fatigue Performance

Therefore, to enhance the anti-rutting ability of the pavement, it should be used in the middle course of the pavement structure. Therefore, the NS RA-modified asphalt mixtures used in the middle course of the pavement structure.

The rutting depth of the pavement structure A was decreased by 44% over pavement structure B. However, the only difference between pavement structure A and B was the asphalt of structure.

The critical value of the fatigue damage is with a specimen stiffness reduction of 50%. The results are shown in Figure 11.

The test load was the half vector wave loading with an unloading time four times the loading time. The test temperature was 15 °C. The strain control mode was adopted, and the NU-14 (Figure 10).

It can be seen from Figure 9 that rut depths of structures A and B were 5.12 and 9.15 mm, respectively.

The Elastic Modulus of aggregate and the Calculated test results.

### Calculation and test results.

Figure 7. Aggregate gradations of the asphalt mixtures.

Figure 8. Calculation and test results.

### Table 6. Calculation parameters of asphalt mixtures.

| Gradation Type | Asphalt Type | Temperature (°C) | E₁ (kg/cm²) | η₁ (Pa.s) | E₂ (kg/cm²) | η₂ (Pa.s) |
|----------------|--------------|------------------|-------------|-----------|-------------|-----------|
| AC-13          | Shell SBS-70 | 60               | 1000        | 34,652    | 450         | 1,684,652 |
|                | modified     | 35               | 3000        | 111,357   | 597         | 1,641,532 |
|                | asphalt      | 20               | 4000        | 74,856    | 1365        | 3,270,865 |
| AC-20          | Shell SBS-70 | 60               | 800         | 9761      | 511         | 1,412,325 |
|                | modified     | 35               | 2200        | 99,462    | 461         | 1,806,501 |
|                | asphalt      | 20               | 3500        | 50,317    | 1647        | 2,334,658 |
| AC-20          | NS RA-modified | 60           | 229         | 117,804   | 277         | 146,463   |
|                | asphalt      | 40               | 738         | 731,707   | 344         | 61,424    |
|                | Zhonghai     | 15               | 7559        | 4,227,813 | 2043        | 433,027   |
| AC-25          | AH-70 base   | 35               | 2050        | 9087      | 1322        | 2,003,491 |
|                | asphalt      | 20               | 2800        | 16,652    | 1597        | 2,628,311 |
|                | Zhonghai     | 60               | 580         | 8245      | 487         | 1,256,866 |
| ATB-25         | AH-70 base   | 35               | 1860        | 72,784    | 1087        | 1,819,868 |
|                | asphalt      | 20               | 2780        | 13,618    | 1394        | 2,588,862 |

### Table 7. Other calculation parameters.

| Material Type | Thickness (cm) | Elastic Modulus (MPa) | Poisson Ratio | Friction Angle (°) | Cohesive Force (kPa) | Density (kg/m³) |
|---------------|----------------|-----------------------|---------------|-------------------|----------------------|-----------------|
| Cement Stabilized aggregate | 19               | 1500                  | 0.25          | -                 | -                    | 2400            |
| Lime soil    | 20              | 550                   | 0.35          | 22                | 55                   | 1930            |
| subgrade     | -               | 48                    | 0.40          | 16                | 30                   | 1900            |
It can be seen from Figure 9 that rut depths of structures A and B were 5.12 and 9.15 mm, respectively. The rutting depth of the pavement structure A was decreased by 44% over pavement structure B. However, the only difference between pavement structure A and B was the asphalt of the middle course. Therefore, the NS RA-modified asphalt mixtures used in the middle course of the pavement could obviously improve the anti-rutting performance of the asphalt pavement. Therefore, to enhance the anti-rutting ability of the pavement, it should be used in the middle course of the asphalt pavement.

4.4. Other Performance Verifications based on Anti-Rutting Performance

4.4.1. Fatigue Performance

To validate the anti-fatigue performance of the modified asphalt mixtures with the optimum NS RA content, the indirect tensile fatigue tests of the NS RA-modified asphalt mixtures with different gradations were conducted by using an asphalt mixture pneumatic servo-test system NU-14 (Figure 10). The test temperature was 15 °C. The strain control mode was adopted, and the test load was the half vector wave loading with an unloading time four times the loading time. The critical value of the fatigue damage is with a specimen stiffness reduction of 50%. The results are shown in Figure 11.

As it is observed in Figure 11, for five kinds of selected gradations, under the same experimental conditions, the fatigue life values of NS RA-modified asphalt mixtures was far higher than that of the base asphalt mixture. The fatigue life values of the NS RA-modified asphalt mixtures were at least 14.5-fold higher than those of the base asphalt mixtures. Therefore, for a NS RA content of 8%, the anti-fatigue performances of its asphalt mixtures can be improved remarkably.
4.4.2. Moisture Susceptibility

To validate the water stability performance of modified asphalt mixtures with the optimum NS RA content, freeze–thaw split tests of NS RA-modified asphalt mixtures with different gradations were performed. The freeze–thaw splitting strength ratio is the ratio of the freeze–thaw splitting strength to splitting strength. A higher splitting strength ratio corresponds to a higher moisture damage resistance. The results are shown in Figure 12.

Figure 12 shows that for five kinds of selected gradations, under the same experimental conditions, the freeze–thaw splitting strength ratio values of NS RA-modified asphalt mixtures are higher than those of the base asphalt mixtures. The freeze–thaw splitting strength ratio value of the NS RA-modified asphalt mixture was improved by at least 9.5% over the base asphalt mixture. Their freeze-thaw splitting strength ratio values were all greater than the requirements of technical specifications (not less than 75%) for the construction of highway asphalt pavements (JTG F40-2004) in China. Therefore, for a NS RA content of 8%, the moisture susceptibility performances of the asphalt mixtures can be improved to some degree, and they are able to meet the requirement of not less than 75%.

Figure 12. The freeze–thaw split test results of NS RA-modified asphalt mixtures with different gradations.
4.4.3. Low-Temperature Performance

To validate the low-temperature anti-cracking performance of modified asphalt mixtures with the optimum NS RA content, small beam bending tests of NS RA-modified asphalt mixtures with different gradations were carried out using an MTS810 material testing system (MTS Systems Inc., Eden Prairie, MN, USA) at $-10\degree C$. For the small beam bending test, the fracture strain is the important evaluation index. A larger value of fracture strain indicates a better low-temperature anti-cracking performance for the NS RA modified asphalt mixture. The results are shown in Figure 13.

![Failure stiffness modulus](image1.png)

![Failure strain](image2.png)

**Figure 13.** The small beam bending test results of NS RA-modified asphalt mixtures with different gradations.

Figure 13 shows that for five kinds of selected gradations, under the same experimental conditions, the failure strain values of NS RA-modified asphalt mixtures were slightly lower than those of the base asphalt mixtures, while their stiffness failure modulus values were higher than those of the base asphalt mixtures. The failure strain value of NS RA-modified asphalt mixture was decreased by, at most, 5.6% over the base asphalt mixture. However, its strain failure values were still more
than 2500. According to the technical specifications for the construction of highway asphalt pavement (JTG F40-2004) in China, NS RA-modified asphalt mixtures can meet the requirements for the zones, with a minimum temperature of no less than \(-21.5^\circ C\) [26]. Therefore, for an NS RA content of 8%, in comparison with base asphalt, the anti-cracking performance of the asphalt mixtures will slightly decrease, but except for extremely low-temperature areas, this will still meet the requirements for low anti-cracking performances of the pavement.

5. Conclusions

(1) In comparison with NA RA, the NS RA has a good modification effect as well. Whether it is original asphalt or aging asphalt, the softening point value of NS RA-modified asphalt is larger, and its penetration value is lower, in comparison with its base asphalt. At the same time, with the increase of NS RA content, its softening point and viscosity values are greatly increased; the penetration ratio is elevated, and its penetration value is greatly decreased. Therefore, NS RA can obviously improve the anti-rutting ability of the asphalt binder, and enhance the anti-aging performance of the asphalt binder as well. In comparison with the base asphalt, the low-temperature performance of NS RA modified asphalt slightly declines, and its low-temperature performance becomes weaker with an increase in NS RA content.

(2) Considering the raw-material price of NS RA, and the anti-rutting performance of NS RA modified asphalt mixture, the optimum NS RA content is about 8%. For an NS RA content of 8%, the dynamic stability values of NS RA modified asphalt mixtures are far greater than the summer hot-area requirements of the dynamic stability value (no less than 2800 times/mm). Therefore, the anti-rutting performances of their modified asphalt mixtures are excellent. At the same time, NS RA-modified asphalt mixtures used in the middle layer of a pavement can obviously improve the anti-rutting performance of the pavement.

(3) For the optimum NS RA content of 8%, its modified asphalt mixtures have good anti-water damage and ability anti-fatigue ability, and its anti-cracking performance meets the requirements for the zones with a minimum temperature of no less than \(-21.5^\circ C\). Therefore, it is feasible to determine the optimum NS RA content, based on its anti-rutting performance, and except for extremely low temperature areas, an effective method for solving the rutting problem of asphalt pavement could involve the use of NS RA-modified asphalt.

Author Contributions: Writing—original draft preparation, L.L.; project administration, Z.H.; analyzing test data and writing—review and editing, W.L.; performing the experiment, C.H.

Funding: This research was funded by the Hunan Provincial Natural Science Foundation of China (Grant No. 2015JJ2073), Hunan Provincial Department of Education of China (Grant No. 16A082) and the construct program of applied characteristic discipline in Hunan University of Science and Engineering.

Conflicts of Interest: The authors declare no conflict of interest.

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